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Karrikin: A New Age Phytohormone

Ankita Singh, Harsh Mishra, Kuldeep Rajpoot and Poonam Chaturvedi

Abstract

After a wildfire, landscapes often recover with an unexpected burst of new plant growth. Scientists discovered that this revival is driven by smoke-derived chemicals called karrikins, produced when plant materials such as cellulose burn. These compounds stimulate dormant seeds to germinate, especially in fire-prone ecosystems like Australia, South Africa, and California. Karrikins work by activating special receptor proteins inside seeds, which switch on growth-related genes and hormonal pathways needed for germination. At the same time, they can prevent germination under stressful conditions such as extreme heat or high salinity, helping plants survive unfavourable environments. Today, agricultural researchers are using karrikins and smoke-water treatments to improve seed germination and crop growth under drought, salinity, and temperature stress. They are also valuable in plant tissue culture and artificial seed production. As climate change increases pressure on global agriculture, these smoke-born molecules provide a promising natural tool for improving crop resilience and productivity.

Introduction

Karrikins are a small family of closely related chemical compounds found in smoke and charred plant material, produced naturally through the pyrolysis of carbohydrates like cellulose and sugars. Characterized structurally by a five-membered butanolide ring fused to a six-membered pyran ring, these compounds classified from KAR1 to KAR6 play a crucial role in plant biology by triggering seed germination and accelerating seedling growth. Initially discovered for their ability to regenerate "fire-following" flora in Mediterranean climates (such as parts of Australia, South Africa, and California), their molecular pathways have been extensively mapped using the model organism *Arabidopsis thaliana*. Today, karrikins are emerging as a powerful asset in modern agricultural biotechnology. When environmental stressors like drought, salinity, or extreme temperatures threaten to reduce crop yields by up to 50%, pre-sowing seed priming techniques using smoke-water or isolated KAR1 help ensure uniform germination, vigorous seedling emergence and enhanced stress tolerance. Furthermore, their application has expanded into *in vitro* plant tissue cultures to successfully regulate somatic embryogenesis and maximize mass plant propagation.

Structure and Chemistry of Karrikins

Similar to Strigolactones, Karrikins have a characteristic butanolide ring structure. This ring acts as a primary target for chemical reactions during signalling in plants. Karrikins lack a clear, built-in

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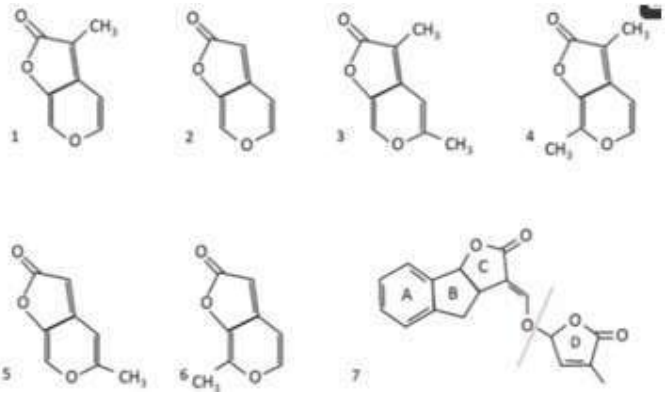
leaving group attached via an ether bridge to their butanolide ring. Karrikins are categorised as furano benzopyrans, consisting of a furan ring fused to a pyran ring, which is additionally linked to the butanolide ring. There are various naturally present karrikins designated as KAR1, KAR 2, KAR4, KAR 4, KAR 5 and KAR6. The difference between these six is entirely based on methyl group substitution on the core rings. The IUPAC name of Karrikins is 3-methyl-2H-furo[2,3-c]pyran-2-one. The two rings it contains are purely organic and have only carbon, hydrogen, and oxygen atoms. Karrikins are perceived by the receptor protein KAI2. It features as a hydrophobic binding pocket lined with highly conserved amino acids. This binding pocket of KAI2 is divided into two distinct gaps or cavities separated by a conserved phenylalanine (Phe) residue. If this Phe's side chain moves, it alters the shape of the second cavity, directly influencing what molecules can bind. KAI2 contains a highly conserved catalytic triad made up of three amino acids, namely Serine, Histidine, and Aspartic acid. Karrikins are crystalline substances in appearance. They have a melting point of 118 to 119 degrees Celsius. They quickly dissolve in organic solvents but are only mildly soluble in water. The major difference from strigolactones, apart from structure, is that strigolactones are naturally produ-ced in plants themselves from carotenoids, whereas karrikins are not naturally produced internally; instead, they are formed externally through the heating of carbohydrates, due to which they are present in wildfire smoke.

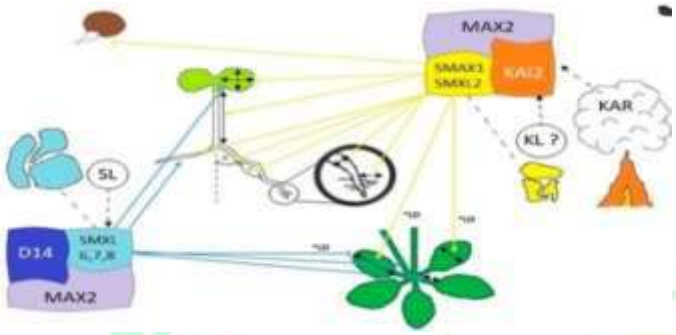


The known chemical structures of karrikin family representatives and strigolactone analog GR24. 1. KAR1 2. KAR2. 3. KAR3, 4 KAR4, 5. KAR5, 6. KAR6, 7. Strigolactone analog GR-24, the red line separates a lactone D ring, which is similar to the KARs butenolide ring.

Molecular signalling in Karrikins

Karrikins are externally produced signal molecules; a molecule of KAR1 binds specifically to the KAI2 receptor, which changes the physical shape of the KAI2 receptor and activates it. After activation by karrikins, KAI2 interacts with the helper protein called MAX2. Together with the repressor proteins (SMAX1/SMAX2), they lock together to form a multi-protein complex. The primary work of the MAX2 protein in this complex is to target the repressor proteins for destruction, which systematic-ally clears out SMAX1/SMAX2. This triggers light-responsive genes(like CHALCONE SYNTHASE) and leads to physical changes in the plant, like Seed germination, cotyledon expansion, shortening of petioles, chlorophyll, and anthocyanin accumulation. Plants possess an unidentified ligand called KL or KAI2 Ligand that utilizes the same signalling mechanism. The KAI2 signalling pathway exists in

non-vascular plants like bryophytes, long before the Karrikin receptor D14 evolved. Karrikin signalling suppresses auxin transport and signalling in the hypocotyl, which directly counteracts the elongation effects induced by shade. Karrikins also upregulate the biosynthesis of gibberellin during breaking down the ABA to trigger seed germination. Karrikins are also supported by ethylene for germination.



Model of signaling and effect of karrikins (KARs) and strigolactones (SLs) on *Arabidopsis thaliana* in different stages of ontogenesis. KARs produced by the burning of plant material and yet unidentified KAI2 ligand (KL) are perceived by the KAI2 receptor, which, by interaction with F-box protein MAX2, causes degradation of SMAX1 and SMXL2. SMAX1 represses seed germination, SMA X1 and/or SMXL2 repress cotyledon expansion, root straightness, root width, and root hair development, and promote lateral root development and root skewness and hypocotyl elongation by reduction of seedling light sensitivity; SMAX1 promotes expansion of rosette leaves blade under long-day conditions (*LD), SLs are perceived by receptor protein D14, which interacts with MAX2 and causes degradation of SMXL6,7,8. SMXL6,7,8 promotes cotyledon expansion, branching, and lateral root development; SMXL6,7,8 represses petiole and leaf blade elongation under long-day conditions.

Impact of Karrikins on Plant Growth and Development

Arabidopsis thaliana is a model plant for the study of plant physiology and is used for various research in science. It is not a fire-following species but is still very sensitive to karrikins, especially KAR2. This proves that biological mechanisms to detect karrikins are used by all plants to sense environmental cues and not exclusively for wildfire. GR24 ent-5DS is a stereoisomer of GR24-5DS, which turns on the Karrikin pathway and strigol-actone pathways, respectively. Therefore, both the molecules act together or Karrikins act alone in major physiological functions, while strigolactones support.

Germination and stem inhibition: Karrikins alone act on this during the initial stages of seedling and help the plant to establish, keeping the stem short and strong while increasing root area.

Leaf morphology: Karrikins, along with strigola-ctones, regulate the leaf formation in new plants after their establishment.

Root hair development: Karrikins improve the root-to-shoot ratio for maximizing nutrient absorption in plants. It protects plants from wilting or desiccation due to a lack of moisture.

Protection of Germination: KAR2 triggers germi-nation under favourable conditions in *Arabidopsis,* whereas under hostile environments such as high salinity or heat, these molecules prevent seed germi-

nation to protect the plant.

ROS production: In plants like wild oats (*Avena fatua*), karrikins trigger germination and an increase in Reactive Oxygen Species (ROS), which may be harmful for cells. Therefore, plants like maize and beans have evolved production of high levels of antioxidants to protect their tissues.

Modern Agricultural Applications of Karrikins

Smoke water, which is an aqueous solution produced by bubbling wildfire or burnt plant smoke through water, contains thousands of organic compounds, whereas Karrikin 1(KAR1), which is a pure, isolated and synthetically manufactured furanobenzopyran compound, is utilized in agriculture with a focus on primarily 2 practical applications: seed priming and seed tissue culture or biotechnology.

Seed priming or Pre-sowing treatment: It is a technique where seeds are soaked in a solution of smoke water or KAR1 and then dried before being planted. This gives seeds the following advantages: Better germination under stress conditions, where it helps in seedling establishment in unfavourable situations such as high heat up to 40 degrees Celsius or high salinity which prevents proper water absorption in the root zone. It also supports high vigour in plants and helps them sprout faster with more dry weight and grow into stronger seedlings for better chances of survival. It also increases chlorophyll content and carotenoid levels in plants, which boosts their photosynthesis.

Seed biotechnology and tissue culture: SW application induces flowering in fire following species and stimulates pollen grain germination and supports pollen tube growth. This leads to better fertilization and higher yields in crops. In somatic embryogenesis, where artificial seeds are produced from explants in the lab, SW and KAR1 act as chemical boosters that increase the success rate of embryogenesis. These chemicals have also been found to be useful for successfully germinating lab-grown embryos into fully formed plantlets. This method has been successful in wild plants (*Baloskion tetraphyllum*), ornamental flowers (*Pelargonium*), crops (*Brassica napus* / Rapeseed), and trees (*Pinus wallichiana* / Pine).

Karrikins have emerged as powerful natural signalling molecules with immense ecological and agricultural importance. Originally recognized for their role in post-wildfire seed germination, they are now known to regulate multiple aspects of plant growth through the KAI2–MAX2 signalling pathway. By promoting germination, enhancing stress tolerance, regulating plant development, and improving seedling vigour, karrikins provide plants with a sophisticated mechanism to survive changing environmental conditions. Their successful application in seed priming, tissue culture, and crop improvement highlights their potential in sustainable agriculture. As climate change and environmental stress increasingly threaten global food security, harnessing karrikin-based technologies offers a promising strategy for improving plant resilience, productivity, and future agricultural sustainability.

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Effect of Climate Change on Crop Production

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Abstract

In the twenty-first century, climate change has emerged as one of the greatest challenges to global agriculture and food security. Rising temperatures, erratic rainfall patterns, an increasing frequency of droughts and floods, and the occurrence of extreme weather events are significantly impacting crop productivity worldwide. Agriculture relies heavily on climatic conditions, and even slight variations in temperature, precipitation, and atmospheric carbon dioxide levels can affect crop growth, yield, and quality. Developing nations where farming depends largely on natural rainfall and traditional agricultural practices are particularly vulnerable to climate-related risks. Climate change not only diminishes crop production but also impacts soil fertility, water availability, the incidence of pests and diseases, and the socio-economic status of farmers. The productivity of major food crops such as wheat, rice, maize, and pulses is witnessing fluctuations due to changing climatic conditions. Furthermore, climate change has exacerbated abiotic stresses such as heat stress, salinity, waterlogging, and drought, resulting in substantial crop losses. To address these challenges, sustainable agricultural practices, climate-resilient crop varieties, efficient irrigation systems, integrated nutrient management, and modern technologies are becoming increasingly crucial. This article discusses the impact of climate change on crop production, the key factors contributing to agriculture's vulnerability, and potential adaptation and mitigation strategies to ensure future food security and sustainable agricultural development.

Introduction

Climate plays a pivotal role in agricultural production. Temperature, rainfall, humidity, solar radiation, and wind directly influence the growth and development of crops. For high yields, agriculture has historically relied on favourable climatic conditions. However, over the past few decades, human activities such as deforestation, industrialization, the burning of fossil fuels, and the excessive emission of greenhouse gases have led to rapid shifts in global climatic patterns. These changes have resulted in global warming, alterations in rainfall distribution, and an increased frequency of extreme weather events. Climate change refers to long-term

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shifts in temperature, precipitation, and weather conditions over time. According to scientists, the Earth's average temperature has risen significantly over the past century; the primary cause of this is the increase in greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases trap heat within the atmosphere, leading to global warming and disrupting the natural climatic balance. Agriculture is one of the most climate-sensitive sectors. Crop production is profoundly influenced by environmental changes, as crops require specific climatic conditions for germination, growth, flowering, and grain formation. Even slight shifts in climate can diminish agricultural productivity and pose a threat to food security. Developing nations like India are particularly vulnerable in this regard, as a significant portion of their population relies on agriculture for their livelihood.

The impact of climate change on crop production is now clearly evident manifesting as reduced yields, declining crop quality, increased pest infestations, water scarcity, and soil degradation. Due to unpredictable climatic conditions, farmers face significant challenges in maintaining stable crop production. Therefore, understanding the intricate relationship between climate change and agriculture is crucial for formulating effective strategies to safeguard crop productivity and ensure sustainable food production.

Causes of Climate Change

Greenhouse Gas Emissions: The primary cause of climate change is the increase in greenhouse gas emissions. Carbon dioxide released from industries, vehicles, and the burning of fossil fuels contributes significantly to global warming. The agricultural sector also emits methane and nitrous oxide gases through livestock rearing, rice cultivation, and the use of fertilizers.

Deforestation: Forests act as 'carbon sinks' by absorbing the carbon dioxide present in the atmosphere. Large-scale deforestation for urbanization, industrialization, and agricultural expansion diminishes the Earth's capacity to absorb greenhouse gases, thereby leading to a rise in global temperatures.

Industrialization and Urbanization: Rapid industrial development and urban expansion have led to an increase in energy consumption and pollution. Factories and transportation systems emit large quantities of greenhouse gases, which contribute to climate change.

Unsustainable Agricultural Practices: The excessive use of chemical fertilizers and pesticides, improper irrigation systems, and the burning of crop residues all of these contribute to environmental pollution and greenhouse gas emissions, thereby accelerating the pace of climate change.

Effects of Climate Change on Crop Production

Rise in Temperature: Rising temperatures negatively affect crop growth and productivity by disturbing important physiological and biochemical processes. Excess heat reduces photosynthesis, increases respiration, and causes moisture loss, leading to poor plant development.

Heat stress during flowering and grain filling particularly reduces yields in crops like wheat, rice, and maize. As a result, farmers experience lower production and economic losses.

Irregular Rainfall Patterns: Rising temperatures adversely affect crop growth and productivity by disrupting essential physiological and biochemical activities in plants. High temperatures reduce photosynthesis, increase respiration, and accelerate moisture loss, resulting in poor plant growth and development. Heat stress during critical stages such as flowering and grain filling significantly lowers yields in major crops like wheat, rice, and maize. Consequently, reduced agricultural production leads to economic losses for farmers.

Drought Stress: Drought is one of the most severe consequences of climate change. Prolonged periods of low rainfall reduce water availability for crops and livestock. Drought stress affects crops in the ways by reducing photosynthesis, by decreasing nutrient uptake, by limiting plant growth, by causing wilting and desiccation. Water scarcity during critical stages of development leads to a significant decline in crop productivity. Crops such as maize, pulses, and oilseeds are highly susceptible to drought conditions. Recurrent droughts also deplete groundwater levels and diminish soil fertility, making agriculture in arid and semi-arid regions less sustainable.

Flooding and Waterlogging: Due to climate change, the frequency and intensity of flooding have increased in many regions. Heavy rainfall and cyclones trigger severe floods, resulting in crop destruction and soil erosion.Waterlogging reduces oxygen availability in the root zone, adversely affecting root respiration and nutrient uptake. Prolonged flooding causes damage to crops such as wheat, pulses, and vegetables. Floods wash away fertile topsoil, destroy irrigation infrastructure, spread plant diseases, delay sowing and harvesting. As a result, farmers suffer major economic losses and food shortages may occur.

Increasing Incidence of Pests and Diseases: Climate change creates favorable conditions for the proliferation and spread of pests, insects, weeds, and pathogens. Elevated temperatures and humidity levels increase the reproductive rates and survival rates of pests. Due to changing climatic conditions, several crop diseases are becoming increasingly severe. For example, fungal diseases surge in humid conditions, insect populations multiply in warmer temperatures, new pests invade regions that were previously unaffected by them. Increased pest infestations lead to a decline in both crop yield and quality. Farmers often resort to using higher quantities of pesticides to control pests, which drives up production costs and exacerbates environmental pollution.

Soil Degradation: Climate change contributes to soil degradation through processes such as soil erosion, salinization, nutrient depletion, and the loss of organic matter. Heavy rainfall washes away fertile topsoil, resulting in soil erosion. Droughts and elevated temperatures diminish the activity of soil microorganisms and reduce the levels of organic

carbon present in the soil. In coastal regions, rising sea levels lead to increased soil salinity, which adversely affects crop growth. Poor soil health reduces nutrient availability and water-retention capacity, ultimately leading to a decline in agricultural productivity.

Impact on Food Security: Climate change threatens global food security by reducing agricultural productivity and increasing food prices. Lower crop yields lead to reduced food availability, especially in developing countries. Food insecurity affects nutrition, human health, rural livelihoods, economic stability. Small and marginal farmers are the most vulnerable because they have limited resources and depend heavily on agriculture for income. Population growth combined with declining crop productivity may create serious food shortages in the future if proper measures are not taken.

Socio-Economic Impact on Farmers: Climate change affects not only crop production but also the socio-economic condition of farmers. Crop failures, reduced income, and increased production costs create financial stress among farming communities. Farmers face debt burden, migration, unemployment, mental stress. Extreme weather events destroy crops and livestock, making recovery difficult for poor farmers. Agricultural instability also affects national economies, especially in countries where agriculture contributes significantly to GDP and employment.

Adaptation Strategies for Climate Change

Development of Climate-Resilient Varieties: Scientists are developing crop varieties that can tolerate drought, heat, salinity, and flooding. These climate-resilient varieties help maintain productivity under adverse environmental conditions. Examples include Heat-resistant wheat, Salt-tolerant crop

Efficient Water Management: Efficient use of water is essential for sustainable agriculture under climate change. Techniques include Drip irrigation, Sprinkler irrigation, Rainwater harvesting, mulching. These methods improve water-use efficiency and reduce water loss.

Sustainable Agricultural Practices: Adopting sustainable farming methods can reduce the negative impact of climate change. Important practices include organic farming, crop rotation, conservation tillage, agroforestry, integrated nutrient management. These practices improve soil fertility, conserve biodiversity, and reduce greenhouse gas emissions.

Use of Modern Technology: Modern technologies help farmers adapt to climate variability. Examples include Weather forecasting systems, Remote sensing, Precision agriculture, Mobile-based advisory services. These technologies assist farmers in making informed decisions regarding irrigation, fertilization, and pest management.

Government Initiatives and Policies: Many governments and international organizations are working to address climate change and agricultural sustainability.

Conclusion

Climate change has become a major threat to global agriculture and crop production. Rising temp-

eratures, irregular rainfall, droughts, floods, pest outbreaks, and soil degradation are significantly affecting agricultural productivity and food security. Developing countries are particularly vulnerable because agriculture remains the primary source of livelihood for millions of people. The impact of climate change on crop production is complex and multidimensional. It affects not only crop yield and quality but also the socio-economic condition of farmers and the stability of food systems. Major crops such as wheat, rice, maize, and pulses are already showing reduced productivity under changing climatic conditions. To overcome these challenges, there is an urgent need to adopt climate-resilient agricultural practices, improve water and soil management, develop stress-tolerant crop varieties, and promote sustainable farming systems. Governments, scientists, policymakers, and farmers must work together to ensure agricultural sustainability and future food security Climate-smart agriculture, technological innovation, and environmental conservation can play an important role in reducing the adverse effects of climate change. By adopting effective adaptation and mitigation strategies, it is possible to protect crop production and support sustainable development for future generations.

Export Diversification: Why India Cannot Depend on One Basket Anymore

Sebin Sara Solomon, Sreya Sripada, Kuldeep Rajpoot and Poonam Chaturvedi

Introduction

When people hear the word "exports," they often imagine giant ships carrying containers across oceans or businessmen negotiating international deals. But exports are not just about trade statistics and ports; they quietly shape the lives of ordinary Indians every day. The smartphone assembled in a factory in Tamil Nadu, the basmati rice grown in Punjab, the software coded in Bengaluru, and the medicines manufactured in Hyderabad are all part of India's growing export story. For decades, India depended heavily on a few export products such as textiles, tea, petroleum products, spices, and agricultural commodities. This dependence created a risky situation. If global demand for one product fell, or if international prices crashed, India's economy and millions of livelihoods were affected. Gradually, economists and policymakers realized that no country can sustainably grow by depending on only a narrow range of exports. This gave rise to the idea of export diversification expanding the variety of products and markets a country export to. Today, that picture is gradually changing. India is diversifying its exports by expanding into sectors such as engineering goods, electronics, pharmaceuticals, software services, processed foods, and automobiles. India's total exports of goods and services crossed nearly US$ 820 billion in FY 2024-25, showing the growing importance of trade in the economy. Merchandise exports contributed around US$ 437 billion, while services exports crossed US$ 380 billion. This shows that India is no longer dependent only on physical commodities but is also becoming a major exporter of digital and knowledge-based services.

The Nature of Change: From Traditional Products to Value-Added Products

The nature of exports in India is gradually changing. Earlier, exports were dominated by raw commodities with limited value addition. Today, global consumers are increasingly demanding processed and high-quality products such as frozen foods, ready-to-eat items, organic produce, processed fruits, dairy products, and seafood. One of the strongest examples of diversification is India's marine export sector. Shrimp exports have become a major source of export earnings, especially for coastal states such as Andhra Pradesh and Gujarat. India is among the world's leading shrimp exporters, supplying major markets like the United States, China, Japan, and Europe. Similarly, exports of fruits

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such as grapes, mangoes, bananas, and pomegranates are increasing steadily. Spices continue to remain an important strength for India. Products like turmeric, chilli, cumin, cardamom, and pepper have strong global demand. At the same time, processed food exports are gaining momentum due to rising international demand for packaged and convenience foods. This transformation is important because value-added exports generate higher income compared to raw commodity exports. A processed food product earns far more foreign exchange than exporting raw produce alone. Diversification therefore not only improves export earnings but also increases profitability for farmers, processors, and exporters.

Why Export Diversification is Important?

Export diversification is important because depending on only one or two products can be dangerous during global crises. International markets are highly uncertain. Oil price fluctuations, economic recessions, pandemics, or wars can suddenly reduce demand for certain products. The COVID-19 pandemic and recent geopolitical tensions clearly demonstrated this vulnerability. Countries that depended heavily on limited exports suffered major economic shocks. Diversification acts like an economic safety net. If one sector performs poorly, another sector can support growth and reduce economic losses. For India, diversification also creates employment opportunities across different sectors. Agricultural exports support farmers, manufacturing exports create factory jobs, and service exports generate employment for skilled youth in cities. As exports grow, industries expand, incomes rise, and government revenue increases.

A Recent Reminder of Why Diversification Really Matters

As India's exports continued expanding into global markets, recent global events once again highlighted why diversification is so important for a developing economy. The West Asia crisis and disruptions in the Red Sea route showed how closely agriculture, trade, transportation, and energy markets are connected. India imports more than 85% of its crude oil from West Asian countries like Saudi Arabia and Iraq. During the crisis, rising crude oil prices increased diesel and transportation costs, making irrigation, cold storage, food processing, and export transport more expensive for agriculture. This increased pressure on both farmers and exporters. The marine export sector, especially shrimp exports, also faced difficulties. Red Sea shipping disruptions increased freight and insurance costs and delayed exports to international markets. At the same time, Indian shrimp exports faced nearly 58% tariff pressure, reducing competitiveness against countries like Ecuador and Vietnam. These challenges particularly affected shrimp farmers and exporters in coastal states such as Andhra Pradesh and Gujarat. The situation highlighted an important lesson that depending heavily on limited markets, routes, or products can make exports vulnerable during global disruptions. This is why strengthening diversified and value-added exports has become increasingly

important for India's long-term agricultural and economic stability.

How Export Diversification Helps Common People

Export diversification is not just about economic statistics, it affects daily life. When exports expand across different industries, employment opportunities increase. Growth in electronics manufacturing creates jobs for youth. Agricultural diversification towards fruits, vegetables, spices, dairy products, and processed foods improves farmers' income. India's IT and software exports, which contribute a large share of service exports, have created millions of skilled jobs in cities such as Bengaluru, Hyderabad, Pune and Chennai. Similarly, growth in food processing and manufacturing industries supports rural employment and small businesses. Diversification also strengthens foreign exchange earnings. Higher foreign exchange reserves help stabilize the economy during crises and support imports of essential goods such as crude oil, fertilizers, and technology.

Challenges Still Remain

Despite progress, India still faces several barriers in achieving stronger export diversification. Logistics costs in India remain relatively high compared to countries like China and Vietnam. Poor storage facilities, port congestion, and transportation delays increase export costs. Another major issue is low value addition. India still exports many raw or semi-processed agricultural products instead of branded and processed goods. This reduces profit margins and global competitiveness. Quality standards also remain a challenge. Many small producers struggle to meet international packaging, safety, and certification requirements, limiting their access to global markets.

What India must do next

To strengthen export diversification further, India must focus on value-added production, infrastructure development, and innovation. Investments in ports, cold storage, warehouses, and transportation systems are necessary to reduce logistics costs.

India must also support: Research and development, Skill development, Digital trade, and small exporters. Agricultural exports should move towards high-value products such as organic foods, processed foods, spices, dairy products, and horticultural products. India should also reduce dependence on a few export markets by strengthening trade relations with Africa, Southeast Asia, and Latin America.

Government Initiatives Supporting Export Diversification

To strengthen export diversification, the Government of India has introduced several initiatives such as Make in India, the Production Linked Incentive (PLI) Scheme, and the Agriculture Export Policy (2018). These programmes encourage manufacturing, value addition, food processing, and agricultural exports. Schemes like PM Kisan Sampada Yojana and PM- Formalisation of Micro Food Processing Enterprises Scheme support cold storage, food processing, and supply chain infrastructure. The Marine Products Export Development

Authority (MPEDA) also helps marine exporters through quality certification and export promotion. Along with this, India is expanding trade relations with Africa, Southeast Asia, and Latin America to reduce dependence on a few traditional export markets.

Conclusion

India's export economy is gradually transforming from traditional commodity dependence towards diversified and value-added exports. From processed foods and marine products to electronics and software services, India is expanding its presence across global markets. However, recent global events clearly showed that depending heavily on limited products, markets, or trade routes can create serious economic risks. Export diversification is therefore no longer simply an economic strategy, it is essential for protecting farmers' incomes, generating employment, strengthening rural livelihoods, and ensuring long-term economic stability. In an uncertain global economy, diversification gives India the ability not only to withstand global shocks but also to emerge stronger from them.

Farming is becoming a Gamble: Climate Change and Agriculture

Sebin Sara Solomon, K. Nagaraju, Abdul Haseeb and Veena Rathore

Introduction

Farming has always been a game of chance, relying on the mercy of weather and nature to yield a successful harvest. But today, the stakes are unimaginably high. Climate change has transformed age-old farming practices into an unpredictable gamble where rising temperatures, erratic rainfall, biological disruptions threaten the global food supply. Today, farmers are no longer up against an occasional bad season; they are facing a paradigm shift that tests the limits of their resilience. To protect the global food supply, and hence our future, we must first understand the fundamental concept of this underlying issue, the shifting landscape, acknowledge the problems it creates, study the evidence of its impact and deploy robust measures to flip the odds back in our favour.

Concept

Understanding the current agricultural crisis requires distinguishing between a few core concepts. Global warming is the heating of the Earth's surface atmosphere over a long period due to emission of greenhouse gases like carbon dioxide, which trap outgoing infrared radiation. This leads to climate change, which encompasses long-term alterations in surface air temperature and adverse impacts on rainfall patterns, while year-to-year fluctuations are known as climate variability. Agriculture finds itself in a unique position: it is highly sensitive to climate change, yet it is also one of the major drivers of it.

To counter this, the concept of "Climate-Smart Agriculture" (CSA) has emerged. CSA focuses on creating a conducive environment for farmers by adapting policies and utilizing risk management tools to make food systems more resilient. Whether these objectives are met depends heavily on the collaborative engagement of governments, the private sector, and civil society (NGOs) to promote sustainable practices, test new agricultural systems like the System of Rice Intensification (SRI) and provide essential financing and knowledge to farmers.

Problem

The problems introduced by climate change are severe and multifaceted, particularly for nations like India where about 60% to two-thirds of cultivated land is rain-fed and highly exposed to abiotic and biotic stresses. The Earth's global temperatures have risen unusually rapidly over the last few decades, triggering a domino effect of environmental disasters.

Extreme Weather: The frequency of extreme

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events like heat waves, cold waves, floods, and severe droughts has increased, causing massive destruction. For instance, lack of tree cover exacerbates drought, making soil dry out faster, while heavy precipitation strips the land of topsoil.

Physiological Crop Stress: Elevated temperatures constrain crop productivity. They reduce crop duration, increase crop respiration rates, and can lead to heat stress at critical growth stages, which negatively impacts yields for major staples like wheat and rice.

Biological Shifts & Pest Expansion: Climate change is significantly altering the dynamics of agricultural pests and diseases. Rising temperatures expand the geographical range and abundance of devastating pests like the cotton bollworm (*Helicoverpa armigera*) and the brown plant hopper (BPH) due to rapid generation turnover. Consequently, minor pests can rapidly evolve into major threats. Furthermore, unpredictable weather patterns, such as prolonged droughts followed by high intermittent rains, have caused severe outbreaks of dry root rot in chickpeas and Phytophthora blight in pigeon peas.

Carbon-to-Nitrogen Shifts & Lowered Plant Defenses: Elevated CO_2 levels increase the Carbon-to-Nitrogen ratio in plant tissues, which slows the decomposition of leaf litter and increases pathogen survival rates. Additionally, increased CO_2 levels result in a decreased production of secondary metabolites, which effectively lowers a plant's natural defenses against insect attacks.

Evidence

The tangible evidence of this gamble is seen in both localized crop failures and global economic shocks. In 2024 alone, extreme weather events occurred on about 90% of days from January to September in India, affecting 3.2 million hectares of crops.

Yield Declines: Data models predict a bleak future if our adaptation practices fail. By 2050, average yields in South Asia could plummet with wheat dropping by up to 50%, rice by 17%, and maize by 6%. The physiological sensitivity of these crops is so acute that every 1°C rise in temperature is estimated to reduce Indian wheat production by 4 to 5 million tons.

Economic Losses: The financial toll is already massive. The 1997-98 El Nino event cost the global economy nearly US$ 100 billion. In India, the "All-India drought" of 2002 caused a staggering 19.1% drop in *kharif* food grain production. More recently, experts warn that without climate-smart agriculture, the sector could face 15% to 20% average production losses over the next 15 years.

Global Domino Effects: When climate threats strike domestic agriculture, the ripple effects hit the global market. Fearing production drops, India frequently imposes export restrictions on staples like rice, wheat, and onions. Because India supplies 40% of the world's rice exports, these bans such as the July 2023 restriction on non-basmati white rice that led to a 34% reduction in total rice exports cause severe global price surges. This threatens food security in

numerous developing nations, and is particularly detrimental to African nations, where India's market share of rice imports often surpasses 80%.

Policy

To hedge against these monumental risks, governments and institutions are rolling out vital policy frameworks and technological interventions.

Technological Innovations & Altered Planting: The Indian Council of Agricultural Research (ICAR) launched the National Innovations in Climate Resilient Agriculture (NICRA) project, which has released 2,177 crop varieties tolerant to biotic and abiotic stresses over the last decade. Changing planting dates such as sowing wheat earlier to escape terminal heat stress, or changing the planting time of potatoes is also heavily promoted as a critical, low-cost climate-smart strategy.

Emissions Reductions through Conservation Agriculture: The government is heavily promoting Conservation Agriculture, which relies on resource-conserving technologies (RCTs) like zero-tillage to improve energy and water efficiency while reducing greenhouse gas emissions. For example, direct-seeding rice in fields (rather than growing it in nurseries and transplanting) not only saves water but reduces greenhouse gas emissions from the crop by about 40%.

Risk Mapping AND Resilient Villages: The government has conducted vulnerability assessments across 651 predominantly agricultural districts, identifying 109 as 'very high' risk, and is establishing “Climate Resilient Villages” in these areas to demonstrate adaptation technologies.

Financial and Insurance Safety Nets: Policies like the Pradhan Mantri Fasal Bima Yojana (PMFBY) provide full insured amounts for crop losses due to natural calamities, acting as a crucial buffer for farmers. Looking to the future, Union Budget 2026 expectations emphasize the need to expand the ambit of drip irrigation, promote organic farming, and specifically increase the limits of Kisan Credit Cards (KCC) to ensure farmers have the capital to invest in modern techniques.

Market and Regulatory Frameworks: Effective climate-smart policy utilizes market-based instruments, such as input subsidies for water-saving technologies (like micro-irrigation under the Per Drop More Crop scheme), and payments for environmental services (PES). Additionally, securing land tenure rights is emphasized as a foundational regulatory instrument, empowering smallholders to make long-term investments in sustainable landscape management without the fear of losing their land.

Conclusion

Modern agriculture is facing a period of intense transition. While climate change has introduced significant challenges for farmers ranging from erratic weather patterns to aggressive pests and shrinking yields these issues are not insurmountable. By actively integrating climate-smart concepts, taking the evidence of crop losses seriously, and implementing forward-thinking policies, we can create a more stable environment for food production. Ultimately, providing farmers with resilient

seeds, sustainable technologies, and reliable financial safety nets will be the key to securing the global food supply. Farming will always involve some level of unpredictability, but with the right preparation, we can effectively manage the risks and ensure a dependable future for agriculture.

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Fertilizer Crisis & Global Conflicts

Sebin Sara Solomon, K. Nagaraju, Abdul Haseeb and Pratik Kumar

Introduction

The global fertilizer crisis triggered by disruptions in the Strait of Hormuz is emerging as a serious threat to world food security. According to the Food and Agriculture Organization (FAO), interruptions in fertilizer supply chains could lead to lower crop yields and tightening food supplies in 2026 and 2027. The crisis extends far beyond geopolitics, increasingly affecting food production, agricultural inputs, trade and access to food worldwide. FAO Director-General Qu Dongyu warned that disruptions in maritime trade routes are already tightening fertilizer markets and increasing energy costs, with potentially severe consequences for agricultural production and food prices. He emphasized that agriculture operates within a fixed crop calendar where fertilizers must be applied at critical stages of crop growth. Even delays of a few weeks in fertilizer availability can reduce yields and threaten future harvests, particularly in import-dependent countries already facing food insecurity and economic vulnerability.

Concept

Global Fertilizer Market Disruption: The ongoing Iran conflict has intensified disruptions in the Strait of Hormuz, one of the world's most strategic maritime trade corridors. According to IFPRI, nearly 30% of global fertilizer trade, 20% of liquefied natural gas (LNG), and 27% of globally traded oil pass through this route. Restrictions on shipping and attacks on production facilities and export hubs in the Gulf region have already disrupted fertilizer and energy supply chains worldwide. Since the Persian Gulf is a major hub for nitrogen and phosphate fertilizer production, any prolonged disturbance threatens global agricultural production and food security. The Gulf countries accounted for 36% of global urea exports during 2023-25, while the region also contributed 26% of global DAP exports and 13% of MAP exports. Qatar alone supplies around 10% of globally traded natural gas, which is a key raw material for nitrogen fertilizer production. IFPRI further notes that sulfur exports from Gulf countries account for nearly 50% of globally traded sulfur, an essential component for phosphate fertilizer processing. These figures clearly indicate how heavily the world depends on the Gulf region for fertilizer production and trade.

Rising Fertilizer Prices: The conflict has already caused sharp increases in fertilizer and energy prices across international markets. IFPRI reports that disruptions in LNG supplies and fertilizer exports

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from the Gulf region have significantly increased the prices of urea, ammonia and DAP fertilizers. Rising natural gas prices are increasing fertilizer production costs globally because natural gas is both a major feedstock and the primary energy source for producing ammonia, the foundation of nitrogen fertilizers. The report also warns that prices are likely to continue rising as long as production and shipping from the Gulf remain disrupted. European fertilizer producers have already requested government support to sustain domestic production due to surging gas prices. Countries heavily dependent on Gulf LNG imports, including India and Pakistan, are facing increasing pressure on fertilizer availability and production costs. The present crisis resembles earlier fertilizer shocks witnessed during the Russia–Ukraine war and the COVID-19 period, both of which caused severe price spikes in global fertilizer markets.

Impact on Agriculture: Higher fertilizer prices directly threaten agricultural production by increasing input costs for farmers. IFPRI explains that rising fertilizer and energy costs are occurring at a time when agricultural commodity prices are comparatively lower, creating an unfavorable input-output price ratio. As fertilizer becomes more expensive, farmers tend to reduce fertilizer use, which may ultimately lower crop productivity. The report warns that a prolonged increase in fertilizer prices, especially nitrogen-based fertilizers, could significantly affect yields of fertilizer-intensive crops such as rice and wheat. IFPRI also notes that countries in Africa and South Asia are particularly vulnerable because they rely heavily on imported fertilizers. Fertilizer use in Africa reportedly declined by 25% following the Russia–Ukraine conflict, demonstrating how geopolitical shocks can directly reduce agricultural input usage. Furthermore, delayed fertilizer availability can disturb crop cycles because fertilizers must be applied at specific stages of crop growth. If disruptions continue, farmers may be forced to shift toward less fertilizer-intensive crops, potentially affecting overall agricultural output and cropping patterns.

Food Inflation & Food Security: The fertilizer crisis is increasingly becoming a food security crisis. IFPRI warns that reduced fertilizer use and lower crop yields could eventually lead to sharp increases in food prices, especially in countries highly dependent on imported fertilizers and food commodities. Since fertilizers are essential for maintaining global agricultural productivity, prolonged supply disruptions threaten both food availability and affordability. The report highlights that vulnerable regions, particularly Africa and parts of Asia, are likely to face the greatest risks due to import dependence, weak purchasing power and existing food insecurity. The International Rice Research Institute also warned that continued disruptions in fertilizer and energy channels through the Strait of Hormuz could become major short- and medium-term risks for Asia's crop cycle. IFPRI concludes that the Iran conflict represents the third major global fertilizer shock in the past six years after COVID-19

and the Russia-Ukraine war. Despite some resilience in fertilizer markets, heavy dependence on fossil fuels, concentrated production in a few regions and fragile global trade systems continue to expose world agriculture to severe food security risks.

Evidence

The ongoing Iran conflict has exposed the extreme dependence of the global fertilizer market on the Persian Gulf region. According to IFPRI, nearly 30% of global fertilizer trade, 20% of liquefied natural gas (LNG), and 27% of globally traded oil pass through the Strait of Hormuz. Any disruption in this critical maritime corridor directly affects fertilizer production, transportation and global food systems. IFPRI further reports that Gulf countries accounted for 36% of global urea exports during 2023-25, making the region the largest exporter of nitrogen fertilizers. The Gulf region also contributed 26% of global DAP exports and 13% of MAP exports. Qatar alone supplies around 10% of globally traded natural gas, which is a key feedstock for ammonia and nitrogen fertilizer production worldwide. The report highlights that countries such as India, Pakistan, Bangladesh and several African nations are highly vulnerable because of their dependence on Gulf LNG and fertilizer imports. Fertilizer use in Africa reportedly declined by 25% following the Russia-Ukraine war due to rising prices and supply disruptions, demonstrating how geopolitical conflicts can directly reduce agricultural input usage and threaten food security. IFPRI also notes that fertilizer prices have already risen sharply due to disruptions in LNG supplies and maritime shipping through the Gulf region. Rising natural gas prices are increasing fertilizer production costs globally, particularly for nitrogen fertilizers such as urea and ammonia. The report warns that prolonged disruptions could lead to lower fertilizer use, reduced crop yields and higher food prices, especially in import-dependent developing countries. The study concludes that the ongoing Iran conflict represents the third major global fertilizer shock in the last six years after the COVID-19 pandemic and the Russia-Ukraine war. Despite some resilience in global markets, fertilizer production and trade remain highly concentrated in a few regions, leaving world agriculture increasingly vulnerable to geopolitical conflicts and supply chain disruptions.

Solutions

The present fertilizer crisis highlights the urgent need to build resilient and sustainable agricultural systems. According to the World Economic Forum (WEF), improving soil health and promoting regenerative agriculture can help reduce excessive dependence on chemical fertilizers. Sustainable farming practices such as crop diversification, balanced nutrient management and efficient fertilizer application can improve long-term agricultural resilience. IFPRI also emphasizes the importance of protecting global fertilizer supply chains during geopolitical conflicts. Governments should avoid export restrictions and ensure uninterrupted fertilizer shipments because such restrictions further increase global prices and worsen food insecurity.

International cooperation and diversified trade routes are essential to reduce dependency on conflict-prone regions such as the Persian Gulf. The reports further suggest increasing investment in domestic fertilizer production, strategic fertilizer reserves and alternative energy sources. Expanding the production of green ammonia using renewable energy could reduce dependence on fossil fuels and create a more sustainable fertilizer industry in the future. Balanced and efficient fertilizer use should also be promoted to minimize nutrient losses and reduce over-dependence on nitrogen fertilizers. Greater use of organic fertilizers, microbial fertilizers and slow-release nutrient technologies can help strengthen food systems against future geopolitical and market shocks.

Conclusion

The fertilizer crisis caused by rising geopolitical conflicts has emerged as a serious challenge to global agriculture and food security. The ongoing disruptions in the Strait of Hormuz, along with tensions involving Iran, Israel and major global powers, have exposed the vulnerability of fertilizer supply chains that are heavily concentrated in a few regions. Rising fertilizer and energy prices are increasing production costs, reducing fertilizer accessibility and threatening agricultural productivity across many developing countries. The findings from FAO and IFPRI clearly show that fertilizer security is no longer only an agricultural issue but also a matter of economic stability and global food security. Repeated shocks caused by the COVID-19 pandemic, the Russia-Ukraine war and the present Iran conflict demonstrate how fragile global fertilizer systems have become under geopolitical uncertainty. To reduce future risks, countries must strengthen resilient fertilizer supply chains, diversify import sources and promote sustainable agricultural practices. Greater international cooperation, balanced fertilizer policies and investment in climate-smart and regenerative agriculture will be essential for ensuring stable food production and protecting farmers from future global crises.

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Germplasm: Insurance for Food and Farming Futures

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Germplasm is the basic biological resource of crop improvement. It includes landraces, old varieties, modern cultivars, breeding lines, wild relatives, and other plant materials that carry useful genes for yield, quality, resistance, and adaptation. Every breeding programme ultimately depends on the diversity present in its germplasm, because no breeder can develop a new variety unless useful variation for the target trait is available somewhere in the gene pool. This makes germplasm valuable not only for the present, but even more for the future. As climates shift, new pests spread, rainfall becomes erratic and nutritional demands rise, crop improvement will increasingly depend on access to diverse genes preserved from the past and available for future use. Germplasm is the foundation of crop improvement. The success of plant breeding depends on the diversity of genetic resources available. Broad variability gives breeders more options to combine genes for yield, quality, resilience, and adaptation, while narrow diversity slows progress. It is the reason tgermplasm is called the "raw material" of breeding as every high-yielding, biofortified, disease-resistant, or climate-resilient variety traces back to conserved genetic resources. Even modern cultivars rely on hidden reserves of diversity stored in gene banks and farmers' fields for their future improvement.

Germplasm and the challenge of the future

The future value of germplasm is rising because agriculture is entering a period of compounding pressure. The global population continues to grow, and food systems must provide not only more calories but also better nutrition, while facing water scarcity, land degradation, climate shocks, and emerging pests and diseases. FAO has emphasized that crop diversity is central to food security and nutrition, and that conserving and using plant genetic resources is now a matter of urgency. According to FAO's recent assessment, 42 percent of crop genetic diversity was no longer found in at least one of the areas where it had been present only 10 to 15 years earlier, showing how fast diversity can erode under environmental and human pressure. The same report noted that more than 4,000 disasters affected 1.3 billion people between 2012 and 2019, and more than two-thirds of those disasters were climate related (FAO, 2021). Under these conditions, genes for heat tolerance, drought escape, salinity tolerance, flood survival, and resistance to new

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pathogens will become increasingly valuable.

Germplasm improvement: conservation is not enough

Conservation is essential, but stored diversity must also be characterized, evaluated, and used. Germplasm improvement includes collecting accessions, documenting traits, evaluating them under different conditions, identifying useful genes or donor parents, and bringing those traits into breeding populations through pre-breeding and selection. In other words, germplasm becomes truly valuable when it moves from storage to use. This process is especially important for difficult traits. Genes for stress tolerance, resistance to emerging diseases, or quality traits often occur in landraces, wild relatives, or old farmer-maintained populations rather than in elite cultivars. Such materials may have poor agronomic performance by themselves, but they carry rare alleles that can be transferred into adapted backgrounds through long-term breeding work.

Public sector conservation and the role of farmers : The public sector has done major work in conserving plant genetic resources through national and institutional gene banks. In India, the National Genebank at ICAR-NBPGR, New Delhi conserves plant genetic resources for long-term use, including landraces and traditional varieties that are valuable sources of agriculturally important genes. As reported by the Government of India, the National Genebank held 441,253 accessions belonging to 1,948 species by June 2019, including 83,394 accessions of landraces and primitive varieties (PIB, 2019). This is a major national achievement, but ex situ conservation alone is not sufficient. Many valuable materials continue to survive not in cold storage but in farmers' seed systems, where selection and adaptation continue from season to season. Community-level conservation therefore complements formal gene banks by keeping diversity alive, locally adapted, and available for practical use.

Community seed banks and local access

Local seed banks are especially important because they connect conservation with use. A national gene bank protects diversity at scale, but a community or local seed bank helps farmers access seed, multiply local varieties, exchange planting material, and return seed back into the system after harvest. This kind of "in and out" access is vital if conservation is to benefit ordinary farmers rather than remain limited to institutions.

Examples from India show the potential of such systems. Community seed banks supported through local initiatives have helped collect and conserve more than 200 climate-resilient crop varieties in India while improving farmers' access to quality seed (Farmers Rights. (n.d.)). Similar approaches are also being strengthened through international partnerships in India and Kenya, where community seed banks are being used to conserve agrobiodiversity, support climate resilience, and improve local livelihoods.

Indian examples and the importance of local custodians

India is globally recognized as a mega-centre of agrobiodiversity, and this diversity is linked closely with local communities and traditional farming landscapes. Studies from the Central Western Ghats recorded 671 landraces belonging to 60 crops across 24 sites, showing that remarkable diversity still exists where on-farm conservation remains active.The same study noted that the National Genebank at ICAR-NBPGR conserves around 550 accessions of landraces collected from that surveyed region, demonstrating the value of linking on-farm and ex situ conservation. Tribal communities and traditional cultivators often preserve landraces not because they are "old," but because they remain useful for taste, nutrition, resilience, and cultural fit. For breeding in a climate-uncertain future, this farmer-conserved diversity may become one of agriculture's most important strategic assets.

International perspective

Gene banks have become central to global food security. FAO reported that by December 2022, more than 5.9 million accessions were being conserved in 116 countries and in 17 international and regional gene banks. These collections act as a global insurance system for crop diversity, especially when varieties disappear from farmers' fields or wild habitats are degraded (FAO UN, 2022). The lesson from the international experience is clear. Large national and international gene banks are essential for long-term conservation, but local and community-based seed systems are equally important for keeping diversity dynamic, accessible, and socially rooted. Future-ready conservation must therefore connect laboratory cold storage with living field-level stewardship.

Threats to germplasm and agrobiodiversity

The threats to germplasm are both human-made and natural. Major human-driven threats include replacement of diverse local varieties by a narrow range of uniform modern cultivars, habitat destruction, monocropping, market-driven homogenization, weak support for traditional seed systems, and loss of indigenous knowledge about local crops. Natural and climate-linked threats include droughts, floods, heat waves, salinity, invasive pests, diseases, and ecological shifts that can eliminate rare populations before they are collected and conserved. The phrase "use it or lose it" captures this risk well. When genetic resources disappear from fields and landscapes, the genes they contain may be lost forever, reducing future breeding options and making agriculture more vulnerable. This is why the loss of germplasm is not just a conservation issue; it is a direct threat to long-term agricultural productivity and food system resilience.

Conservation strategies for the future

Future conservation must be strategic, decentralized, and linked to use. A strong national system should continue collecting, documenting, and safely storing germplasm from different geographical regions, especially landraces, wild relatives, and old farmer varieties that may contain rare adaptive genes. At the same time, local and regional

seed banks should be established or strengthened so that farmers can access conserved varieties at affordable cost, deposit seed after harvest, and participate actively in seed circulation and maintenance. A practical future strategy would include several parallel actions.

- ✓ Systematic collection of germplasm from each agro-ecological region before further erosion occurs.
- ✓ Strengthening national, state, university, and community seed banks and linking them through clear data-sharing and accession tracking.
- ✓ Making local seed banks farmer-friendly, with simple rules for borrowing, returning, and multiplying seed.
- ✓ Characterizing germplasm for stress tolerance, quality, and nutritional traits so that conserved material is ready for breeding use.
- ✓ Supporting custodian farmers, especially women, tribal communities, and marginal farmers who maintain diversity on-farm.
- ✓ Integrating conservation with public breeding, climate adaptation plans, and nutritional security programmes.

Germplasm is not a passive collection of old seeds; it is the living foundation of present and future agriculture. The strength of any breeding programme depends on the depth and diversity of the genetic resources it can access, conserve, understand, and use. In an era of climate uncertainty, nutritional need, and rising pressure on food systems, conserving germplasm and agrobiodiversity is one of the most practical investments agriculture can make.

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Global Uncertainty and the Indian Economy: Understanding the Impact of the Iran-US Conflict

Poonam Chaturvedi, Sebin Sara Solomon, Kiran Parel and Kuldeep Rajpoot

Introduction

The world economy is currently experiencing a period of uncertainty marked by geopolitical conflicts, inflation, disruptions in global trade, and slowing economic activity. One of the most closely watched developments is the growing tension involving Iran, the United States, and Israel in the West Asian region. Although the conflict is centered far from India, its economic effects are being felt across countries that depend heavily on imported energy and global trade networks. India, being one of the world's fastest-growing economies and also a major importer of crude oil, is particularly sensitive to such international developments. Rising fuel prices, inflationary pressure, uncertainty in financial markets, and increasing production costs are some of the immediate consequences that have emerged due to instability in the Middle East.

Background of the Conflict

The strained relationship between Iran and the United States has existed for several decades. The situation became tense after the Iranian Revolution in 1979, which changed Iran's political structure and significantly weakened diplomatic relations with the United States. Since then, disagreements over Iran's nuclear activities, economic sanctions, regional influence, and military alliances have repeatedly increased tensions between the two countries. In recent years, the conflict intensified because of military actions involving Israel, attacks on commercial shipping routes in the Gulf region, and the growing role of Iranian-backed armed groups operating in parts of Syria, Iraq, Lebanon, and Yemen. Several retaliatory attacks and military responses further increased fears that the conflict could expand into a larger regional war. A major reason why global markets react strongly to this situation is the strategic importance of the Strait of Hormuz. This narrow maritime route carries nearly 20 percent of global crude oil shipments. Any threat to this route immediately creates concerns regarding global oil supply disruptions. As tensions escalated, international crude oil prices crossed 100 dollars per barrel during several trading sessions.

Present Status of the Situation

At present, the conflict has not turned into a direct large-scale war between Iran and the United States. However, military tensions, naval confrontations, cyberattacks, and proxy conflicts continue to create instability across the region. International financial institutions, including the IMF and World Bank, have warned that prolonged geopolitical instability may reduce global economic growth and revive inflationary pressure worldwide.

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Although India continues to maintain comparatively strong economic growth, the country remains vulnerable because of its dependence on imported energy. Nearly 85 percent of India's crude oil requirement is imported from foreign countries, much of it from the Middle East. Consequently, fluctuations in global oil prices directly affect India's domestic economy.

Rising Oil Prices and Inflationary Pressure

One of the earliest and most visible consequences of the conflict has been the sharp increase in international crude oil prices. Fears regarding possible supply disruptions pushed Brent crude prices above 107-112 dollars per barrel. As global oil prices increased, fuel prices in India also began rising. Petrol and diesel prices increased in major Indian cities, raising transportation and logistics costs throughout the economy. Higher fuel prices eventually influence the prices of food products, manufactured goods, electricity, and essential services. Economic experts estimate that every 10-dollar increase in crude oil prices can reduce India's GDP growth rate by approximately 0.1-0.2 percentage points while simultaneously increasing inflation levels. Inflation creates multiple economic problems. When the prices of fuel, food, transport and household necessities rise continuously, the purchasing power of consumers declines. Families begin reducing non-essential spending, which weakens demand for consumer products and services. This can eventually slow industrial production, business expansion, and employment generation.

Sectors Facing Direct Economic Impact

Aviation Sector: The aviation sector is among the most affected industries because Aviation Turbine Fuel (ATF) forms a significant portion of airline operating expenses in India. Rising crude oil prices directly increase airline costs and reduce profitability. Higher fuel costs often lead to increased ticket prices, which may reduce passenger demand, especially on domestic routes where price sensitivity is high. Major airlines are therefore likely to face operational pressure if fuel prices remain elevated over an extended period.

Transportation and Logistics: The transport and logistics sector experiences immediate cost increases because diesel is the primary fuel used for freight movement. As transportation expenses rise, the cost of distributing goods across the country also increases. This eventually affects the prices of vegetables, food grains, consumer goods, and industrial products. Small businesses and rural consumers are particularly affected because higher transport costs reduce profit margins as well as purchasing power.

Fertilizer and Agriculture Sector: India depends significantly on imported fertilizer inputs and energy-linked raw materials. When global energy prices rise, fertilizer production and import costs also increase. As a result, cultivation expenses for farmers increase through higher diesel, irrigation, transportation and fertilizer costs. Small and marginal farmers are especially vulnerable because rising input expe-

nses reduce farm profitability and income stability.

Automobile Industry: The automobile industry is also facing rising production costs because higher fuel prices increase transportation expenses and commodity prices. Costs associated with steel, aluminium, freight services, and logistics have increased due to global uncertainty. Several automobile manufacturers have already indicated that geopolitical instability is affecting supply chains and creating inflationary pressure within the industry. Rising diesel prices may also reduce demand for commercial vehicles and freight transportation services.

Oil Marketing Companies (OMCs)

Public sector oil marketing companies such as Indian Oil, BPCL, and HPCL are under financial pressure because rising global crude prices are not always immediately transferred to consumers. When international oil prices rise sharply, these companies may incur significant under-recovery losses if retail fuel prices are controlled for political or economic reasons. This can increase fiscal pressure on the government and affect public finances.

Impact on Employment and Household Income

Global economic uncertainty generally discourages private investment and slows industrial activity. Export-oriented industries such as manufacturing, textiles, automobiles, logistics, and chemicals may reduce hiring if international demand weakens. Small and medium enterprises (MSMEs), which provide large-scale employment in India, are especially vulnerable because they operate with limited financial flexibility and are highly sensitive to rising operational costs. At the household level, inflation reduces real income. As spending on fuel, food, transport, LPG, and electricity increases, families reduce expenditure on discretionary goods and services. This affects retail trade, hospitality, tourism, consumer products, and service industries.

Financial Markets and Exchange Rate Pressure

Geopolitical conflicts often create instability in international financial markets, prompting investors to move their funds toward comparatively safer assets such as gold and US government securities. This shift generally results in capital outflows from emerging economies, including India. After tensions intensified in West Asia, foreign portfolio investors reportedly pulled out more than ₹18,000 crore from Indian equity markets during April-May 2026, increasing volatility in domestic financial markets.

At the same time, rising global crude oil prices increased India's import expenditure and exerted additional pressure on the Indian rupee. The rupee weakened from nearly ₹82.8 per US dollar in early 2025 to around ₹85-86 per dollar during phases of heightened geopolitical uncertainty in 2026. Depreciation of the domestic currency makes imports such as crude oil, fertilizers, machinery, and electronic products more expensive, thereby adding to inflationary pressure within the economy. Since India relies on imports for nearly 85 percent of its crude oil requirement, exchange rate fluctuations significantly influence fuel import costs and the current account deficit.

RBI assessments also indicate that a 5 percent depreciation in the rupee may increase imported inflation by nearly 20-25 basis points over the medium term.

Why India Still Maintains Relative Stability

Despite external challenges, India possesses several structural advantages that help maintain economic resilience. Strong domestic consumption, rising infrastructure investment, digital expansion, and a large internal market continue supporting economic activity. Government expenditure on highways, railways, renewable energy, logistics, and manufacturing infrastructure is also helping sustain economic momentum. In addition, India's expanding digital economy and financial inclusion systems provide greater flexibility during periods of global uncertainty.

Future Prospects and Policy Measures

The present crisis highlights the importance of long-term economic preparedness, particularly for countries like India that depend heavily on imported energy. Reducing excessive reliance on fossil-fuel imports and strengthening domestic economic resilience should therefore become major policy priorities.

Strengthening Energy Security

Expanding renewable energy generation: India should increase investment in renewable energy sources such as solar, wind, hydro, and green hydrogen. Greater renewable energy capacity can reduce crude oil dependence while supporting sustainable economic growth.

Increasing strategic petroleum reserves: Expanding emergency petroleum reserves can help the country manage temporary global supply disruptions and stabilize the domestic economy during geopolitical crises.

Promoting electric mobility and energy diversification: Encouraging electric vehicles, public transport, biofuels, and alternative energy sources can gradually reduce exposure to volatile global oil prices and lower import bills.

Supporting Vulnerable Industries

Financial assistance for MSMEs: Small businesses are highly sensitive to rising fuel and production costs. Easier credit access, low-interest loans, and temporary policy support can help MSMEs sustain operations and employment.

Better fertilizer subsidy targeting: Rising energy prices increase fertilizer costs and cultivation expenses. Efficient subsidy mechanisms can reduce the burden on farmers and support agricultural production.

Support for transport and logistics sectors: Since transportation costs rise directly with fuel prices, infrastructure support and fuel-cost management can help maintain supply-chain stability and reduce inflationary pressure.

Controlling Inflation

Improving supply-chain efficiency: Better transportation, storage, and distribution systems can reduce unnecessary price increases caused by supply disruptions.

Maintaining food supply stability: Adequate food-

grain stocks, timely procurement, and effective distribution systems are essential to prevent food inflation during economic uncertainty.

Balancing fuel-price management with fiscal discipline: Although controlling fuel prices is important for inflation management, excessive subsidies may increase fiscal pressure. Therefore, price control measures should be balanced with long-term fiscal sustainability.

Expanding Employment Opportunities

Promoting labour-intensive industries: Sectors such as textiles, food processing, tourism, construction, and MSMEs can generate large-scale employment and reduce the impact of economic slowdown.

Increasing infrastructure-based employment: Public investment in roads, railways, logistics, renewable energy, and urban infrastructure can stimulate economic activity and create both direct and indirect employment opportunities.

Enhancing skill development initiatives: Strengthening vocational training, technical education, and digital skills can improve workforce adaptability to changing industrial and technological requirements.

Reducing External Dependence

Diversifying trade partnerships: Expanding trade relations with multiple countries can reduce risks associated with geopolitical conflicts and external market dependence.

Expanding domestic manufacturing: Strengthening manufacturing through initiatives such as Make in India and PLI schemes can reduce import dependence and improve industrial self-reliance.

Strengthening export competitiveness: Improving productivity, infrastructure, technology adoption, and product quality can help Indian industries compete more effectively in global markets and support export growth.

Conclusion

The Iran-US tensions demonstrate how geopolitical instability in one region can influence economies across the world. For India, the consequences are visible in rising fuel prices, inflation, pressure on household income, industrial cost escalation, and uncertainty in financial markets. At the same time, such crises also underline the importance of economic resilience and strategic planning. If India strengthens domestic manufacturing, renewable energy capacity, agricultural stability, and infrastructure development, the country can reduce its vulnerability to future global shocks and maintain long-term economic growth despite an uncertain international environment.

Indian Agriculture and the Food Security Challenge in a Changing Economy

Poonam Chaturvedi, Kiran Parel, Kuldeep Rajpoot and Ankita Singh

Introduction

Indian agriculture has long been the back-bone of the country's economy and food system. Even today, agriculture supports the livelihoods of millions of rural households and plays a critical role in ensuring food availability for the country's large population. Over the decades, India has achieved remarkable progress in agricultural production through technological advancement, policy support, irrigation development, and expansion of high-yielding crop varieties. As a result, the country transformed itself from a food-deficit nation into one of the world's leading producers of foodgrains, milk, fruits, and vegetables. However, the economic environment surrounding Indian agriculture is changing rapidly. Climate variability, inflation, global geopolitical tensions, rising cultivation costs, shrinking landholdings, changing consumption patterns, and market uncertainty are creating new challenges for both farmers and policymakers. In this changing economic scenario, maintaining food security has become more complex than simply increasing food production. It now requires stable supply systems, affordable prices, nutritional adequacy, sustainable resource management, and protection of farmer livelihoods.

Indian Agriculture in a Changing Economic Environment

The structure of the Indian economy has undergone major transformation over the last few decades. While the contribution of agriculture to Gross Domestic Product (GDP) has gradually declined with the growth of industry and services, the sector still remains crucial for employment and rural income generation. Nearly 45 percent of India's workforce continues to depend on agriculture and allied activities. Indian agriculture is increasingly influenced by changes in the global economy. Rising fuel prices, trade disruptions, fertilizer shortages, and global inflation have significantly increased cultivation costs in India. Since the country imports nearly 85 percent of its crude oil requirement, increases in international oil prices directly raise expenses related to irrigation, transportation, and farm machinery. During 2026, geopolitical tensions in West Asia pushed crude oil prices above 100 dollars per barrel, contributing to a rise of nearly ₹3 per litre in petrol and diesel prices in India.

Global instability has also affected fertilizer markets. World Bank estimates indicate that global fertilizer prices increased by nearly 15 percent during 2025, while DAP prices rose by around 23 percent.

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In several Indian states, fertilizer prices reportedly increased by ₹200–350 per bag due to rising production and raw-material costs. These economic pressures have particularly affected small and marginal farmers, who constitute over 86 percent of India's farming households and remain highly vulnerable to rising input costs and market uncertainty.

Growth in Agricultural Production and Food Availability

India has achieved significant growth in foodgrain production over the years. According to the Ministry of Agriculture and Farmers Welfare, India's foodgrain production is estimated to reach nearly 348.6 million tonnes during 2025-26, reflecting continuous improvement in agricultural output. Rice and wheat continue to dominate Indian agriculture, while production of pulses, oilseeds, fruits, vegetables, and dairy products has also increased substantially. Government programs such as the Minimum Support Price (MSP) system, PM-KISAN, crop insurance schemes, fertilizer subsidies, and irrigation development have contributed to higher agricultural production and food availability. India's Public Distribution System (PDS) and the National Food Security Act (NFSA) have also played a major role in improving food access for economically vulnerable populations. Nearly 800 million people receive subsidized foodgrains under government food-security programs. Despite these achievements, rising population and changing dietary needs continue to increase pressure on agricultural systems and food distribution networks.

Food Security Challenges in India

Climate Change and Production Instability: Climate change has emerged as one of the biggest threats to Indian agriculture. Rising temperatures, irregular rainfall, droughts, floods, and heatwaves are increasingly affecting crop productivity and farm income. Agriculture in many parts of India still depends heavily on monsoon rainfall. In rainfed regions, poor rainfall distribution or extreme weather conditions often result in crop losses, lower productivity, and income instability for farmers. Climate-related uncertainty not only affects food production but also contributes to fluctuations in food prices, thereby influencing food affordability for consumers.

Rising Input Costs and Inflation: One of the major challenges facing Indian agriculture today is the continuous increase in cultivation costs. Prices of fertilizers, diesel, electricity, seeds, pesticides, and transportation have increased significantly in recent years. Global economic uncertainty and geopolitical tensions have further increased fuel and fertilizer prices. As production costs rise, farm profitability declines and food prices for consumers also increase. This creates pressure on both farmers and low-income households. Food inflation has therefore become an important economic concern in India, particularly for economically weaker sections of society.

Shrinking Landholdings and Rural Distress: Rapid population growth and fragmentation of

agricultural land have reduced the average size of landholdings in India. Small and fragmented farms often face difficulties in mechanization, irrigation investment, and adoption of advanced technologies. Many farmers also continue to face challenges related to inadequate storage facilities, limited market access, low bargaining power, and dependence on intermediaries. Migration of rural youth toward urban areas has further changed the structure of rural labour markets. These issues affect both agricultural productivity and long-term food security.

Nutritional Security and Malnutrition: Food security is not only about the availability of food but also about access to nutritious diets. Although India has achieved self-sufficiency in foodgrain production, nutritional challenges remain significant. According to the Global Hunger Index 2025, India continues to face serious concerns related to child malnutrition, stunting, and wasting. Rising food prices and income inequality often reduce access to nutritious food among vulnerable populations. Therefore, improving nutritional security has become equally important as increasing agricultural production.

Emerging Opportunities for Indian Agriculture: Despite these challenges, Indian agriculture also possesses several opportunities for future growth and transformation. Technological advancements such as precision farming, digital agriculture, drone technology, remote sensing, climate-resilient crop varieties, and AI-based advisory systems are increasingly improving farm management and productivity. Government initiatives promoting irrigation expansion, renewable energy use in agriculture, Farmer Producer Organizations (FPOs), and agro-processing are also creating new opportunities for improving farmer income and agricultural efficiency. India's agricultural exports have shown resilience despite global uncertainty. Growing international demand for rice, spices, fruits, vegetables, and processed foods provides significant export potential for Indian agriculture.

Policy Measures for Strengthening Food Security

Promoting Sustainable Agriculture: Adoption of climate-resilient and resource-efficient farming practices is necessary for ensuring long-term agricultural sustainability. Water conservation, balanced fertilizer use, crop diversification, and soil-health management should receive greater policy attention.

Improving Agricultural Infrastructure: Better irrigation systems, rural roads, storage facilities, cold chains, and transportation networks can reduce post-harvest losses and improve market efficiency.

Supporting Farmers and Rural Livelihoods: Improved access to institutional credit, crop insurance, extension services and modern technologies can strengthen farmer resilience and reduce income instability.

Strengthening Food Distribution Systems: Efficient implementation of the Public Distribution System and nutritional support programs is essential for ensuring food access among vulnerable populati-

ons.

Encouraging Agricultural Diversification: Diversification toward pulses, oilseeds, horticulture, dairy, and agro-processing can improve farm profitability, nutritional security, and export competitiveness.

Conclusion

Indian agriculture continues to remain central to the country's economic stability and food security. However, the sector is now operating within a rapidly changing economic environment characterized by climate uncertainty, inflation, rising input costs, and global market instability. The food-security challenge facing India is therefore no longer limited to increasing agricultural production alone. It now involves ensuring affordability, nutritional quality, sustainability, and stable farmer income in an increasingly uncertain economy. Strengthening agricultural resilience through technology, infrastructure development, policy support, and sustainable resource management will be essential for securing India's food future and supporting inclusive economic growth in the years ahead.

Agrotourism: An Emerging Dimension of Farming

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Introduction

Agriculture is the backbone of the Indian economy, supporting about 42.3% of the population and contributing nearly 18.2% to the country's GDP. Beyond being an occupation, agriculture is deeply connected to Indian culture. However, farming is highly dependent on uncertain factors such as climate variability, market fluctuations, and crop failures, especially in dryland regions. To reduce these risks, farmers adopt Integrated Farming Systems (IFS), combining enterprises such as crops, livestock, poultry, fisheries, and plantations to ensure stable income and sustainability. In recent years, farmers have also started exploring innovative income sources like agrotourism, which combines agriculture and tourism. Agrotourism allows visitors to experience rural life, farming activities, local traditions, and natural environments while providing farmers with additional income opportunities. Tourists visit farms to relax, reconnect with nature, enjoy local food, and escape the stress of urban life. Agrotourism is rapidly growing in India and worldwide due to increasing interest in sustainable and experience-based tourism. It supports rural development by generating employment, promoting local products, and improving living standards in villages. At the same time, it helps preserve agricultural heritage, local culture, and environmental sustainability. Activities such as farm stays, fruit picking, village tours, and participation in farming practices create educational and recreational experiences for visitor. In India, agrotourism highlights the country's agricultural diversity and cultural richness through experiences such as tea garden visits in Assam, paddy farming in Kerala, and mango orchards in Maharashtra. It strengthens the connection between urban and rural communities and increases awareness about the importance of farmers and agriculture in society.

Different Types of Agrotourism in India

Agrotourism activities ranging from educational tour to animal interaction, are varied and designed for diverse audience. Agritourism experiences fall into one or more of five overlapping categories: education, hospitality, outdoor recreation, entertainment, and on-farm direct sales

Agriculture educational Tours: School trip to visit local farms fall under this category. Adult also visit a farm and enjoy a guided tour for our farm or farm assistant explains the different aspects of farming like agricultural practices, livestock management, and sustainability. When student visit farms, they

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begin to appreciate the true value of food. Once they see firsthand the hard work farmers put into cultivating crops, they stop taking food for granted and avoid wasting it.

Hospitality: This category of agrotourism based on the concept of farm is family and family is farm. Hospitality from family friendly interactive farms to relaxing adult only retreats complete with hot tubs there**.** Agrotourism gives farmers an opportunity to extend hospitality to tourists. They manage visitors, cook delicious traditional food using traditional methods, offer guided tours, and maintain facilities for visitors. It also helps generate additional income for farmers.

Outdoor recreation: Hunting, horseback riding and meeting monkey on the seafront all of these are recreational type of agrotourism.

Agri-Adventure Tourism/ entertainment: Activities like haunted hay ride, tractor rides, ploughing, or fishing are offered as part of a rural adventure experience.

On farm direct sales: this includes farm stand and pick. A farm stand is, as the name suggests is somewhere you can visit to buy produce directly from a farm. A farmer market similar to this somewhere you go to purchase the goods from different farmers who have travelled to a particular location to sell their produce this can range from egg to cheese to meat farms. You can also visit to farms to pick your own goods.

Significance and Layered Benefits of Agritourism

Agritourism has emerged as a critical instrument for fostering sustainable rural development, delivering socio-economic, environmental, and cultural benefits across multiple stakeholder groups. The specific merits of this are:

For farmers and their community: Agrotourism provides farmers with an additional and stable source of income by diversifying their farming activities. It enables farmers to directly sell farm products at better prices without depending on intermediaries. Farm stays attract tourists because they are affordable, peaceful, and connected to nature. Visitors also support local economies by purchasing local food, fresh produce, and handmade products. Additionally, agrotourism creates employment opportunities and helps farmers earn income during agricultural off-seasons.

For visitors: Farm stays provide visitors with authentic rural experiences and a closer connection to nature and local culture. Tourists can learn directly from farmers about traditional lifestyles and food production, increasing their appreciation for agriculture. Agrotourism also strengthens the relationship between farmers and visitors while promoting sustainable and ethical travel.

Economic contribution: The advantages of agrotourism extend beyond the individual farmer and the visiting public to positively impact local communities. A thriving agrotourism destination can become an asset, drawing visitors who meaningfully contribute to the local economy. Agrotourism significantly help to contribute national GDP and

help to improve infrastructure and road etc. India has achieved great success and has attracted 8.03 million international tourists and 1,432 million domestic tourists to various touristic destinations. The agrotourism market globally was valued at $42.46 billion in 2019 and is expected to reach $62.98 billion by 2027, registering a Compound Annual Growth Rate (CAGR) of 13.4% between 2020 and 2027. Currently, India's revenue from agrotourism is growing at an annual growth rate of 20%.

Environmental sustainability: Agrotourism can support sustainable agriculture practices, conserve-ation efforts, and biodiversity preservation. Farmers are encouraged to adopt eco-friendly methods and practices that enhance visitor experiences while safeguarding the land's natural beauty and resources. Sustainable agriculture methods can also improve the farm's long-term viability and benefit the environment. Farmers and communities may adopt conservation measures to protect natural habitats, wildlife, and biodiversity, which can lead to positive ecological impacts. Integrated farming based agrotourism increases resource use efficiency, environmental sustainability and economic viability via resource recycling and circular integration of farm produce. Strategically utilization of farm bunds for growing multipurpose trees for fruits, fibre and fuel. Biomass generated through pruning operations can be repurposed as biofuel for domestic energy requirements, particularly within farm kitchens. Additionally, By-products from cattle sheds including crop residues, dung, and urine play a pivotal role in the waste - to - resource continuum. These materials can be efficiently utilized for biogas generation, providing a renewable energy source for cooking and other operations.

Need of regulatory framework for agrotourism

In order to ensure continuous focus, further evolution of the strategy, development of actionable plans and schemes for agrotourism in the country, agritourism forums have acknowledged the need to create efficient supply chains and promote local cuisine. Despite significant deliberations, the development of an agritourism policy is still in infancy. There is proposed policy framework for inclusive growth including four key elements:

Government incentives: Tourism is widely recognized to need government involvement to spread all over the country. Initially, government involvement in tourism could be described as an 'infrastructure and facility provider', primarily concerned with roads and utilities in tourism. The coordination and involvement of the government in tourism planning is necessary since profit-motivated private sector entrepreneurs are unlikely to develop tourism optimally In India, many states have taken the initiative to expand the agrotourism. For example in Maharashtra, Agri Tourism Policy 2020 has been initiated, providing loans to agricultural practitioners who want to start startups in Agrotourism.

Marketing: Marketing is the process of determining what customers want and of using that information to provide service to satisfied for customers. As agrotourism business generally depends on repeat

customers so building and maintaining good contact list of customers is most effective marketing strategy important for overall development of agrotourism business. You must let customers know where your farm is and how visiting it benefits them. If you market your agrotourism business well, the chances of the business succeeding improve. A marketing plan is the backbone of any marketing endeavour. One of the most important aspects of marketing your business is the formulation of a marketing plan that includes who are your customer, what's locally available product they need or know preferences, branding the product by labelling such as the organic nature of produce, freshness of ingredients, benefits and price etc. promotion of locally available product is also a game changing strategy of making. Advertising in agrotourism has traditionally come from customer-to-customer word of mouth communication but now a days social media is become a powerful tool for attracting visitors.

Linkage: Agritourism is widely situated in villages or far away from the city. There is necessity to link road and hotel or farm stay for traveling and accommodation of visitors. For the development of agritourism business there is need to make policy and frame work, agripreneurs, farmer organizations, co-operatives, funding institutions, NGOs and agri-business companies need to come together to take up these ventures together with the help of farmers, government agencies and tour operators.

Tourist product: A holistic 'Agritourism Experience' entails lodging and board-on farm, farm activeties, traditional and cultural exchanges, and educational experiences. The agritourism framework should focus on developing and improving agritourism products including farm stays, farm tours and organised local food experiences. Tourists preferred easily accessible working farms, offering accommodation, food and farm activities with value for money experiences. They are interested in cultural interactions, educational and culinary experiences, and on-farm activities on affordable packages. This highlights the need to redefine agritourism as a value for money experience rather than a niche market, and judicious examination of tourist preferences for agritourism product development is needed.

Challenges in Agrotourism Development

Despite its transformative potential, agri-tourism in India encounters several structural and operational challenges:

- ✓ A significant proportion of farmers and potential tourists remain inadequately informed about the concept, scope, and benefits of agrotourism.
- ✓ Inadequate rural connectivity, lack of basic amenities and insufficient marketing mechanisms constrain the scalability and accessibility of agrotourism ventures.
- ✓ Limited government support, fragmented policy frameworks, and absence of clear regulatory guidelines impede systematic growth and standardization of the sector.
- ✓ Addressing these challenges necessitates targeted awareness campaigns, capacity building initi-

atives, infrastructure investments, and coherent policy support mechanisms, including financial incentives and institutional backing

Conclusion

Agritourism in India represents a dynamic, emerging, promising and rapidly evolving sector that synergistically integrates agricultural practices with tourism to create unique experiences, thereby creating a multifunctional rural enterprise model. This concept allows guests to immerse themselves in enjoyable rural pursuits such as participating in guided farm visits, crop picking, and discovering authentic customs of village existence, thereby showcasing the country's vibrant farming legacy along with its profound cultural variety. Additional revenue streams for growers come from offering tourism-related services while also helping to preserve their age-old customs and methods. Moreover, with suitable support and improved facilities from government and related agencies, it can make significant progress toward long-term rural growth. As this form of tourism promotes financial advancement, it simultaneously safeguards heritage and places visitors in an environmentally conscious setting through the adoption of green initiatives. It holds a strong potential for creating an opportunity for the youth of the country to come back to farming unlocking it's hidden potential thus adding new heights to India's farming sector.

Modern Approaches to Sustainable Crop Production

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Introduction

Sustainable crop production is an agricultural system that aims to produce food, fiber, and other plant products while protecting natural resources, maintaining environmental quality, and ensuring economic profitability for farmers. With increasing population, climate change, soil degradation, water scarcity, and pollution, modern agriculture faces many challenges. Therefore, modern approaches to sustainable crop production have become essential for ensuring food security and environmental conservation. Sustainable agriculture combines traditional farming wisdom with advanced scientific technologies to increase productivity without harming the ecosystem. It promotes efficient use of resources such as soil, water, energy, and biodiversity while reducing dependence on harmful chemicals.

Modern Approaches to Sustainable Crop Production

Precision Agriculture: Precision agriculture is a modern farming technique that uses advanced technologies such as GPS, sensors, drones, satellite imagery, and data analytics to manage crops more efficiently.

Features

- ✓ Site-specific nutrient management
- ✓ Real-time crop monitoring
- ✓ Automated irrigation systems
- ✓ Yield mapping
- ✓ Variable rate fertilizer application

Advantages: Reduces wastage of inputs**,** improves crop yield**,** saves water and fertilizers, and reduces environmental pollution.

Applications: Farmers can identify nutrient-deficient areas and apply fertilizers only where needed. This improves nutrient use efficiency and lowers production costs.

Conservation Agriculture: Conservation agriculture is based on minimum soil disturbance, permanent soil cover, and crop rotation.

Principles

- ✓ Minimum tillage
- ✓ Crop residue retention
- ✓ Diversified crop rotation

Benefits: Prevents soil erosion**,** improves soil organic matter**,** conserves moisture and enhances soil biodiversity.

Organic Farming: Organic farming avoids synthetic fertilizers, pesticides, herbicides, and genetically modified organisms (GMOs). It relies on natural inputs and ecological processes.

Organic Inputs

- ✓ Farmyard manure (FYM)
- ✓ Vermicompost
- ✓ Green manure
- ✓ Biofertilizers

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- ✓ Biopesticides

Advantages: Produces safe and healthy food, improves soil health, reduces pollution and maintains ecological balance.

Challenges

- ✓ Lower initial yield
- ✓ Certification issues
- ✓ Higher labor requirement

Organic farming is gaining popularity worldwide due to increasing demand for chemical-free food.

Integrated Nutrient Management (INM): Integrated Nutrient Management involves the balanced use of chemical fertilizers, organic manures, crop residues, and biofertilizers to maintain soil fertility.

Components

- ✓ Chemical fertilizers
- ✓ Organic manures
- ✓ Compost
- ✓ Biofertilizers
- ✓ Crop residues

Advantages: Improves soil fertility, enhances nutrient use efficiency, reduces fertilizer cost and maintains soil microbial activity.

INM helps achieve sustainable productivity while minimizing nutrient losses.

Climate Smart Agriculture: Climate Smart Agriculture (CSA) is an approach that helps agriculture adapt to climate change while increasing productivity and reducing greenhouse gas emissions.

Objectives

- ✓ Increase crop productivity
- ✓ Enhance resilience to climate stress
- ✓ Reduce carbon emissions

Practices

- ✓ Drought-tolerant crop varieties
- ✓ Efficient irrigation systems
- ✓ Agroforestry
- ✓ Weather-based crop planning

CSA is important for sustainable agriculture under changing climatic conditions.

Agroforestry Systems: Agroforestry is the integration of trees, crops, and livestock on the same land.

Types

- ✓ Agrisilviculture
- ✓ Silvopasture
- ✓ Agrihorticulture

Benefits: Improves soil fertility, prevents erosion, enhances biodiversity and provides additional income.

Trees help recycle nutrients and improve the microclimate of agricultural fields.

Water Management Technologies: Efficient water management is essential for sustainable crop production.

Modern Irrigation Methods

- ✓ Drip irrigation
- ✓ Sprinkler irrigation
- ✓ Rainwater harvesting
- ✓ Micro-irrigation systems

Advantages: Saves water, reduces evaporation loss, increases water use efficiency and improves crop productivity.

Drip irrigation delivers water directly to plant roots and minimizes wastage.

Crop Diversification: Crop diversification means growing different crops instead of depending on a single crop.

Advantages: Reduces risk of crop failure**,** improves soil fertility, enhances farm income and reduces pest and disease incidence.

Examples

- ✓ Intercropping
- ✓ Mixed cropping
- ✓ Sequential cropping

Diversification improves ecological stability and farm sustainability.

Digital Agriculture and Smart Farming: Digital agriculture uses information technology, artificial intelligence (AI), Internet of Things (IoT), and robotics in farming operations.

Technologies Used

- ✓ Smart sensors
- ✓ Mobile applications
- ✓ Drones
- ✓ Artificial intelligence
- ✓ Farm management software

Benefits: Better decision making, accurate weather forecasting, efficient farm management and reduced labour requirement.

Smart farming improves productivity and resource efficiency.

Sustainable Soil Management: Healthy soil is the foundation of sustainable agriculture.

Sustainable Soil Practices

- ✓ Addition of organic matter
- ✓ Crop rotation
- ✓ Reduced tillage
- ✓ Soil testing
- ✓ Balanced fertilization

Importance: Maintains nutrient balance**,** improves soil structure, enhances microbial activity and prevents degradation.

Soil health management ensures long-term agricultural productivity.

Role of Farmers in Sustainable Crop Production: Farmers play a major role in adopting sustainable agricultural practices.

Responsibilities

- ✓ Proper use of fertilizers and pesticides
- ✓ Adoption of eco-friendly technologies
- ✓ Conservation of water and soil
- ✓ Use of quality seeds
- ✓ Diversification of crops

Farmer awareness and training are essential for successful implementation of sustainable farming practices.

Challenges in Sustainable Crop Production: Despite many benefits, sustainable crop production faces several challenges:

- ✓ High initial investment
- ✓ Lack of technical knowledge
- ✓ Small land holdings
- ✓ Limited access to modern technology
- ✓ Climate change impacts
- ✓ Market and policy constraints

Government support, research, and extension

services are necessary to overcome these challenges.

Future Prospects

The future of sustainable crop production depends on integrating modern science with traditional knowledge. Emerging technologies such as artificial intelligence, remote sensing, robotics, nanotechnology, and climate-resilient agriculture will play an important role.

Greater emphasis should be given to:

- ✓ Renewable energy in agriculture
- ✓ Carbon-neutral farming
- ✓ Sustainable supply chains
- ✓ Organic and natural farming
- ✓ Circular agricultural systems

Sustainable agriculture is not only important for food production but also for environmental protection and social welfare.

Conclusion

Modern approaches to sustainable crop production aim to achieve higher agricultural productivity while conserving natural resources and protecting the environment. Techniques such as precision agriculture, conservation agriculture, integrated nutrient management, organic farming, climate-smart agriculture, biotechnology, and digital farming are transforming modern agriculture into a more efficient and eco-friendly system. Sustainable crop production is essential for ensuring food security for future generations while maintaining ecological balance. Adoption of these modern approaches by farmers, supported by government policies and scientific research, can lead to a resilient and sustainable agricultural future.

Data-Driven Revolution: How Statistics is Transforming Indian Agriculture for Higher Yields and Sustainability

Kuldeep Rajpoot, Neelmani Bootauliya, Kartikey Acharya and Umesh Singh

Introduction

Agriculture is the main livelihood for a huge section of India's population and plays a central role in the country's economic framework. Yet, the sector continues to struggle with several pressing issues such as erratic climatic conditions, small and divided land parcels, falling soil health, and severe water shortages. Conventional agricultural practices are finding it hard to meet the rising food demand of the nation without harming the environment. In the present time, the intelligent application of statistics together with predictive analytics, machine learning, and big data is creating a remarkable change by introducing accuracy, efficiency, and climate resilience into farming. This article throws light on how statistical techniques are contributing significantly to higher crop production and long-term agricultural sustainability (Raji and Njoku, 2024).

The Current Landscape of Indian Agriculture

In recent years, India has made notable progress in total foodgrain production. Nevertheless, a substantial gap continues between current productivity levels and the actual potential. Small and marginal farmers, who cultivate the majority of the land, remain highly susceptible to weather uncertainties and market instability. The systematic statistical study of historical yield data, climate records, soil conditions, and market trends is proving highly effective in recognising problem areas and supporting improved decision-making (Beriya and Saroja, 2019).

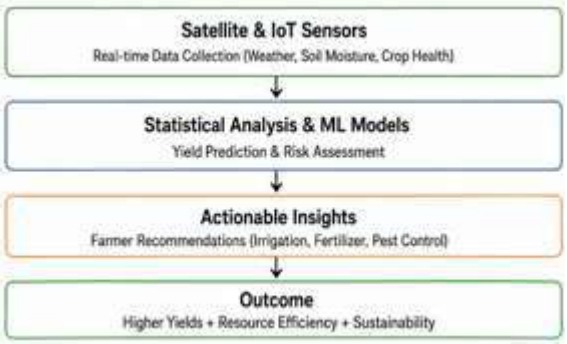

Fig. 1: Data Flow in Modern Agriculture
(Source: Kamilaris and Prenafeta-Boldú, 2018)

Role of Statistics in Modern Agriculture

Statistics is the fundamental pillar of modern and intelligent farming systems. Its main applications include:

Descriptive Statistics: Examining historical trends in crop output, rainfall, and resource utilisation.

Inferential Statistics: Reaching reliable conclusions based on sample surveys and field trials.

Predictive Modeling: Forecasting upcoming crop yields through regression analysis and machine learning methods.

Prescriptive Analytics: Offering optimal recommendations for farming operations using advanced optimisation.

These statistical approaches transform large

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quantities of raw agricultural data into valuable and practical insights for farmers (Wolfert *et al*., 2017).

Key Applications Transforming Indian Farms

Crop Yield Prediction: High-level statistical and machine learning models developed using past records of rainfall, temperature, soil nutrients, and earlier harvests are now generating dependable predictions for major crops such as rice, wheat, and maize. Approaches like Random Forest and hybrid models have performed remarkably well. These forecasts enable farmers to take more informed decisions on marketing, storage, and insurance matters (Surana and Khandelwal, 2024).

Fig. 2: Process of Machine Learning-based Crop Yield Prediction **(**Source: Surana and Khandelwal, 2024).

Precision Agriculture and Resource Optimization: When statistical methods are combined with drone technology, satellite imagery, and IoT sensors, farmers can practise location-specific nutrient management and variable rate application. This strategy helps cut down excess use of water and fertilisers, raises overall productivity, and promotes ecological balance (Raji and Njoku, 2024).

Key Benefits Observed

- ✓ Improved efficiency in fertiliser and water application
- ✓ Significant reduction in farming costs
- ✓ Progressive improvement in soil condition
- ✓ More stable and enhanced crop production

Climate Risk Management: Statistical modelling techniques study long-term weather and climate information to forecast droughts, floods, and pest outbreaks. These advance warnings allow farmers to implement preventive strategies and minimise crop losses in the face of growing climate challenges (International Research Institute for Climate and Society, 2008).

Government Initiatives Supporting Data Revolution

Under the Soil Health Card Scheme, millions of farmers have received scientifically prepared nutrient recommendations. Other major initiatives such as PM-KISAN, crop insurance programmes, and satellite-based monitoring are also increasingly depending on data analytics to deliver more precise and effective assistance to farmers (Singh *et al*., 2022).

Challenges in Adoption

Although encouraging outcomes are visible, several hurdles continue to slow down large-scale adoption. These include small farm sizes, limited digital skills among farmers, data security concerns, and the initial investment required for new technologies. Sustained training programmes and awareness efforts are crucial to bridge this gap (Rahman, 2024).

Conclusion

The use of statistics and data science is bringing a deep transformation in Indian agriculture by raising productivity levels, ensuring better utilisation of resources, and developing stronger climate resilience. Effective partnership between

government agencies, researchers, agricultural extension services, and farmers is essential so that even small and marginal farmers can take advantage of these innovations. The data-driven transformation in Indian agriculture has already begun and offers a bright pathway toward more profitable and environmentally sustainable farming.

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Race against Time: The Marketing Challenge of Perishables

Sebin Sara Solomon, Arushi Anand, Aradhna Singh and Poonam Chaturvedi

A Morning in the Fields

At sunrise in Nashik, Ramesh bends over rows of grapevines, carefully clipping bunches heavy with fruit. The air is cool, but his mind is racing. By noon, these grapes must be packed, chilled, and loaded onto trucks. By evening, they should be in Mumbai's wholesale market. If the chain breaks anywhere a delayed truck, a power cut in cold storage, or a missed buyer the fruit loses its sparkle, and so does Ramesh's income. This is the invisible drama behind every fresh apple, loaf of bread, or packet of milk we consume. Perishables are not just products; they are ticking clocks. Their marketing is a daily race against time.

Why Perishables are Different

Unlike durable goods like clothes, electronics, furniture perishables cannot wait.

Short shelf life: Tomatoes bruise, bread hardens, milk spoils.

High consumer expectation: Shoppers want crisp vegetables and creamy dairy, not wilted spinach or sour milk.

Price volatility: A glut of produce can crash prices overnight, while scarcity can double them.

India currently loses an estimated 30-40% of horticultural produce post-harvest. But what is lost is not just food it is the farmer's pricing power. Without adequate cold storage, farmers are forced to sell at harvest-time price (when supply is maximum and prices are minimum), rather than timing the market. This fragility makes perishables the most challenging category in agricultural marketing. Every decision from harvest timing to packaging design must be made with speed and precision.

Agriculture today is no longer only about growing crops. It is increasingly about managing timing, temperature, traceability, logistics, consumer preference, and coordinated execution across the entire value chain. A common missing link in agribusiness and agricultural supply chains is the lack of integration between production, market demand, logistics, and real-time decision-making. In many cases:

- ✓ Farmers produce without clear visibility of actual market demand
- ✓ Supply chains focus on movement, not quality preservation
- ✓ Logistics operate separately from farm planning
- ✓ Post-harvest handling receives less attention than production

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- ✓ Data exists, but remains fragmented across stakeholders
- ✓ Consumers stay disconnected from farmers and traceability systems

As a result:

- ✓ Post-harvest losses increase
- ✓ Price volatility rises
- ✓ Farmers lose bargaining power
- ✓ Retail quality becomes inconsistent
- ✓ Waste grows across the chain

The real missing link is often a coordinated demand-driven ecosystem where farmers, ware-houses, logistics providers, processors, retailers, and consumers operate through connected information, quality standards, traceability, and synchronized planning.

The Marketing Puzzle

Marketing perishables is not just about selling; it's about managing time, trust, and technology.

Speedy Supply Chains: Cold chains, refrigerated trucks, and efficient distribution networks are lifelines. A delay of even a few hours can mean tonnes of wasted produce. India's growing network of cold storages is helping farmers extend shelf life, but gaps remain.

Packaging as a Promise: Smart packaging is more than a wrapper it's a guarantee. Breathable films keep vegetables crisp, QR codes allow consumers to trace origins, and biodegradable wraps appeal to eco-conscious buyers. Packaging becomes part of the marketing story.

Branding Freshness: Labels like organic, farm fresh, or GI-certified Alphonso mangoes transform ordinary produce into premium products. Branding helps perishables stand out in crowded markets and reassures consumers about quality.

The Branding Architecture behind Alphonso's Premium

Alphonso mangoes build their brand not through ads but through land. Only the Konkan belt Ratnagiri, Devgad, Sindhudurg, Raigad produces the true taste, shaped by laterite soil, sea air, and perfect temperatures. This link to place works like Champagne in France, where origin itself becomes value. To protect this uniqueness, Alphonso carries a Geographical Indication tag from the Government. The GI mark builds trust, proving the fruit's origin and shielding it from fakes. Courts in India and abroad enforce these rules, blocking knockoffs and keeping prices strong. Scarcity adds another layer Alphonso appears only between March and June, turning each season into an event. People wait, celebrate, and pay more because rarity makes it special. Quality signals matter too. GI-tagged fruit faces strict checks, while some growers go further with organic methods and natural ripening. Buyers pay extra for flavor, fairness, and authenticity. Finally, culture crowns Alphonso the "King of Mangoes." This title wasn't invented by marketers but passed down through families, making the fruit part of identity. Together, land, law, scarcity, quality, and culture shape Alphonso into more than food it becomes a premium symbol of pride and trust.

Packaging as the First Touchpoint of Trust

Modern food packaging operates on three simultaneous levels:

Functional level: Modified Atmosphere Packaging (MAP) alters the gas composition inside packs to slow respiration and microbial growth. Strawberries packed under MAP can last 14-21 days versus 3-5 days without. This is not just shelf life extension; it is a window of marketing opportunity.

Communication level: QR codes on produce packaging now enable full farm-to-fork traceability. A consumer can scan a pack of tomatoes and see the farm name, harvest date, pesticide use records, and cold chain temperature log. This is storytelling at the point of sale and studies show it significantly increases willingness to pay a premium.

Sustainability level: Biodegradable and compost-able packaging has moved from niche to mainstream expectation, particularly among urban, educated consumers. Brands that use sustainable packaging are not just reducing environmental impact; they are signalling values alignment with their target customer which is a core marketing function.

Battling Wastage

Globally, nearly one-third of food produced is wasted, much of it perishable. This is both an economic and ethical challenge. Innovative campa-igns now market "ugly produce" misshapen carrots or blemished apples as equally nutritious, reducing waste and creating new consumer segments. Restaurants and startups are partnering with farmers to buy surplus produce at lower rates, turning potential losses into opportunities. Apps like Too Good To Go in Europe and similar initiatives in India are helping consumers access discounted perishables that would otherwise be discarded.

The Competitive Edge

Perishables don't just demand speed, they spark competition. Retailers battle to be the first to offer the freshest produce, bakeries race to sell bread while it's still warm, and delivery apps fight to promise "10-minute groceries." In this race, whoever manages time best wins consumer loyalty.

First-Mover Advantage: The store that gets mangoes on shelves before others can charge a premium.

Differentiation through Freshness: Competing brands highlight "picked today," "baked this morning," or "delivered straight from farm" to stand out.

Tech as a Weapon: AI-driven demand forecasting, dynamic pricing, and freshness sensors are now competitive tools, helping businesses outpace rivals.

Conclusion: Freshness as a Race

Every tomato, every loaf of bread, every litre of milk carries a ticking clock. Marketing perishables is not just about selling. It's about orchestrating a complex dance of logistics, branding, and consumer trust. For farmers like Ramesh, the race against time is a daily reality. For consumers, it's invisible they simply enjoy the crisp apple or creamy paneer. But behind every bite lies a marketing challenge that blends science, management, and storytelling. Freshness may fade, but innovation ensures the race

continues and that the finish line is always within reach.

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Risk in Agriculture: A Hidden Gamble for Indian Farmers

Kuldeep Rajpoot, Amit Kumar, Sebin Sara Solomon and Poonam Chaturvedi

Abstract

Indian agriculture is characterized as a high-stakes, volatile sector, with systemic vulnerabilities spanning economic, climatic, technological, institutional, and personal dimensions. Agriculture in India is inherently volatile, functioning as a high-stakes economic gamble for smallholder cultivators. This article examines the multi-dimensional nature of agricultural risk under five core dimensions: economic, biological/climatic, technological, institutional, and personal. Operating at the intersection of climate change and fragmented markets, these risks trigger cascading socio-economic consequences.

Introduction

Agriculture is one of the risky professions with uncertain outcomes and a variety of risks are faced by Indian farmers over the whole growing season. Every time an Indian farmer sows a seed, they are not just planting a crop, they are placing a high-stakes bet against nature and the farm market. India is a developing nation, where urbanization, the depletion of natural resources, and rapid population growth have already adversely impacted agriculture. One of the most vital agricultural risks is the production or biological risk, which is mostly brought on by climate variability (such as irregular rainfall and unstable temperature), and it is getting worse every day as a result of climate change. However, many other factors, such as financial, legal, marketing, technological, social, and human personal factors (health issues, etc.) can contribute to agricultural risk in addition to this climate change effect and farmers have to deal with that all these risk sources (Rajpoot *et al.*, 2024). Despite decades of policy intervention, Indian agriculture continues to be defined by structural vulnerabilities that expose smallholder farmers to compounding these farm risks.

Risk and agriculture Risk

Risk and agricultural risk have already been defined in several ways in the scientific literature that is presently available. Risk is characterized as an undesirable component of a cluster of uncertain outcomes (Harwood *et al.*, 1999). Risk is the result of a hazardous event, which is expressed as a combination of the likelihood and magnitude of the risk (FAO and MOAC, 2010. According to (IPCC, 2014) risk is frequently defined as the chances of occurrence of hazardous drifts or events multiplied

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by the impact of those events that have occurred.

While discussing about agriculture risk or farm risk, the World Bank defines agricultural risk as "Agricultural risk is a combination of the possibility of a hazardous event or exposure(s) and the severity of the losses that can be caused by the event or exposure(s)" (World Bank, 2016). Therefore, agricultural risk is described as the multiplication of the degree of yield loss and the likelihood of the occurrence of a risky event, where yield loss indicates a possible reduction in yield due to the inverse effect of the risk. Agricultural risk is linked to unfavourable consequences that result from biological, climate, and price variables that are difficult to anticipate as per that this agriculture risk can be classified in several categories.

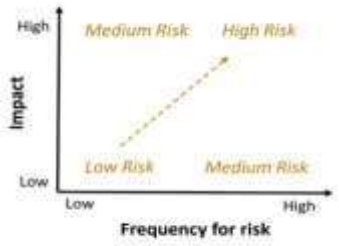

Fig. 1: Risk as impact and likelihood

Fig. 2: Classification of agricultural risk

Classification of agriculture risk

As per the various sources of risk caused risk during the farming this farm risk is classified into five categories *viz.*, (i) Economic risk (ii) Biological or climate risk, (iii) Technological risk, (iv) Institutional risk, and (v) Personal risk. These different kinds of risks are further defined as follows:

Economic or market risk: The farmers in most nations face differences in price for the inputs and outputs from what they might have estimated at the time of preparing the farm plan. Farmers lack real-time price information and cold storage, forcing them to sell immediately at whatever price local middlemen offer. So these risks which originate from fluctuations in the price of farm input and output as well as agricultural markets are defined as economic risk. The farm commodities prices are extremely volatile and this price variability originates from both endogenous and exogenous market shocks.

Biological or climate risk: Agriculture is often characterized by high variability of production outcomes. Unlike most other entrepreneurs, farmers are not able to calculate the amount of production output with certainty because of some uncontrolled external factors such as weather (rain or storm, drought, etc), attacks of insect pests, and diseases. So biological or climate risk is defined as the reduction in agricultural production caused by all biotic factors, such as insects, pests, disease-causing pathogens, etc., as well as abiotic factors, such as climate change or changing weather patterns.

Technological risk: The expected outcome of technological advancement is that the same level of input may create a greater output. The upward movement in the production function indicates that, as technology advances, more output can be produced at each level of input. However, all farmers specifically small and marginal farmers mostly don't have access to these technologies, so their agricultural production will suffer due to lack of access to these advanced farm technologies, which is referred to as a technological risk.

Institutional or policies risk: Institutions like gove-

rnment, bank, etc., may also become a reason of risk for a specific farmer. Institutional risk refers to factors such as sudden changes in government regulations, credit restrictions by banks and malfunctions, corruption in organizations like agricultural cooperative societies, and agricultural markets, that can negatively affect farmers.

Personal risk: The farmer, similar to any other economic business person, is also exposed to personal risks affecting the life and the well-being of people who work on the farm including his family members. The farm plan may be negatively impacted or delayed as a result of some unforeseen occurrences, such as an accident or mishappening and health issues experienced by the farmer's home or his permanent labor force as well as due to probable loss (damage) or theft of equipment or other farm assets, and these all are considered as a personal risk.

Conclusion

Ultimately, risk in Indian agriculture is not an inherent trait of farming, but a structural failure of mitigation systems. The compounding impact of climate volatility, exclusionary credit markets, and flawed price discovery transforms agriculture from a productive economic sector into a systemic gamble. Indian agriculture is a high-stakes endeavour, where farmers navigate compounding risks from climate change, market volatility and structural vulnerabilities. These challenges trigger a cascading crisis impacting micro-level households, rural economies, and national food security, necessitating proactive, data-driven risk management.

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Risk Mitigation Techniques: A Safeguard against Farm Risk for Indian Farmers

Kuldeep Rajpoot, Ruchi Rajpoot, Neelmani Bootauliya and Kiran Patel

Abstract

Indian agriculture faces significant threats from various risk-related climate, Insect-pest, Technological drifts and market volatility, which compound into micro-level debt traps, meso-level rural distress, and macro-level economic inflation. To mitigate the effect of various farm risk there is a need for urgent attention to the study of different agricultural risk management strategies to reduce the impact of these risks on agricultural production. This article describes about fundamental of risk mitigation strategies and classifies mitigation strategies into preventive (ex-ante), reactive (ex-post), and risk-transfer methods to safeguard farmer livelihoods and stabilize the national food supply.

Introduction

Agriculture is one of the risky profession with uncertain outcomes and a variety of risks faced by Indian farmers during the growing season. Agriculture is vulnerable throughout the whole production cycle, which exposes it to numerous risks during the production process. India is a developing nation, where urbanization, the depletion of natural resources, and rapid population growth have already adversely impacted agriculture. The contribution of the agriculture sector to India's GDP is still decreasing continuously. A major reason for this reduction in GDP contribution might be an increase in all kinds of agricultural risks, such as flood, drought, hail storms, unstable prices, unavailability of the market, and irregular rainfall distribution over time, which harm the agriculture sector. To resolve these risks farmers implemented a variety of risk management approaches to address the declining trend in stagnant yields (Jain and Parshad, 2007; Mahdi *et al.,* 2015). The process of choosing an appropriate strategy from a variety of choices used for minimizing risk is known as risk management (Harwood *et al.,* 1999). As a safeguard against agricultural risks and to mitigate the bad effects of risk on the farms' fields, every farmer adopts one or more risk management practices.

Why risk mitigation is essential for agriculture

Lots of studies, research and reports are indicating the huge impact of all kinds of risks on agriculture production. For example, Choudhury *et al.* (2019) observed a reduction in yield in a frost-affected year; the yield on the same farm was on average, 870 kg ha^{-1} less than in comparison to prior

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frost-free year. According to the FAO's global information and early warning system for food and agriculture, the percentage of all-natural disasters that are sudden-onset, particularly floods, has climbed from 14% in the 1980s to 20% in the 1990s and 27% since 2000 (FAO, 2008). India was seventh out of the top ten nations affected by climate or other risks in 2019. To find solutions, reduce this risk and, and to stabilize farmers' income and production, proper risk mitigation adoption is essential.

The compounded effects of risk related to climate volatility, credit constraints, and poor price discovery extend far beyond the farm it will effect rural and national economy. These effects can be analyzed across three distinct dimensions: micro-level (household), meso-level (rural economy), and macro-level (national economy).

Micro-Level Effects (The Farm Household)

The Debt Trap: Crop failures force farmers to take new informal loans to pay off old ones, leading to generational indebtedness.

De-peasantisation: Financial ruin forces small-holders to lease out or sell their land, transitioning from independent cultivators to landless agricultural labourers.

Human Capital Degradation: Income shocks lead households to pull children out of higher education and reduce expenditure on healthcare and nutrition.

Meso-Level Effects (The Rural Economy)

Distress Migration: Seasonal and permanent migration to urban slums spikes as farming becomes economically non-viable.

Depressed Rural Demand: Lower disposable farm incomes reduce rural spending on consumer goods, slowing down the entire rural manufacturing and service sectors.

Informal Market Monopoly: Local moneylenders and middlemen consolidate power, gaining tighter control over input and output markets.

Macro-Level Effects (The National Economy)

Food Insecurity and Inflation: Volatile yields cause supply shocks in volatile commodities like pulses and vegetables, driving up national food inflation indices.

Increment in inflation: Due to these farm risk productions of crops and farm commodities will significantly decrease, which ultimately increases the price for all food commodities.

Banking Sector Strain: Widespread defaults lead to high Non-Performing Assets (NPAs) in rural banking sectors, forcing controversial state-funded farm loan waivers.

Fiscal Deficit Pressures: Governments must spend heavily on emergency relief subsidies, diverting public funds away from long-term agricultural research and infrastructure investment.

To find the resolution of these bad effects of various farm risks, there is a need for urgent attention to the study of different agricultural risk management strategies to reduce the impact of this risk on agricultural production. Agriculture could be grown successfully only if the risks are managed correctly using suitable risk mitigation techniques, and in the absence of proper risk mitigation techniques, food

security and agricultural development will be in danger.

Classification of risk mitigation techniques

All farmers adopted one or more risk management strategies to safeguard themselves against agricultural risks on their farms, Based on the adoption time and nature of adopted risk management techniques, these risk mitigation approaches are further classified into three categories *viz.*, preventive (ex-ante), reactive (ex-post), and risk transfer strategies (Jain and Parshad, 2007). These all kinds of risk mitigation techniques can be defined as:

Preventive risk management strategies: These kinds of risk strategies are also known as ex-ante risk management strategies. All the strategies that are adopted before the occurrence of risk are known as preventive risk management strategies.

Reactive risk management strategies: These kinds of risk strategies are also known as ex-post risk management strategies. All the strategies which are adopted after the occurrence of risk are known as reactive risk management strategies.

Risk transfer strategies: Insurance and contract farming etc., work on the principle of shifting a farm risk from one party which is the farmers to another party, these risk strategies represent the risk transfer method.

Conclusion

Indian agriculture faces escalating farm risks from climate volatility, policy change and market instability. Managing agricultural risk is not just a necessity for individual farm survival, but a critical prerequisite for India's macroeconomic stability. The socio-economic impacts of unmitigated farm risks cascade rapidly from household debt traps to national food inflation and fiscal deficits. To break this cycle, a structured approach utilizing a combination of preventive (ex-ante), reactive (ex-post), and risk-transfer strategies such as crop insurance and contract farming is essential. Transitioning from reactive crisis management to proactive risk mitigation will secure stable farmer incomes, protect vulnerable rural economies, and guarantee long-term national food security.

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Soil Testing: A Key to Better Crop Production

Kiran Patel, Poonam Chaturvedi, Kuldeep Rajpoot and Ankita Singh

Introduction

Soil is the foundation of agriculture and plays a vital role in crop production. Healthy soil provides essential nutrients, water, and support to plants. However, continuous cultivation, excessive use of fertilizers, erosion, and poor management practices reduce soil fertility over time. To maintain soil productivity and obtain higher yields, farmers need to understand the condition of their soil. Soil testing is one of the most effective scientific methods to evaluate soil health and fertility. Soil testing refers to the laboratory analysis of soil samples to determine nutrient status, pH, organic matter, salinity, and other important characteristics. It helps farmers apply the right type and amount of fertilizers and soil amendments. Soil testing improves crop productivity, reduces production costs, and protects the environment from excessive chemical use. Today, soil testing has become an essential tool in modern and sustainable agriculture.

Meaning and Definition of Soil Testing: Soil testing is the scientific process of collecting soil samples and analyzing them in a laboratory to determine the physical, chemical, and biological properties of the soil. It measures the availability of nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium, magnesium, sulfur, and micronutrients. It also evaluates soil pH, electrical conductivity, organic carbon, and lime requirement.

According to agricultural experts, soil testing serves as a guide for profitable and balanced fertilizer use. It helps in making accurate decisions regarding nutrient management and crop planning.

Importance of Soil Testing in Crop Production

Soil testing is extremely important for increasing agricultural productivity and maintaining soil health. Its major benefits are described below:

Determines Soil Fertility Status: Soil testing helps identify the nutrient content present in the soil. It shows whether the soil is deficient or rich in nutrients such as nitrogen, phosphorus, potassium, zinc, iron, and sulfur. This information helps farmers select suitable fertilizers for crops.

Helps in Balanced Fertilizer Application: Many farmers apply fertilizers without knowing the actual requirement of the soil. Excessive fertilizer use increases production costs and damages the soil. Soil testing recommends the proper quantity of fertilizers needed for optimum crop growth. Balanced fertilization improves nutrient use efficiency and increases crop yield.

Improves Crop Yield and Quality: Healthy soil with proper nutrients supports better root growth, flowering, and grain formation. Soil testing helps maintain ideal nutrient balance, resulting in higher crop production and improved quality of grains,

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fruits, and vegetables.

Reduces Cost of Cultivation: When fertilizers are applied according to soil test recommendations, unnecessary expenditure on fertilizers is reduced. Farmers can save money by avoiding excess application of nutrients that are already available in the soil.

Maintains Soil Health: Continuous use of chemical fertilizers without testing can make soil acidic, alkaline, or saline. Soil testing helps monitor soil pH and organic matter status. It encourages the use of organic manure, compost, biofertilizers, and lime where needed, thereby maintaining long-term soil health.

Protects the Environment: Overuse of fertilizers leads to pollution of water bodies and soil degradation. Soil testing prevents nutrient losses and minimizes environmental pollution. Proper nutrient management supports sustainable agriculture.

Assists in Crop Selection: Different crops require different soil conditions and nutrient levels. Soil testing helps farmers select crops suitable for their soil type and fertility status, leading to better productivity.

Components Analyzed in Soil Testing

Soil testing generally includes analysis of the following components:

Soil Property	Importance
Soil pH	Indicates acidity or alkalinity
Nitrogen (N)	Essential for vegetative growth
Phosphorus (P)	Promotes root and flower development
Potassium (K)	Improves disease resistance and quality
Organic Carbon	Indicates organic matter content
Electrical Conductivity (EC)	Measures salinity
Micronutrients	Zinc, iron, boron, manganese, copper etc.
Calcium and Magnesium	Important for plant structure and growth

Soil pH is one of the most important factors because it controls nutrient availability to plants. Most crops grow well in soils having pH between 6.5 and 7.5.

Procedure of Soil Testing

Soil testing involves several steps:

Collection of Soil Sample: The accuracy of soil testing mainly depends on proper soil sampling. Samples should be collected from different parts of the field at a uniform depth. Stones, roots, and plant residues should be removed.

Steps for Sampling

- ✓ Divide the field into uniform sections.
- ✓ Collect soil from 10-15 spots.
- ✓ Take samples from 15-20 cm depth for field crops.
- ✓ Mix all samples thoroughly.
- ✓ Dry the sample in shade and place it in a clean bag.
- ✓ Label the sample properly before sending it to the laboratory.

Laboratory Analysis: The soil sample is analyzed using scientific instruments and chemical methods to determine nutrient levels, pH, salinity, and organic matter.

Interpretation of Results: Experts interpret the test results and classify nutrient levels as low, medium, or high.

Fertilizer Recommendation: Based on the analysis, suitable fertilizer doses and soil amendments are

recommended for specific crops.

Types of Soil Testing

Chemical Soil Testing: It measures nutrient availability, pH, salinity, and chemical composition of soil.

Physical Soil Testing: It examines soil texture, structure, bulk density, and water-holding capacity.

Biological Soil Testing: It evaluates microbial activity and organic matter content in soil.

Soil Health Testing: This modern approach studies physical, chemical and biological properties together for overall soil health assessment.

Role of Soil Testing in Sustainable Agriculture

Sustainable agriculture aims to meet present food needs without damaging natural resources. Soil testing supports sustainable farming in several ways:

- ✓ Encourages balanced fertilizer use
- ✓ Reduces soil degradation
- ✓ Prevents nutrient imbalance
- ✓ Promotes integrated nutrient management
- ✓ Increases fertilizer efficiency
- ✓ Conserves soil fertility for future generations

Governments and agricultural institutions promote soil testing through soil health card programs and extension services. In India, the Soil Health Card Scheme helps farmers understand the nutrient status of their fields and adopt scientific nutrient management practices.

Modern Technologies in Soil Testing: Advancements in science and technology have improved soil testing methods. Modern tools include:

Digital Soil Testing Kits: Portable soil testing kits provide quick information about soil pH and nutrients.

GPS and GIS Technology: Precision agriculture uses GPS and GIS to map soil variability within fields and apply fertilizers accurately.

Remote Sensing and Sensors: Sensors help monitor soil moisture, temperature, and nutrient status in real time.

Artificial Intelligence and Machine Learning: AI-based systems analyze soil data and recommend suitable crops and fertilizer practices. Recent studies show that intelligent systems can improve crop recommendations and precision farming.

Suggestions for Effective Soil Testing

To improve the effectiveness of soil testing, the following measures should be adopted:

- ✓ Soil should be tested regularly every 2-3 years.
- ✓ Samples must be collected scientifically.
- ✓ Farmers should follow laboratory recommendations carefully.
- ✓ Organic manures and biofertilizers should be integrated with chemical fertilizers.
- ✓ Awareness programs should be conducted in rural areas.
- ✓ Mobile soil testing laboratories should be expanded.
- ✓ Farmers should maintain records of soil test reports for future planning.

Conclusion

Soil testing is a key tool for achieving better crop production and sustainable agriculture. It helps farmers understand soil fertility, apply balanced

fertilizers, reduce cultivation costs, and improve crop yield and quality. Soil testing also protects the environment by preventing excessive use of chemicals and maintaining long-term soil health. In modern agriculture, scientific soil management is essential to meet the growing food demand of the increasing population. Therefore, farmers should adopt regular soil testing practices and use soil health recommendations for profitable and eco-friendly farming. Healthy soil ultimately leads to healthy crops, healthy farmers, and a healthy nation.

Strigolactones: Tiny Plant Hormones with a Big Agricultural Future

Ankita Singh, Harsh Mishra, Sebin Sara Solomon and Amit Kumar

Plants may appear silent and motionless, yet beneath the soil they communicate, compete, and survive using remarkable chemical signals. Among the most fascinating of these signals are strigolactones a group of plant hormones that have transformed our understanding of plant biology and sustainable agriculture. Originally discovered through their role in stimulating the germination of parasitic weeds such as *Striga* ("witchweed"), strigolactones are now recognized as multifunctional compounds that regulate plant growth, root architecture, nutrient uptake, and interactions with soil microorganisms. Today, scientists consider them one of the most promising tools for climate-resilient agriculture.

What are Strigolactones?

Strigolactones are carotenoid-derived plant hormones produced mainly in plant roots. They are released into the soil in very small quantities but exert powerful effects on surrounding organisms and on the plant itself. The first strigolactone, "strigol," was identified in cotton root exudates because it triggered the germination of *Striga* seeds. Since then, many natural and synthetic strigolactones have been discovered. These compounds are especially important under nutrient-deficient conditions, particularly when phosphorus availability is low. Plants increase strigolactone production during stress to improve their chances of survival.

Role in Plant Growth and Development

One of the major functions of strigolactones is the regulation of plant architecture. They suppress excessive shoot branching, helping plants use energy more efficiently. Plants deficient in strigolactones often appear bushy with many branches.

Strigolactones also influence:

- ✓ Root elongation and root hair development
- ✓ Leaf senescence
- ✓ Stem growth
- ✓ Seed germination
- ✓ Responses to environmental stress

Through these functions, strigolactones help plants balance growth according to available resources.

Communication beneath the Soil

The soil around plant roots is a highly active biological zone called the rhizosphere. Strigolactones serve as communication signals in this underground world.

Beneficial Interaction with Fungi

Strigolactones attract arbuscular mycorrhizal

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fungi, beneficial soil fungi that form symbiotic associations with plant roots. These fungi help plants absorb phosphorus, nitrogen, and water more efficiently. In return, the plant provides carbohydrates to the fungi. This relationship is especially valuable in nutrient-poor soils and reduces dependence on chemical fertilizers.

The Problem of Parasitic Weeds

Unfortunately, parasitic weeds such as *Striga* and *Orobanche* exploit the same signal. Their seeds remain dormant in the soil until they detect strigolactones released by nearby host roots. Once germinated, the parasites attach to the host plant and steal water and nutrients, causing severe crop losses. In many parts of Africa and Asia, *Striga* infestation threatens crops like sorghum, maize, millet, and rice, reducing agricultural productivity and food security.

Strigolactones and Sustainable Agriculture

Modern agriculture faces major challenges, including climate change, declining soil fertility, water scarcity, and excessive fertilizer use. Strigolactones may provide innovative solutions to several of these problems.

Improving Nutrient Efficiency: Because strigolactones enhance symbiosis with mycorrhizal fungi, they can improve nutrient uptake naturally. Crops with optimized strigolactone signaling may require lower fertilizer inputs.

Enhancing Stress Tolerance: Research suggests that strigolactones help plants tolerate drought, salinity, and temperature stress by regulating hormonal balance and root development.

Controlling Weeds: Scientists are exploring "suicidal germination" strategies using synthetic strigolactones. In this approach, parasitic weed seeds are stimulated to germinate in the absence of a host crop, causing them to die before they can infect plants.

Crop Improvement: Plant breeders are studying genes involved in strigolactone biosynthesis and signaling to develop climate-resilient crops with better nutrient efficiency and optimized plant architecture.

Future Prospects

The discovery of strigolactones has opened an exciting frontier in plant physiology and agricultural biotechnology. What began as a study of parasitic weed germination has evolved into a deeper understanding of plant communication and adaptation.

Future research may lead to:

- ✓ Eco-friendly weed management
- ✓ Reduced dependence on fertilizers
- ✓ Improved crop productivity under stress
- ✓ Sustainable farming systems for changing climates

As agriculture seeks greener and smarter solutions, strigolactones represent a powerful example of how tiny molecules can have enormous impacts on global food security and environmental sustainability.

Conclusion

Strigolactones are far more than simple plant hormones. They are master regulators that connect

plants with their environment, soil microbes, and even competing organisms. Their diverse roles in plant growth, nutrient management, and stress adaptation make them one of the most promising discoveries in modern plant science. In the coming decades, strigolactone research may help farmers produce more food with fewer resources, supporting both agricultural productivity and ecological balance in a rapidly changing world.

Traditional Varieties: Living Wealth for Agriculture and the Future

Amit Kumar, Prateek Kumar, Kuldeep Rajpoot and Ankita Singh

Traditional varieties are not just old seeds from the past. They are living crop resources that have been cultivated, selected, and preserved by farmers over generations, and they remain highly valuable for agriculture even today. In an age of climate uncertainty, nutritional challenges, and rising pressure on food systems, these varieties are becoming even more important because they carry useful genes and local adaptation that modern breeding will increasingly need.

What are traditional varieties?

Traditional varieties are crop populations that have been grown and maintained by farmers over a long period under local conditions. In Indian policy language, farmers' varieties include varieties that have been traditionally cultivated and evolved by farmers in their fields, as well as wild relatives, landraces, and varieties about which farmers possess common knowledge. This definition itself shows that traditional varieties are closely linked with farmer selection, local adaptation and community knowledge. These varieties are often called landraces or farmers' varieties, though exact terms may vary by context. Unlike highly uniform modern varieties, traditional varieties are usually more heterogeneous, meaning that the plants within them may not all look exactly the same. This apparent variability is actually one of their strengths, because it reflects a broad genetic base built through long-term cultivation under real field conditions.

What do traditional varieties contain?

Traditional varieties contain a rich pool of genes that breeders and farmers can use for crop improvement. They often possess genes or gene combinations for drought tolerance, low-input adaptation, pest and disease resistance, tolerance to poor soils, special grain quality, medicinal value, taste, cooking quality, and nutritional traits. Many such traits may be absent or weak in modern uniform varieties, especially when breeding has focused mainly on yield under favorable conditions. They also contain something equally important: accumulated local experience. Traditional varieties are not only biological materials but also part of a farming system shaped by climate, soils, culture, food habits, and farmer knowledge. In that sense, they represent both genetic diversity and traditional wisdom working together.

Why are traditional varieties important?

Traditional varieties are important because

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they act as the raw material for future crop breeding. Modern crop improvement depends on access to useful genes, and landraces with broad genetic variability are widely recognized as basic source materials for developing improved varieties through modern breeding. When breeders need tolerance to drought, flood, heat, salinity, or new diseases, they often have to search beyond elite cultivars and look into traditional materials where such genes have been maintained over time. Their importance has increased further under climate change. FAO has emphasized that traditional crops and other plant varieties are in urgent need of protection from climate change and other environmental stresses, and that the conservation and sustainable use of plant genetic resources are essential for feeding a growing population in the future (FAO, 2010). Traditional varieties are often more genetically diverse than modern varieties, which can help them withstand environmental stress such as water shortage, poor nutrients, and uncertain growing conditions. They are equally important for food security and nutritional security. As population increases, agriculture must produce more food, but it must also provide better nutrition, resilience, and stability. Many traditional varieties are known for special nutritional, medicinal, or culinary properties, and some rice landraces in India have been specifically highlighted for drought resistance, flood tolerance, and nutritional or medicinal value. This makes them relevant not only to breeders but also to communities, consumers, and public nutrition systems.

Utility of traditional varieties in crop improvement

The practical utility of traditional varieties in breeding is very high. They serve as donor parents in breeding programmes, widen the genetic base of crops, support pre-breeding work, and help breeders identify rare or useful alleles that may not be available in elite materials. In many cases, a traditional variety may not be high yielding by itself, but it may carry one or two highly valuable traits that can be transferred into improved backgrounds. Traditional varieties are also useful directly at the farm level. Farmers in difficult environments often continue cultivating them because of adaptation to local rainfall, soil conditions, mixed cropping systems, grain quality, fodder value, and household preferences. Their utility is therefore dual: they are immediate livelihood resources for farmers and long-term genetic resources for crop improvement.

Why conservation is necessary

The conservation of traditional varieties is becoming urgent because many are disappearing from farmers' fields. The spread of uniform modern cultivars, market preference for a narrow range of crops, changing lifestyles, habitat degradation, and climate stress are all contributing to genetic erosion. Once a traditional variety disappears, the unique genes and local knowledge associated with it may also be lost permanently. This loss is not only a cultural issue; it is a breeding problem and a food-system problem. If agriculture depends on a narrow genetic base, it becomes more vulnerable to pests,

diseases and environmental shocks. Conserving traditional varieties therefore means protecting future options for breeding, adaptation and resilience.

Conservation strategies

Traditional varieties can be conserved through both ex situ and in situ approaches. Ex situ conservation means storing seeds or planting material outside their original growing environment, such as in gene banks, seed banks, or institutional collections. In situ or on-farm conservation means maintaining varieties in the farmers' own fields where they continue to evolve under local conditions. Both methods are important, but on-farm conservation is especially critical for the continued life of farmers' varieties because it keeps selection, adaptation, and local use active.

A strong conservation strategy should include the following:

- ✓ Systematic collection of landraces and farmers' varieties from different agro-ecological regions before they disappear.
- ✓ Proper characterization and documentation of traits such as stress tolerance, grain quality, nutritional value, and disease resistance.
- ✓ Strengthening national and state-level seed and gene banks for safe long-term storage.
- ✓ Promoting community seed banks and local seed exchange systems so that farmers can access and multiply traditional seed.
- ✓ Supporting participatory conservation in which farmers, scientists, and local institutions work together.

Indian examples of conservation

India provides several encouraging examples. In Wayanad, tribal communities such as Kurichiya and Kuruma were recognized for the on-farm conservation of traditional rice varieties under the PPV&FR framework. In Tamil Nadu, community seed bank initiatives have traced, collected, restored, and multiplied around 20 heritage rice varieties through seed exchange and field gene bank activities. These efforts show that conservation is most effective when traditional knowledge, community participation, and scientific support are combined. Community seed bank movements in India have also shown that conservation can be linked with farmer access. In Karnataka, a community seed bank network has served more than 2,500 farmers across more than 50 villages while maintaining a large collection of traditional rice, millet, and vegetable varieties (Fridtjof Nansen Institute, 2024). Such examples demonstrate that traditional varieties can be conserved not as museum material, but as living agricultural resources in active use.

Farmers as custodians of traditional varieties

One of the most important facts about traditional varieties is that they have been conserved mainly by farmers, especially small, marginal, and tribal communities. Public institutions and legal systems are important, but the everyday work of maintaining, selecting, exchanging, and re-sowing these varieties is often done by rural communities. These farmers are not merely seed users; they are

conservers, selectors and custodians of agrobio-diversity.

Recognizing this role is essential for future conservation planning. Support should not only go to central gene banks, but also to local seed systems, farmer groups, and community institutions that keep traditional varieties alive in real farming conditions. Affordable access, seed exchange, small-scale multiplication and farmer-led conservation networks can make traditional variety conservation both practical and sustainable.

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Water Crisis and Sustainability in Agriculture

Sebin Sara Solomon, K. Nagaraju, Abdul Haseeb and Amit Kumar

Introduction

Every meal we consume on a daily basis carries a hidden hydrological cost, and the planet is struggling to pay the bill. Water is the fundamental lifeblood of our terrestrial ecosystems, yet the mechanics of modern farming are pushing global hydrology to its absolute breaking point. Today, the agricultural sector stands as the undisputed heavy-weight of global water consumption, accounting for roughly 72 percent of all freshwater withdrawals. This immense thirst is now colliding with an inescapable demographic reality. As the human population climbs toward a projected 9.7 billion by the year 2050, global demand for food, feed, and fibre is expected to surge by more than 50 percent compared to 2012 levels. We are demanding vastly more from a natural resource base that is rapidly depleting. The consequences of this imbalance are no longer theoretical; an estimated 1.2 billion people roughly one-sixth of the global population already live in agricultural regions facing severe water constraints. Understanding how we arrived at this critical juncture, and how we can innovate our way out of it, is essential for securing the future of our food supply.

Concept

Groundwater depletion and the virtual water trade: The anatomy of this crisis is most visible below ground. Between 1990 and 2020, global groundwater withdrawals tripled, jumping from 227 billion to 879 billion cubic meters, leaving a quarter of the world's river basins heavily overexploited. In highly cultivated regions like northwestern India, the intensive farming of water-heavy crops such as rice and wheat has pushed extraction rates far beyond the natural recharge capacity of local aquifers.

Compounding the strain on these local aquifers is the globalized nature of modern food markets and the concept of the “virtual water trade.” Virtual water refers to the volume of water consumed during the entire production process of agricultural commodities. When products travel across international borders, the water embedded in their production is traded alongside them. Oddly, nations experiencing severe physical water stress are frequently massive exporters of embedded water. India, for instance, exports substantial volumes of virtual water through commodities like rice and castor oil. Consequently, water-scarce regions are effectively subsidizing the export of their most precious and finite resource to the rest of the world, often without pricing the true ecological cost of that

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water into the exported goods.

Evidence

Socio-Economic Impacts and the Subsidy Trap: The fallout from drying aquifers extends far beyond hydrology, deeply fracturing rural societies. When water tables plummet, farming communities are forced to dig progressively deeper wells and invest in heavier, more expensive pumping equipment. These capital-heavy adaptations act as a regressive tax on rural populations. Marginal and smallholder farmers, lacking the financial liquidity to keep chasing the water downward, face mounting debt and severe agrarian distress. As irrigation access fails, the employment-generating capacity of farming shrinks. Cropping intensity drops, which subsequently reduces the demand for agricultural labor, driving vulnerable landless laborers to migrate to urban centers in search of work. Women bear a dispro-portionate share of the burden. When local groundwater sources dry up, the time and physical exertion required for women and girls to collect domestic water increase drastically, stripping away hours that could be spent on education or income-generating activities. Despite these harsh realities, simply outlawing groundwater extraction is not a viable fix. Predictive models show that abruptly halting groundwater overdraft without introducing complementary measures would trigger sharp declines in the production of staple crops. This would inevitably drive up international prices for rice and wheat by roughly 6 to 7 percent, putting 24 million additional people at risk of hunger, primarily in low- and middle-income nations. Instead, the crisis is heavily driven by misaligned policy incentives. In many areas, the combination of minimum support prices for water-intensive crops and untargeted electricity subsidies for agricultural pumps creates a perilous environment. When farmers pay near-zero marginal costs for the electricity used to pump water, there is absolutely no economic motivation to conserve it, resulting in a textbook tragedy of the commons.

Solution

Rethinking Cultivation: Soil Health and Future Smart Foods: Solving this crisis requires rebuilding farming's physical foundation: the soil. Conventional agriculture degrades soil structure and moisture retention. Regenerative practices like no-till farming, cover cropping, and rotational grazing reverse this damage, effectively transforming the soil into a moisture-absorbing sponge. When framed as Conservation Agriculture (CA), these practices yield measurable global benefits; CA can increase water infiltration, reduce soil erosion by 50 percent, and boost crop yields by 15 to 25 percent in regions like Southern Africa. Furthermore, increasing soil organic matter by just 1 percent allows an acre of soil to hold an additional 20,000 gallons of water.

Farmers must also reconsider crop selection. A shift toward “Future Smart Food” crops such as dryland legumes, sorghum, and millets offers a highly practical adaptation strategy. These crops require much less water than traditional staples like paddy rice, while enhancing soil health and provid-

ing critical nutrients like iron, zinc, and protein. This crop diversification aligns with "nutritional water productivity," focusing on cultiva-ting foods with high nutritional density rather than purely maximizing raw tonnage. Crucially, much of the future surge in global food demand can be met by closing the "yield gap" the difference between current and attainable crop yields on existing agricultural land through better management, rather than expanding agricultural footprints. This efficiency can be pushed further by designing water systems for multiple uses, such as integrated rice-fish farming, which synergistically recycles water and nutrients, boosting household revenue without requiring additional freshwater withdrawals.

Precision Technology and Soilless Systems

On the technological front, the Internet of Things (IoT) is revolutionizing how water is delivered to crops. Traditional flood irrigation is notoriously inefficient. Today, smart irrigation systems utilize networks of soil moisture, pH, and NPK (nitrogen, phosphorus, potassium) sensors planted at root depth to monitor field conditions in real-time. Connected to microcontrollers and cloud platforms, these systems automatically trigger irrigation pumps only when moisture drops below precise, crop-specific thresholds. Field testing shows that automated, IoT-driven irrigation can reduce water application frequency by approximately 30 percent compared to conventional timed schedules, all while preventing nutrient leaching caused by overwatering. For highly controlled environments, soilless farming techniques push water conservation even further. Hydroponics relies on water-based nutrient solutions rather than soil to cultivate plants, operating in closed-loop systems that recapture and recirculate water. Aeroponics takes a different approach by leaving plant roots entirely suspended in the air within a dark chamber, delivering hydration and nutrients via a finely calibrated mist. By eliminating standing water entirely, aeroponic systems reduce evaporation and can operate using 30 to 50 percent less water than hydroponic setups, making them exceptionally valuable for regions facing severe water scarcity.

Conclusion

The agricultural water crisis is an urgent global challenge that directly threatens our food security and the livelihoods of farming communities. As the global population grows and dietary preferences shift, the immense pressure on our finite freshwater resources is colliding with the compound-ing impacts of climate change, resulting in severe water shortages and rapid groundwater depletion. We cannot solve this crisis through simple extraction bans, as abruptly halting water use would severely disrupt global food supplies and exacerbate hunger among the most vulnerable populations. Instead, a fundamental transformation of our agricultural systems and policy frameworks is required. By embracing integrated land and water governance frameworks and fostering collaboration across all sectors, we can transition away from water-depleting practices. This unified approach is the only way to

build a resilient, equitable food system that nourishes humanity while safeguarding the planet's most vital resource for future generations.

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Women Agripreneurs in India: From Silent Contributors to Transformative Leaders

Sebin Sara Solomon, Shagini D., Abdul Haseeb, Kiran Patel and Ankita Singh

Abstract

Across India's vast farmlands, women constitute nearly 46 percent of the agricultural workforce and play a central role in crop cultivation, livestock management, food processing, and allied activities. Despite their enormous contribution, they own only about 13 percent of farmland, receive a disproportionately small share of formal credit, and largely operate as micro-entrepreneurs in the informal sector. This article explores the lived realities of women agripreneurs - their formidable barriers, remarkable resilience, and the evolving support ecosystem designed to empower them. As the United Nations observes the International Year of the Woman Farmer in 2026, it highlights how government schemes, women-led Farmer Producer Organizations (FPOs), and digital innovations are creating new momentum. Empowering women agripreneurs is not only essential for gender equity but also a strategic driver for sustainable agriculture, rural prosperity, and India's economic growth.

Introduction: Who are Women Agripreneurs?

A woman agripreneur is a woman who transforms agriculture into a profitable and sustainable business. She goes beyond traditional farming roles to start, manage, and grow enterprises such as dairy units, food processing, mushroom cultivation, beekeeping, organic farming, poultry, or value-added handicrafts. She combines traditional knowledge with modern practices using better techniques, digital tools, branding, and direct market linkages to earn more from the land. In India, millions of such determined women are working quietly in villages. They manage homes, fields, and animals while dreaming of building better lives for their families. Their success means stronger households, prosperous villages, and a more self-reliant nation. This article tells their inspiring yet challenging story.

The Current Scenario

Women are the backbone of Indian agriculture. In many regions, they perform up to 85% of the actual farm work. Their contribution is immense, yet when it comes to ownership and entrepreneurship, their share remains painfully low. They own only about 13% of farmland and receive merely 7% of formal bank credit. Most run tiny, informal businesses from home with limited resources.

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However, positive changes are emerging. More women are forming Self-Help Groups, leading Farmer Producer Organizations (FPOs), learning new skills, and using mobile phones to sell directly. Reports show a four-fold increase in women taking business loans in recent years. Hope is growing.

The Persistent Challenges: Barriers That Hold Them Back

Women agripreneurs face multiple, interconnected obstacles every day. Giglio's (2020) systematic literature review identifies four major dimensions, while the SAFE framework developed by MicroSave Consulting and NITI Aayog (2022) provides a clear and practical way to understand why many women-led enterprises struggle to grow. The SAFE framework stands for Sustainable, Autonomous, Formal, and Employment-Generating. According to this framework, a large number of women enterprises fall short on these important aspects:

Sustainable: Many businesses are highly vulnerable to crises. They often lack sufficient savings, diversified income, or strong market linkages to survive difficult periods. During the COVID-19 pandemic, for example, 73% of women-run enterprises saw their revenue drop sharply, and many-faced complete loss of income. Without proper financial buffers, even small shocks can push them back into poverty.

Autonomous: Due to deep-rooted social norms and family structures, many women do not have full control over their business decisions, finances, or profits. Husbands or male family members often influence or control key choices, limiting women's ability to invest boldly, take risks, or expand their enterprises independently.

Formal: Over 95% of women-led enterprises operate informally. They remain unregistered, which denies them legal protection, access to formal credit, government subsidies, insurance, and better market opportunities. Informality keeps them small, vulnerable, and invisible to the system.

Employment-Generating: Most enterprises are single-person or very small micro-units. They rarely grow big enough to employ others, limiting their contribution to job creation and broader rural economic development.

Together, these four dimensions explain why, despite hard work and dedication, many women agripreneurs find it extremely difficult to scale their businesses and achieve lasting prosperity.

Government Support: Hope on the Horizon

The Government of India has introduced several important schemes such as Stand-Up India, Pradhan Mantri Mudra Yojana, PMEGP, MKSP, and the national programme for women-led FPOs. Over 1,175 women-led FPOs are now functioning across the country. Training through Krishi Vigyan Kendras and ATMA is helping women learn new skills. The 2025 From Borrowers to Builders report shows real progress in credit access. The upcoming International Year of the Woman Farmer 2026 brings fresh global focus and an excellent opportunity to strengthen these efforts.

Emerging Opportunities and Collective Strength

Women-led FPOs have become one of the most promising models. By working together, women gain better bargaining power, set up processing units, and reach bigger markets. Many are successfully running dairy businesses, organic farms, and value-added product units. Rising demand for healthy, organic, and ready-to-eat foods, along with e-commerce platforms, is creating exciting new opportunities. Digital tools and mobile technology are slowly breaking old barriers of distance and information gaps.

A notable success story comes from Maharashtra, where a women-led Farmer Producer Organization (FPO) established a dairy cooperative that now supplies milk and value-added products directly to urban markets. Initially, the women were small-scale dairy farmers selling raw milk to local traders at low margins. By forming an FPO, they pooled resources to purchase bulk chilling equipment, improve cattle feed, and adopt hygienic practices. With access to formal credit, they invested in pasteurization and packaging units, allowing them to brand their products and sell directly to urban consumers in Pune and Mumbai. Within two years, household incomes rose by over 40 percent, and the cooperative created new employment opportunities for local women in processing, distribution, and marketing. This case illustrates how collective organization, combined with financial inclusion, can transform traditional subsistence dairying into a profitable agribusiness model.

Kerala offers another inspiring success story through the Kudumbashree Mission's collective farming initiatives. Women farmers, many of whom had limited land ownership, came together under the Mahila Kisan Sashaktikaran Pariyojana (MKSP) scheme to cultivate vegetables and bananas collectively. By pooling land, labor, and resources, they improved crop yields and secured better incomes. Kudumbashree also supported them with training in sustainable practices and market linkages, enabling women to sell directly to local markets and government procurement programs. Studies show that women involved in these collective farming groups reported significant improvements in socio-economic conditions, including enhanced decision-making power within households and greater financial independence. This initiative demonstrates how community-driven models can empower women to overcome structural barriers and achieve sustainable livelihoods.

Together, these examples Maharashtra's dairy FPO and Kerala's Kudumbashree collective farming highlight how women agripreneurs are transforming agriculture through collective strength, credit access, and institutional support. They show that whether through cooperatives or community farming, women can move from subsistence-level activity to scalable agribusiness, reinforcing the broader narrative of empowerment and resilience.

Why this matters

When a woman succeeds as an agripreneur, the benefits spread to the entire community. Her incr-

eased income leads to better nutrition, children's education, and improved family health. Other women get jobs and inspiration. Villages become stronger and more economically active. The whole country gains from better food security and inclusive growth. Studies consistently show that money earned by women is spent more wisely on family welfare than money earned by men.

The Path Forward: What we can do

To help more women become successful agripreneurs, we must act together:

- ✓ Make finance truly accessible with collateral-free loans and faster land rights for women.
- ✓ Expand practical training that combines farming skills with business, digital, and marketing knowledge.
- ✓ Strengthen women-led FPOs with professional guidance and market support.
- ✓ Simplify government schemes and take them to every village.
- ✓ Fully utilise the International Year of the Woman Farmer 2026 for nationwide awareness and special support.

To every woman reading this: You already have the strength, knowledge, and determination. Start small. Join a Self-Help Group or FPO. Learn one new skill. Take that first step with courage. You are not alone many women have walked this path and succeeded. Your success will change your life and inspire many others.

Conclusion: The Time for Empowerment is now

Women agripreneurs are ready to lead. They already feed the nation now they deserve the tools, recognition, and support to build thriving businesses. By removing barriers and strengthening support systems, India can create thousands of success stories and build a stronger, more inclusive future.

The International Year of the Woman Farmer 2026 is not just a celebration. It is a call to action. Let us commit to turning this moment into real change. The fields are ready. The future belongs to empowered women.

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Heat-Induced Toxicants in Processed Foods: Formation, Health Risks and Mitigation Strategies

Akanksha

Abstract

Heat-induced toxicants are harmful chemical compounds generated during thermal food processing methods such as frying, baking, roasting, grilling, extrusion, sterilization, and pasteurization. These toxicants are mainly formed through chemical reactions including the Maillard reaction, caramelization, lipid oxidation, and pyrolysis. Common heat-induced toxicants include acrylamide, hydroxymethylfurfural (HMF), furan, polycyclic aromatic hydrocarbons (PAHs), heterocyclic amines (HCAs), advanced glycation end products (AGEs), and lipid oxidation products. Their formation is influenced by several factors such as temperature, heating duration, moisture content, pH, food composition, and cooking techniques. Continuous dietary exposure to these compounds has been associated with adverse health effects including oxidative stress, neurotoxicity, mutagenicity, inflammation, and carcinogenicity. Increasing consumption of processed and ready-to-eat foods has intensified concerns regarding food safety and public health. Recent research has focused on innovative mitigation strategies including vacuum frying, pulsed electric field processing, cold plasma treatment, microwave-assisted processing, enzyme application, and the use of natural antioxidants to reduce toxicant formation without compromising food quality. Green processing technologies such as air frying, infrared heating, and high-pressure processing also show significant potential for safer and sustainable food production. Furthermore, artificial intelligence, biosensors, nanotechnology-based detection systems, and omics approaches are emerging as advanced tools for monitoring and controlling food toxicants. Future research should emphasize sustainable processing technologies, rapid detection methods, and personalized risk assessment to ensure safer thermally processed foods and improved public health outcomes.

Introduction

Heat-induced toxicants are harmful compounds formed during high-temperature food processing processes such as frying, roasting, baking, and grilling through reactions including the Maillard reaction, lipid oxidation, and pyrolysis (Koszucka and Nowak, 2019). Common toxicants such as acrylamide, furan, HCAs, and PAHs are associated with prospective carcinogenic and neurotoxic effects, enhancing significant concerns regarding food safety and public health (Barzegar *et al.*, 2023). Increasing consumption of processed foods has intensified research efforts toward understanding and reducing the formation of these toxic compounds during food processing

Common heat treatments in households and indu-

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stries

Frying: Frying is a widely used high-temperature cooking method (160-190°C) that enhances the sensory properties of foods, including flavor, texture, and appearance. However, frying can also promote the formation of harmful compounds, such as acrylamide and aldehydes, through Maillard reactions and lipid oxidation, particularly during repeated use of frying oil (Abrante-Pascual *et al.*, 2024).

Baking: Baking uses dry heat to cook foods like bread and biscuits. High baking temperatures may lead to the formation of acrylamide and HMF in carbohydrate-rich foods (Erkıran *et al.*, 2026).

Roasting: Roasting enhances the flavour and aroma of foods such as coffee, nuts, and meat through intense heating. Elevated roasting can produce harmful compounds like furans and acrylamide (Batool *et al.*, 2025).

Grilling: Grilling cooks food over direct heat or flame, producing a smoky flavour and charred surface. High temperatures can give rise to heterocyclic amines (HCAs) and polycyclic aromatic hydrocarbons (PAHs) (Adeyeye *et al.*, 2025).

Extrusion Cooking: Extrusion cooking combines heat, pressure, and shear to produce snacks and cereals. Severe operating conditions may contribute to acrylamide and furan formation (Liu *et al*., 2025).

Sterilization and Pasteurization: Pasteurization and sterilization are thermal preservation processes used to improve food safety and extend shelf life by destroying microorganisms. However, high-temperature processing, particularly sterilization, may promote the formation of harmful compounds such as furans and oxidized lipids in processed foods (Zoller *et al.*, 2007)

Chemical reactions occurring during heating

Maillard Reaction: The Maillard reaction is a non-enzymatic browning process occurring between reducing sugars and amino acids during heating above 120°C, promoting to the flavor, aroma, and color of processed foods. However, it can also generate harmful compounds such as acrylamide and advanced glycation end products (AGEs), based on processing conditions and food composition (Rasool *et al.*, 2025)

Caramelization: Caramelization is the thermal breakdown of sugars at high temperatures, creating brown pigments and sweet flavors. It can produce compounds such as HMF during extensive heating (Marín Parra *et al.*, 2023).

Lipid Oxidation: Lipid oxidation is a degradation process in which fats and oils react with oxygen during heating, producing compounds such as peroxides and aldehydes that reduce food quality and shelf life. During high-temperature processing, oxidised lipids may generate toxic substances associated with adverse health effects, especially when oils are repeatedly heated (Mittu *et al*., 2023)

Pyrolysis: Pyrolysis is the thermal decomposition of food components at very high temperatures, especially during charring and smoking. It promotes to the formation of PAHs and other toxic compounds (Zhang *et al.*, 2025).

Major Heat-Induced Toxicants in Food

Acrylamide: Acrylamide is a major heat-induced contaminant formed during frying, baking, and roasting of carbohydrate-rich foods at temperatures above 120°C. It is mainly formed through the Maillard reaction between asparagine and reducing sugars such as glucose and fructose. Potato chips, French fries, bread, and breakfast cereals are major sources of acrylamide exposure. Studies have reported its neurotoxic, genotoxic, and probable carcinogenic effects in humans (Sahebi *et al.*, 2025).

Hydroxymethylfurfural (HMF): HMF is generated from the dehydration of sugars during thermal processing and prolonged storage. High concentrations of HMF are commonly found in honey, coffee, bakery products, fruit juices, and caramelized foods. Excessive HMF intake is associated with cytotoxicity, oxidative stress, and potential mutagenic effects (Dotto Matondo and Issa-Zacharia, 2026).

Furan and Alkylfurans: Furan and alkylfurans are volatile contaminants formed through thermal degradation of carbohydrates, lipids, amino acids, and ascorbic acid. These compounds are frequently detected in canned, jarred, sterilised, and ready-to-eat foods, including infant foods and coffee products. Infant exposure is considered a major concern because of higher susceptibility to toxic compounds. Furan has been categorized as a possible human carcinogen and significantly enhances dietary exposure risks (Batool *et al.*, 2025).

Polycyclic Aromatic Hydrocarbons (PAHs): Polycyclic aromatic hydrocarbons (PAHs) are formed during incomplete combustion and pyrolysis of organic materials during smoking, grilling, roasting, and barbecuing. Meat, fish, and smoked foods are important dietary sources of PAHs. Several PAHs exhibit mutagenic and carcinogenic properties and are involved with increased cancer risk after long-term exposure (Adeyeye *et al*., 2025).

Heterocyclic Amines (HCAs): Heterocyclic amines (HCAs) are produced when protein-rich foods are cooked at high temperatures. They are formed through reactions among amino acids, creatinine, and reducing sugars during frying, grilling, and barbecuing of meat products. HCAs are recognized for their mutagenic activity and potential association with colorectal, breast, and gastrointestinal cancers (Adeyeye *et al*., 2025).

Advanced Glycation End Products (AGEs): Advanced glycation end products (AGEs) are formed through Maillard reactions between reducing sugars and proteins or lipids during heating and processing. Fried, roasted, and baked foods contain elevated AGE concentrations. Dietary AGEs contribute to oxidative stress and inflammation and are associated with aging, diabetes, cardiovascular diseases, and chronic metabolic disorders (Gill *et al*., 2019).

Lipid Oxidation Products: Lipid oxidation products are generated when fats and oils undergo oxidation during repeated or prolonged heating, particularly during deep-fat frying. Oxidized oils produce aldehydes and reactive compounds that adversely affect food quality and safety. Long-term

consumption of oxidized lipids has been associated with oxidative stress, inflammation, and cardio-vascular diseases (Grootveld, 2022).

Factors Affecting Toxicant Formation

Temperature: High temperatures accelerate chemical reactions such as the Maillard reaction, lipid oxidation, and pyrolysis, increasing the formation of toxicants like acrylamide, HCAs, and PAHs (Koszucka and Nowak, 2019).

Heating Duration: Longer heating times promote greater accumulation of heat-induced toxicants due to prolonged exposure of food components to thermal degradation (Matondo *et al.*, 2026).

Moisture Content: Higher moisture levels generally reduce compounds such as acrylamide by limiting surface temperatures while low moisture conditions favor browning reactions and toxicant formation (Rasool *et al.*, 2025).

pH: The pH of food influence reaction pathways during heating. Acidic conditions can reduce acrylamide formation, whereas neutral or alkaline conditions may enhance Maillard reactions (Stadler and Gökmen, 2024).

Food Composition: The nutritional composition of foods, including carbohydrate, protein, and fat content, affects the type and quantity of toxicants formed during processing (Singh *et al.*, 2023).

Presence of Sugars, Amino Acids, and Fats: Reducing sugars and amino acids, particularly asparagine, are key precursors for acrylamide formation, while fats contribute to lipid oxidation products and PAHs during intense heating (Lingnert *et al.*, 2002).

Processing Equipment and Cooking Techniques: Cooking methods such as frying, grilling, and roasting generate more toxicants than boiling or steaming due to higher temperatures and direct heat exposure. Equipment design and processing conditions also influence toxicant levels (Uyarcan *et al.*, 2025).

Emerging Research and Future Perspectives

Novel Mitigation Technologies: Recent scientific studies has focused on innovative technologies to reduce heat-induced toxicants in foods without compromising nutritional and sensory quality. Advanced approaches such as vacuum frying, pulsed electric field processing, cold plasma treatment, enzyme application, and microwave-assisted processing have shown promising results in reducing acrylamide, HMF, and lipid oxidation products. Natural antioxidants and plant extracts including polyphenols, flavonoids, and dietary fibers are also increasingly explored as mitigation agents in thermally processed foods (Sahebi *et al.*, 2025).

Green Processing Approaches: Green processing technologies such as air frying, infrared heating, and high-pressure processing are increasingly used to reduce toxicant formation, energy consumption, and nutrient loss while supporting sustainable food production (Dotto Matondo and Issa-Zacharia, 2026). Artificial intelligence and smart processing systems help optimize processing conditions to minimize hazardous compounds and improve food safety (Zhang *et al.*, 2025). In addition, rapid screen-

ing tools including biosensors and nanotechnology-based detection systems enable quick monitoring of food toxicants such as acrylamide and PAHs (Nam *et al.*, 2022). Future food toxicology research will focus on advanced omics technologies, personalized risk assessment, and sustainable mitigation strategies to improve food safety and public health (EFSA, 2025)

Conclusion

Heat-induced toxicants such as acrylamide, furans, HCAs, PAHs, AGEs, and lipid oxidation products are commonly formed during high-temperature food processing methods including frying, baking, roasting, and grilling. These compounds are associated with several adverse health effects, including carcinogenic, mutagenic, neurotoxic, and oxidative stress-related disorders. Their formation depends on factors such as temperature, heating time, moisture content, food composition, and processing techniques with the increasing consumption of processed and ready-to-eat foods, minimizing toxicant formation has become an important area of food safety research. Advanced mitigation approaches such as green processing technologies, natural antioxidants, AI-assisted monitoring systems, and rapid detection methods have shown significant potential in reducing toxicant levels while maintaining food quality. Continued research and sustainable processing strategies will play a key role in improving public health and ensuring safer food production.

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Ocean Acidification and Its Effects on Aquaculture Ecosystems

Priyanka Rani, Akansha Khati and Divyanshu Kumar Upadhyay

Introduction

The world's oceans, estuaries, and waterways are all at risk from ocean acidification. It is frequently referred to as "the evil twin of climate change" and is expected to increase as long as carbon dioxide emissions into the atmosphere remain at historically high levels. Carbon dioxide from the atmosphere is being absorbed by our oceans in greater quantities. The seas and marine life, especially shellfish like commercially valuable oysters and clams, suffer as a result of this exchange, which helps control the planet's atmospheric carbon dioxide concentrations. The most well-known impact of ocean acidification on shellfish is its osteoporosis-like effects, which make it challenging for these organisms to form and maintain shells. Other species that are essential to the marine ecosystem are also impacted by acidification, such as pteropods (small snails consumed by many species, including fish and whales) and reef-building corals.

As a major carbon sink, the seas are essential for controlling the amount of carbon dioxide (CO_2) in the atmosphere. There are disadvantages to this absorption. Ocean acidification (OA) is the term used to describe how CO_2 dissolved in water behaves as an acid, decreasing its pH and causing changes in the carbonate chemistry of saltwater. The average pH of the world's surface waters has dropped by around 0.1 units from pre-industrial times, from about 8.2 to 8.1. The effects of other environmental stresses, including rising temperatures, may be made worse by ocean acidification. Additionally, it might help or hinder the growth of some species, changing the makeup of ecosystems.

Zooplankton, shellfish, and coral reefs are some of the first possible casualties. As a result, ocean acidification will have an influence on a number of economic sectors, including tourism, aquaculture, fisheries, and coastal towns. It may also have significant indirect consequences on far larger areas of the global economy and population.

What is Ocean Acidification?

Ocean acidification refers to the reduction in the pH of seawater caused by the absorption of excess atmospheric carbon dioxide. When carbon dioxide dissolves in seawater, it undergoes a series of chemical reactions:

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$$

The release of hydrogen ions (H^+) increases seawater acidity and reduces the availability of carbonate ions, which are essential for shell-forming organisms such as oysters, mussels, clams, and corals. Since the Industrial Revolution, the average ocean pH has dropped from approximately 8.2 to 8.1, representing about a 30% increase in acidity.

Causes of Ocean Acidification

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Uptake of atmospheric CO_2: The primary cause of ocean acidification worldwide is rising atmospheric CO_2. The uptake of anthropogenic CO_2 causes the surface ocean's CO_2 levels to rise, which has a significant impact on the marine carbonate system through well-known chemical processes. It raises the concentration of bicarbonate ions (HCO_3) and decreases pH (increasing acidity), lowers the saturation state of the main carbonate minerals that form shells, such as calcite and aragonite, and reduces the availability of carbonate ions (CO_3). The phenomenon is called "ocean acidification" because the pH of seawater is dropping while surface waters continue to be alkaline.

Coastal acidification due to inputs from land: At smaller spatial scales, some human inputs also make the impacts of ocean acidification worse. These inputs have a disproportionate effect along coastal margins, particularly in bays and estuaries, where anthropogenic stressors are most severe and where oceanic phenomena like upwelling or partial flushing take place.

Impacts of Ocean Acidification

Biological impacts of ocean acidification

Shelled animals including mussels, clams, urchins and starfish are going to have trouble building their shells in more acidic water, just like the corals. Mussels and oysters are expected to grow less shell by 25% and 10% respectively by the end of the century.

Impaired Shell Formation: Shellfish such as oysters, mussels, scallops, and clams rely on calcium carbonate to build shells. Acidified water reduces carbonate ion availability, making shell formation difficult.

Reduced Growth and Survival of Fish: Although fish do not form shells, ocean acidification can still affect their physiology and behaviour. Species cultured in marine aquaculture systems may experience decreased productivity under prolonged acidic conditions.

Damage to Coral Reef Ecosystems: Coral reefs provide breeding grounds, shelter, and feeding areas for many commercially important fish species. Ocean acidification weakens coral skeletons and slows reef growth. Habitat degradation, Loss of biodiversity, reduced fish recruitment, and lower ecosystem productivity indirectly affect coastal aquaculture and fisheries dependent on reef ecosystems.

Alteration of Food Webs: Many planktonic organisms are sensitive to changes in seawater chemistry. Since plankton forms the base of aquatic food chains, acidification can disrupt entire ecosystems.

Increased Disease Susceptibility: Acidic conditi-ons create physiological stress in aquatic organisms, weakening immune responses. Higher disease outbreaks, increased mortality, greater dependency on medications and management interventions raise production costs and threaten aquaculture sustainability.

Economic impacts of ocean acidification

It is difficult to estimate the economic impact

of ocean acidification for several reasons:

- ✓ The direct impact on many commercial species is unknown, let alone the indirect effects via impacts on other important linked ecosystem components.
- ✓ The capability of species and ecosystems to adapt is not well understood.
- ✓ Other commercial species may substitute stressed species.
- ✓ The impact of other stressors varies widely, and the combined impacts are not well understood.

Ecological effects of ocean acidification

These impacts will affect biochemical and cellular processes, which will cascade into the organism, and likely into population and ecosystem processes. Most importantly, these effects will interact with effects that cascade from other forcing (e.g. ocean warming, deoxygenation, etc.) in complex manners. At the species level, it is expected that each species will demonstrate its own 'average' intrinsic resistance to ocean acidification and associated chemical changes. For example, cyanobacteria are generally thought to benefit from CO_2 increases, while diatoms are more likely to be outcompeted. Calcareous species are more likely to be replaced by non-calcareous species as a result of ocean acidification, but competition, predation and other ecosystem processes are likely to be significant in determining overall responses.

Mitigation strategies for ocean acidification

- ✓ Global CO_2 emission reduction remains the cornerstone of mitigation, embedded in international agreements such as the Kyoto Protocol and Paris Agreement.
- ✓ At regional scales, coastal pollution control reduces nutrient-driven acidification.
- ✓ Local adaptation measures offer more immediate relief. These include integrated multi-trophic aquaculture (IMTA), selective breeding for OA resilience, seagrass and algae restoration, and ecosystem-based fisheries management.
- ✓ Protecting and cultivating seagrass ecosystems can act as a natural carbon sink, absorbing CO_2 and helping mitigate OA impacts.
- ✓ The National Ocean Acidification Hub acts as a centralised framework for coordinating India's scientific, policy, and community responses to the pressing issue of OA.
- ✓ Integrating ecological research with carbonate system modelling and socio-economic vulnerability assessments will be crucial to developing targeted and region-specific mitigation plans.
- ✓ Reduce carbon dioxide emissions and enhance ocean health.
- ✓ Establish marine protected areas and halt harmful fishing methods.
- ✓ Add alkali substances to the oceans.
- ✓ Introduce limestone carbonate materials.
- ✓ Plant more trees.
- ✓ Create green belts around industrial zones.

Bharat-VISTAAR: The Connecting Bridge

Nikita, Vishapa Kachhawaha and Digambar Singh

Introduction

Even today, 55% of India's population depends on agriculture, but the methods of farming are still 20 years old. Field report of Krishi Vigyan Kendras 2023 states that due to not receiving the right information at the right time, there is a loss of up to 18% in production every year. This means that instead of getting 100 sacks of wheat, the farmer gets only 82 sacks. To prevent this loss, data-driven farming is now replacing guesswork-based farming, which is called precision farming. In this, Artificial Intelligence (AI), drones, sensors, and satellites work together. The role of AI is to determine how much water is needed in each corner of the field, what types of pests pose a threat, and on which day the best prices of produce will be available in the market. People think that AI-based farming is something completely new, but the government has been preparing for it over the past 8-10 years. Three major pillars are already in place.

Soil Testing - Soil Health Card: This scheme, which started in 2015, has so far provided more than 220 million (22 crore) farmers with a report card of their soil. This card states how much Nitrogen, Phosphorus, and Potash are present in the Soil. This dataset is so large that nothing like it exists anywhere else in the world. For AI, this is the "raw material." Without soil data, AI cannot provide any recommendations. All this data is available for anyone to view at soilhealth.dac.gov.in.

Eyes from the Sky - Kisan Drone Scheme: In February 2022, the government introduced a subsidy of 40% to 75% on drones. As a result, by January 2024, more than 1,000 Kisan Drone Custom Hiring Centres had been set up. In the Jhunjhunu district of Rajasthan alone, 12 FPOs have acquired drones. A single drone can spray Nano Urea over 25 acres in one day. It reduces water usage by 90%, and farmers do not come into contact with toxic chemicals.

Digital Identity: Under the Digital Agriculture Mission 2021-25, a Digital ID is being created for every farmer. This ID will link the farmer's land, crops, and the subsidies they have received. With this, AI will not need to repeatedly ask questions like "how much land do you have?" Once the ID is entered, the system will automatically understand everything.

Bharat-VISTAAR: The Connecting Bridge

The problem is that all these three systems are working separately. There is a different website for soil testing, a separate app for weather information, and farmers have to call FPOs for drone services. This becomes confusing and stressful for farmers. The solution to this problem is 'Bharat-VISTAAR' - Virtually Integrated System for Technology-enabled Agriculture & Resources. As of April 2026, this is

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not a government scheme. It is an idea suggested in Agri-expert discussions and policy papers by NITI Aayog. Its goal is to create a "super app" that connects everything in one place.

Transform Indian agriculture with AI (source: The Hindu Business Line, 2024)

How does Bharat-VISTAAR work?

Imagine a farmer from the Nawa tehsil in the Kuchaman-Didwana district. At 7:00 AM, he receives a voice message on his phone: Greetings, Ram Singh ji. Your Soil Health Card indicates a Zinc deficiency in your Survey No. 2 field. The Meteorological Department predicts no rain for the next five days. Additionally, Bhuvan Satellite data shows that a Whitefly infestation has started just 3 km from your village. We advise you to spray Zinc and the necessary pesticide via drone today. A drone is currently available at your nearest FPO, Nawa Kisan Sangh.' Press 1 to confirm your booking. Right now, through the 1551 Kisan Call center, farmers have to take the initiative to call and ask for help.

The VISTAAR Vision: VISTAAR will proactively reach out to the farmer. It will communicate in his local dialect, identify the specific problems of his unique plot of land, and provide real-time solutions before the crisis hits.

40% Target by 2026: Dream or Reality?

40% target means bringing this technology to 5.8 crore (58 million) farms out of the country's total 14.5 crore farms. Accomplishing such a massive task, but it is not impossible. We can look at UPI as an example: it secured a 40% share of all digital transactions in less than 5 years. The reason was simple: the government laid down the digital highways, tech firms developed user-friendly platforms, and citizens quickly realised the practical value.

Reduce the Cost: At present, the setup cost for IoT sensors per acre is around ₹15,000, which is unaffordable for small landholders. Should the expense in India reduce to approximately Rs 4000 per acre with a direct subsidy system support, large scale outreach to farmers will become feasible. A similar situation was also observed in the UJALA scheme, where government support reduced the price of LED bulbs directly from 400 to 70 rupees.

Rent it, Don't Sell it: Most small farmers cannot afford to buy a drone; the only practical solution is to ensure that farmers have access to drone technology through FPO (farmer producer organisation). The role of FPO is to deliver this technology to farmers, which can function as a paid service. Today, more than 24000 FPOs are registered in India. If each one benefits around 2000 farmers, we extend this benefit to more than 4.8 crore farmers.

Building Farmer Confidence: According to the TRAI report, only 37 to 38% of people in rural areas currently have internet connection. For this reason,

expanding internet access to rural areas and accelerating the expansion of BharatNet are urgent requirements. The most critical aspect provided by AI is accurate. If any farmer suffers crop damage due to a single mistake by AI, it will create distrust towards this technology across the entire community. "Therefore, ensuring that every single AI solution is accurate is a huge responsibility".

The Test of the Next 2 Years: For farmers, AI is no longer just an idea but has become a present-day necessity. This needs two key elements to be present-Kisan Drone Centers, digital identity of farmers. Now, the task for Bharat Vistaar is to create an integrated system from all the scattered elements. The goal is to reach 40-50% of farmers by the year 2026, which shows that the work must now be done at a fast pace, not slowly. The next two years will determine whether AI becomes the most important tool for Indian agriculture or not.

Conclusion

Bharat-VISTAAR is a crucial link that will create a large guidance system by connecting various efforts. Achieving 40% adoption by the end of 2026 is not impossible, but it will certainly be difficult. This project can only be achieved if the cost is less than 5000 per acre, FPO provides a 75% subsidy, and every AI recommendation is accurate. For farmers in India, agriculture powered by AI is shifting from experimental labs to mainstream practice. India is issuing over 22 crore soil health cards to support farmers. With more than a thousand kisan drone hubs and a unique farmer ID available, the core infra-structure is already established.

Disclaimer: The datasets and technical metrics analyzed in this article are synthesized from existing government repositories, policy frameworks, and institutional reports; the authors have not independently collected this primary data but have structured it to evaluate the potential of the Bharat-VISTAAR framework.

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Drone Didi Boom + Namo Drone Didi Scheme: Women SHGs as Precision Farming Service Providers

Vishapa Kachhawaha, Nikita and Digambar Singh

Introduction

Agriculture in India is slowly but surely moving towards technology-based farming. Over the last few years, drone technology has entered the field in a big way. On 15th August, 2023, the Hon'ble Prime Minister Shri Narendra Modi announced the launch of the "Namo Drone Didi" Yojana, which aimed to empower women by hand-holding them into a sustainable business model where they can increase their income by more than Rs 1 lakh and transforming the modern farming ecosystem with drone technology. But what makes the recent push truly unique is not just the technology itself. It is about who is using it. The Namo Drone Didi Scheme, launched by the Government of India, has placed drone technology in the hands of women members of Self-Help Groups (SHGs). Agriculture in India is the foundation of life in areas. For a time, the tools and technologies that small farmers used did not change much even though the world around them was changing fast. The cost of farming was going up; it was getting harder to find people to work on farms, and farmers had to produce food on smaller pieces of land. This made the government and farmers look for solutions. One solution that has gotten a lot of attention in years is the agricultural drone.

What makes this moment interesting is not just that drones are being used in farming in India. It is also about who's using these agricultural drones. The Government of India started the Namo Drone Didi Scheme to give drones to women who are part of self-help groups. These women were already working together to save money and help each other. Now they are being trained to fly drones and provide services to farmers. This article will look at how the scheme started, how drones are used in farming, what benefits the scheme has for women, what good it does for the environment, and what challenges still exist.

Background: Why Women SHGs

Self-help groups have been a strong foundation for rural women's empowerment in India. There are crores of women involved under SHGs under missions like DAY-NRLM (Deendayal Antyodaya Yojana); this group is both large and trusted at ground level. These groups have proven their ability to manage finances, run small businesses, and take collective decisions. Self-help groups are groups of women who live in rural areas so that they can work together and earn some money to help each other. India has one of the networks of self-help groups in the world; 90 million women are part of these groups. Their dedication showed that they can manage resources, run businesses, and build

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trust in their communities. The Namo Drone Didi Scheme is built on this foundation. The scheme uses the self-help groups' network to train the woman on how to use drones in farming. This way the training and services are shared among the group members so that they can gain the knowledge technically also. The women in these groups are made that they can keep working and make decisions.

Fig. 1: Empowering Women Self-help groups (Source: department of agriculture and farmers welfare, Government of India, India.gov.in national portal of India

What the Namo Drone Didi Scheme Offers

Under this scheme, the central government provides the self-help groups with a drone and all the useful equipment. The service providers can charge 500-800 rs from local farmers to spray the crop per acre. The scheme targets covering at least 15,000 women's SHGs across India, with a plan to scale up further. Many states like Madhya Pradesh, Uttar Pradesh, Karnataka, and Rajasthan have already started rolling out the program at the ground level. The Namo Drone Didi Scheme is a plan started by the government of India. The government will spend Rs. 1,261 crore on this scheme from 2023-24 to 2025-26. The main goal is to give drones to 15,000 selfhelp groups across the country. This will help these groups provide services to farmers in their areas. The scheme is managed by a committee that includes secretaries from government departments. At the state level, companies that sell fertilizers will help implement the scheme. They will buy the drones, work with state governments, and make sure the drones are given to the groups. Each group will get money from the government to buy the drones. The group will have to pay 20 percent of the cost, which can be borrowed from a fund. The drone package includes the drone, a spray assembly, a camera, and other tools. The women will be trained to fly the drones and use them for farming.

Fig. 2: Empowering Agriculture: PM Modi with Namo Drone Didi's (Source: Department of Agriculture and Farmers welfare)

Precision Farming and What Drones Actually Do

Precision farming means applying the right input at the right place at the right time. Manual spraying is time consuming, slow, and causes in the backs of farmers using backpack sprayers severe pain at back of farmers using backpack sprayer. In this spraying, a lot of chemicals is waste and the area is not properly covered, so the uneven application affects the crop health and pollutes the soil and water. Precision farming involves the application of an exact amount of water, fertiliser, and pesticides at the perfect time, which eases efficiency. Traditional farming methods can be slow, time consuming.

Drones can spray the fertiliser and pesticides over the fields, which reduces the amount of chemicals used and prevents pollution. A total of 15,000 drones will be provided to selected women's SHGs between 2024-25 and 2025-26. They can take pictures and send them to the farmers, who can then decide what to do. The women of SHG provide the drone services so that small-scale farmers can use the advanced technology without paying the high amount. They simply call the local drone Didi, book a time, and get their field sprayed at an affordable rate. This has been one of the most practical aspects of the whole scheme.

Fig. 3: Trainees on field (Source: Namo Drone Didi portal, Department of Agriculture and Farmers Welfare Ministry of Agriculture and Farmers Welfare)

Economic Aspect for Women SHGs

The Namo Drone Didi Scheme can help women in areas earn more money. Each group can earn least Rs. 1 Lakh per year from providing services to farmers. This can be an amount of money for rural standards. The women will be trained to fly the drones and provide services. They will also get support, from the government and companies like IFFCO. The Namo Drone Didi Scheme is a way for women to earn money. Some women who are part of SelfHelp Groups or SHG groups get to spray things on farms using drones. They also get to sell tiny fertilizers, which helps them earn more money. This is a deal because these women can now earn up to Rs. 15,000 Per month which is a lot more than what they used to earn. The Namo Drone Didi Scheme is not about earning money. It also helps the environment and the health of the people. When drones spray fertilizers and pesticides, they use less of these chemicals than methods. This means that there are bad chemicals in the air and in the water. The World Health Organization says that when people spray pesticides by hand it can cause a lot of health problems. With drones this is not a problem anymore. The scheme is also helping women become more independent and confident. They are learning skills and becoming leaders in their communities. They are no longer members of savings groups but they are also business owners and service providers. The government has launched the scheme. It is being implemented in many states. Karnataka is one of the states that is doing well. The women there are getting trained to use drones. They are starting their own businesses. The government has also set up a portal to monitor the scheme and make sure it is working well. Drone Didi can charge 600rs per acre of service by spraying 5-8 acres per day she can earn 3000 to 4800 daily. This helps a woman to make good amount of income that was not available to her before. Over time, experienced woman can train other women, maintain equipment and manage drone

booking in small villages.

Fig. 4: Trained under drone Didi project (Source: Drone Didi Simranjeet Kaur in Ludhiana (Hindustan times)

Benefits of Drone Didi scheme

The scheme provides specialized training in drone technology, equipping women with advanced skills that are increasingly valuable in modern agriculture. This knowledge enables them to perform tasks like crop monitoring, soil analysis, and precision farming more efficiently.

Empowerment of Women: The scheme provides specialized training in drone technology, equipping women with advanced skills that are increasingly valuable in modern agriculture. This knowledge enables them to perform tasks like crop monitoring, soil analysis, and precision farming more efficiently.

Enhancement of Agricultural Efficiency: Drone technology significantly enhances the precise application of pesticides and fertilizers, transforming traditional agricultural practices. Equipped with advanced GPS and sensor technology, drones can be programmed to follow precise flight paths over fields, ensuring even and targeted application. This precision reduces the overuse of chemicals, minimizing environmental impact and lowering costs for farmers.

Skill Development and Knowledge Expansion: The scheme provides specialized training in drone technology, enabling women to acquire advanced skills in modern agricultural practices such as applying fertilizers, pesticides, and herbicides accurately, ensuring even distribution and optimal usage. Soil and field analysis is streamlined with drones, enabling detailed surveys and fertility assessments. Women can also enhance irrigation management by identifying areas needing more or less water, detecting leaks, and managing water resources efficiently.

Community and Networking Opportunities: Women can connect with a supportive network of fellow participants, fostering a sense of community and collaboration. They have the chance to join forums and workshops where they can share experiences, challenges, and best practices, enhancing their collective knowledge and skills. The scheme also provides access to industry experts, mentors, and agricultural professionals, creating avenues for mentorship and professional growth.

Challenges on the Ground

Like any scheme, Namo Drone Didi also faces some challenges that need to be addressed for it to reach its full potential.

- ✓ Poor supply of electricity leads towards difficulty to charge the drones.
- ✓ In rural remote areas, the replacement of component's and accessing technical support for drone maintenance can be challenging.
- ✓ Drones work best in open fields, tall trees, hilly

terrain and dense vegetation is a major challenge while operation.

- ✓ The operators have to follow the rules and regulations of government and maintaining legal compliance can be a burden for the operators.
- ✓ Some people with social views can make it hard for women to work with drones.

Future Possibilities

- ✓ Government has approved 'Namo Drone Didi' as Central Sector Scheme with an outlay of Rs. 1261 Crores for the period from 2023-24 to 2025-26 for providing drones to the selected Women Self Help Groups (SHGs) for providing rental services to farmers for agriculture purpose (application of fertilizers and pesticides). Central Financial Assistance @ 80% of the cost of drone and accessories/ancillary charges up to a maximum of Rs. 8.0 lakhs is provided to the women SHGs for purchase of drones. The Cluster Level Federations (CLFs) of SHGs may raise the balance amount (total cost of procurement minus subsidy) as loan under National Agriculture Infra Financing Facility (AIF) with interest subvention @ 3%.
- ✓ Under the Namo Drone Didi scheme, the drones are supplied as a package, which consists of basic drone with spray assembly for spraying liquid fertilizers and pesticides. The package includes additional 4 spare battery sets, one spare propeller set, nozzle set, dual channel fast battery charger, battery charger hub, 15 days training for drone pilot, drone assistant training, one-year comprehensive insurance, 2 years annual maintenance contract and applicable GST. The 15 days drone pilot training programme include compulsory training for securing drone pilot licence, preparation for flying, minor repair and maintenance and hands on practice for handling drones for spraying of pesticides and liquid fertilizers.
- ✓ As per the information provided by the Department of Fertilizers, Lead Fertilizer Companies (LFCs) have distributed 500 drones under the Namo Drone Didi Scheme to drone Didi's of SHGs in 2023-24. All these drones Didi's have been provided training at the Remote Pilot Organisations (RPTOs) authorised by DGCA.

Conclusion

- ✓ 1261 Crore allocated for modernizing agriculture with latest drone technology
- ✓ 15,000 drones to empower women from SHGs
- ✓ Amalgamation of Drone Technology and Nano fertilizers
- ✓ Drones as rental services for effective spraying of fertilizers by farmers
- ✓ Advanced Drone Portal for one-stop-solution
- ✓ 15 days of Drone Pilot training with certification

Disclaimer: The datasets and technical metrics analysed in this article are synthesized from existing government repositories, policy frameworks, and institutional reports; the authors have not independently collected this primary data but have structured it.

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Effect of Micronutrients on Growth and Yield of Banana cv Karpooravalli

K. Sha

Introduction

Banana (*Musa spp*.) is one of the most important tropical and subtropical fruit crops grown in India, which belongs to the family Musaceae. The edible banana is believed to have originated in hot tropical regions of South-East Asia. In India banana is known for its antiquity and is interwoven with Indian heritage and culture. The plants considered as the symbol of prosperity and fertility. It is also called as 'Kalpataru', Apple of paradise, Plant of virtue, Adam's fig and Tree of wisdom. Banana is fourth most important fruit crop in the world after rice, wheat and maize and it is the second important fruit crop in India next to mango.

Globally, banana is cultivated in an area of 5.9 million hectares with an average production and productivity of 135 million tonnes and 23 tonnes per hectare respectively (FAOSTAT, 2023). India contributes 26.45 percent of total world production and area of 9.65 lakh hectares among the total area under fruit crops in India with a production of 349.08 lakh tonnes during 2022-2023 (Ministry of Agriculture and Farmer Welfare). Andhra Pradesh is the largest banana producing state, followed by Maharastra, Karnataka, Tamil Nadu and Uttar Pradesh. These five states collectively contribute around 67 percent to India's banana production in the year 2022-2023.

The area under banana cultivation in Tamil Nadu is 1.02 lakh hectares with a production of 42.37 lakh tonnes during 2022-2023. Major banana growing districts are Erode, Thoothukudi, Coimbatore, Theni, Cuddalore, Tirunelveli, Trichy and Kanyakumari (TNAU, Coimbatore). Banana is a very popular fruit due to its low price and high nutritive value. It is consumed in fresh or cooked form both as ripe and raw fruit. It is a dessert fruit and is used in different regions as staple food owing to its rich and easily digestible carbohydrates with a calorific value of 67-137 kcal 100 g^{-1} edible fruit. It is a good source of vitamin A (190 IU per 100 g of edible portion) and vitamin C (100 mg 100 g^{-1}) and fair source of vitamin B and B_2.

Karpooravalli, meaning 'scented flower', is a popular variety of banana largely grown in South India. They are prized for their taste, texture, and portion size. The ash-coated golden yellow skin of these bananas makes it stand out from other bananas in the market. Karpooravalli banana is known for its delicious taste and pleasant aroma. It is mildly sweet and of large size, perfect for adding to desserts, ice cream or any sweet item, or simply eaten as it is. Karpooravalli bananas are rich in dietary fiber that helps regulate digestion and prevent constipation. The high fiber content in bananas helps regulate blood sugar levels, making it a good option for those

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with diabetes. Bananas are rich in vitamin C, which helps boost immunity and prevent infections. The potassium in bananas helps maintain healthy blood pressure levels, reducing the risk of heart disease. Karpooravalli banana is also rich in beta-carotene (143.12 µg per 100 g).

Balanced nutrition is very important for high yield, quality and resistance to diseases. Banana is a high nutrient requiring crop. It requires a continuous supply of nutrients at proper growth stages for enhanced yield and productivity. The unscientific crop management practices being adopted by farmers led to poor utilization of nutrients and thereby resulted in low productivity. Continuous uptake of nutrients from the soil due to intensive cultivation and unscientific methods fertilizer application had resulted in reduced nutrient use efficiency and soil degradation. Micronutrients are often referred to as minor elements and their deficiency can reduce plant yield similar to macronutrient deficiency. So an efficient and judicious use of fertilizers along with micronutrient application is essential for attaining higher yield per unit area. Micronutrients exist in very small amounts in both soil and plants, but their role is essential for the crop growth and equally important as primary and secondary nutrients. They have an important role in the balance of plant nutrition for the stabilization of a crop yield and quality of a produce. Most of the cultivable lands are deficient in micronutrients viz., zinc, iron, magnesium and boron. The role of micronutrients for production of quality traits have been already reported by several scientists. Zinc aids in regulating plant growth hormone and enzyme system, necessary for carbohydrate and starch formation, iron (Fe) promotes formation of chlorophyll pigment, which acts as an oxygen carrier involving cell division and growth and Boron (B) is necessary for translocation of sugars and promotes fruit maturity Micronutrient deficiencies in soil and crops have become prevalent in recent years due to several factors like intensive cropping, loss of top soil, soil erosion and leaching. To meet the required micronutrients demand, foliar application of micro-nutrient is necessary to get more yield.

Role of micronutrients

The importance of micronutrients in Indian agriculture is truly well recognised and their use had significantly contributed to the increased product-ivity of several crops. In recent years, micronutrients are gradually gaining momentum among the fruit growers because of their beneficial nutritional support and their potential to ensure high yield with better quality. The supply of micronutrients is adequate amounts through proper source and appropriate method at correct time control the growth of plants. Micronutrients are to be necessarily taken up by plants from soil or supplemented through fertigation or foliar application for good growth and yield of crop and maximizing the nutrient use efficiency of applied N, P and K. In the absence of micronutrients, the plants may be known to suffer from physiological disorder which eventually leads to imbalanced growth and low yield.

Among the micronutrients, Zn and B deficiency are widespread in soils of Tamil Nadu. Hence the review presented in this chapter traces back the researchers on the effect of zinc, boron, ferrous and other micronutrients on growth, yield and quality of fruit crops.

Hazarika and Megha (2018) reported that combination of foliar spray of $ZnSO_4$ (0.5 %), $FeSO_4$ (0.2 %), $CuSO_4$ (0.2 %) and H_3BO_3 (0.1 %) was recorded the highest psuedostem height, girth, number of functional leaves, leaf area and leaf area index in banana cv. Grand Naine (AAA). Bindu (2019) reported that the soil application of 190:115:300 g NPK plant^{-1} year^{-1} along with Ayar micronutrient mixture at the rate of 100 g plant^{-1} at 2nd and 4th month after planting was increased pseudostem height, pseudostem girth, number of functional leaf and leaf area in Nendran banana than farmer's practice.

Shetty *et al*. (2022) revealed that application of IIHR Banana Special (Micronutrient mixture) @ 0.5 % + CPPU 4 ppm spraying at 6th, 7th, 8th, 9th and 10th MAP observed the highest pseudostem height, pseudostem girth, number of functional leaves, leaf area and number of suckers in banana cv. Rajapuri (Ratoon I). Arthi and shakila (2023) reported that application of 2.0 percent micronutrinet spray of NRCB Banana Shakthi at 45 days interval was most effective in enhancing plant height, pseudostem girth, number of leaves plant^{-1}, leaf area, leaf area index, number of suckers and early flowering in banana cv. Red banana.

It can be observed from the results of the present study that application of micronutrients at various concentrations increased the growth parameters like pseudostem height, pseudostem girth, total number of leaves and leaf area when compared to control. Yield in banana depends significantly on bunch weight and the number of plants per hectare. Therefore, any nutrient management study should focus on maximizing bunch weight to enhance overall productivity effectively. Bunch weight itself is determined primarily by the number of fingers and the weight of each individual finger. Any factor that stimulates higher finger production and improves finger development leads to increased bunch weight.

Reverse Breeding: A Novel Approach for Rapid Development of Hybrid Varieties

Anupriya Rana and Gourav Kumar Mohanty

Abstract

Hybrid varieties play a crucial role in modern agriculture due to their superior yield, adaptability, and stress tolerance. However, the development and maintenance of parental lines required for hybrid seed production often involve lengthy and complex breeding procedures. Reverse breeding has emerged as an innovative breeding technology that enables the reconstruction of parental lines directly from an elite heterozygous plant. By suppressing genetic recombination during meiosis and generating homozygous parental lines, reverse breeding allows breeders to recreate desirable hybrids without prior knowledge of their original parents. This approach offers new opportunities for hybrid breeding, genetic research, and crop improvement. Reverse breeding has the potential to accelerate the development of superior cultivars and enhance breeding efficiency in several crop species. This article discusses the concept, principles, applications, challenges, and future prospects of reverse breeding in modern agriculture.

Introduction

The development of hybrid varieties has significantly contributed to increased agricultural productivity across the world. Hybrid crops often exhibit heterosis or hybrid vigor, resulting in improved yield, enhanced stress tolerance, and superior agronomic performance compared with their parental lines. Consequently, hybrid breeding has become an important strategy for crop improvement in many cereals, vegetables, oilseeds and horticultural crops. Despite its success, conventional hybrid breeding requires the identification, development, and maintenance of suitable parental lines, a process that may take several years. In many cases, elite hybrids are available, but their original parental lines are unknown or inaccessible. This limitation has motivated researchers to explore alternative breeding approaches that can recover parental lines directly from superior hybrids. Reverse breeding represents one such breakthrough technology. Unlike conventional breeding, which combines parental lines to produce hybrids, reverse breeding starts with a superior hybrid and works backward to reconstruct the parental lines responsible for its performance. This innovative approach has opened new possibilities for hybrid development and precision breeding.

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Concept of Reverse Breeding

Reverse breeding is a breeding strategy that enables the generation of homozygous parental lines from a selected heterozygous plant. The technique was first proposed as a method to reconstruct elite hybrid genotypes by preventing or reducing genetic recombination during meiosis. In conventional breeding, breeders cross homozygous parents to produce heterozygous hybrids. Reverse breeding follows the opposite pathway. It begins with a superior hybrid and generates parental lines that can be crossed again to recreate the original hybrid combination. The approach relies on controlling meiotic recombination and producing gametes with intact parental chromosomes. These gametes are subsequently converted into homozygous lines through doubled haploid technology or related methods. The resulting parental lines can then be used to reproduce the original hybrid genotype.

Principles and Components of Reverse Breeding

Suppression of Meiotic Recombination: The foundation of reverse breeding lies in reducing or suppressing crossover events during meiosis. Normally, homologous chromosomes exchange genetic material through recombination, creating new genetic combinations. The suppression of recombination offers several advantages:

- ✓ Preservation of parental chromosome combinations.
- ✓ Production of non-recombinant gametes.
- ✓ Maintenance of elite genetic configurations.
- ✓ Facilitation of parental line reconstruction.

By minimizing recombination, breeders can recover chromosome sets that closely resemble the original parental genomes.

Production of Haploid Gametes: Once recombination is suppressed, gametes containing intact chromosome sets are produced. These gametes represent genetic components of the original hybrid. Major benefits include:

- ✓ Simplification of parental line recovery.
- ✓ Rapid generation of breeding materials.
- ✓ Improved efficiency of line development.
- ✓ Preservation of desirable genetic combinations.

The successful isolation and utilization of these gametes form an essential step in the reverse breeding process.

Development of Homozygous Parental Lines: The haploid gametes are converted into completely homozygous lines through chromosome doubling techniques such as doubled haploid production. Important advantages include:

- ✓ Rapid development of pure lines.
- ✓ Elimination of multiple generations of selfing.
- ✓ Enhanced breeding efficiency.
- ✓ Accurate reconstruction of parental genotypes.

The reconstructed parental lines can subsequently be crossed to recreate the original elite hybrid.

Applications in Crop Improvement

Rapid Development of Hybrid Varieties: One of the most important applications of reverse breeding is the rapid reconstruction of elite hybrids. Breeders can recover parental lines from outstanding hybrid genotypes and reproduce them without extensive

conventional breeding efforts. This significantly reduces the time required for hybrid development and commercialization.

Preservation of Superior Genetic Combinations: Many elite hybrids possess unique combinations of favorable genes that contribute to exceptional performance. Reverse breeding enables the preservation and reproduction of these combinations by recreating the original hybrid genotype.This approach helps maintain valuable genetic resources and breeding achievements.

Accelerating Breeding Programs: The ability to generate parental lines directly from heterozygous plants can substantially accelerate breeding programs. Reverse breeding eliminates several generations of crossing and selection typically required in conventional breeding.As a result, breeders can develop improved cultivars more efficiently and respond rapidly to emerging agricultural challenges.

Genetic Research and Trait Analysis: Reverse breeding also serves as a valuable tool for genetic studies. The reconstructed parental lines provide opportunities to investigate gene interactions, heterosis, chromosome behavior and trait inheritance. Researchers can utilize these materials to better understand the genetic basis of important agronomic traits and improve breeding strategies.

Challenges and Limitations

Despite its considerable potential, reverse breeding faces several technical and practical challenges. Efficient suppression of meiotic recombination remains one of the major hurdles, as complete elimination of crossover events may negatively affect chromosome segregation and fertility. The technology often requires sophisticated molecular and cytogenetic tools, making implementation difficult in some breeding programs. Reverse breeding is also more challenging in species with large chromosome numbers because the probability of obtaining non-recombinant gametes decreases as chromosome number increases. Furthermore, the successful application of doubled haploid technology is essential for generating homozygous parental lines, but efficient haploid production systems are not available for all crop species. These limitations currently restrict the widespread adoption of reverse breeding in certain crops.

Future Prospects

Advances in molecular genetics, genome editing, and haploid induction technologies are expected to enhance the efficiency and applicability of reverse breeding. The integration of reverse breeding with CRISPR-Cas genome editing, genomic selection, and speed breeding may further accelerate crop improvement programs. Researchers are developing improved methods for controlling meiotic recombination and increasing the production of non-recombinant gametes. As breeding programs increasingly focus on precision breeding and rapid cultivar development, reverse breeding is likely to become an important component of next-generation crop improvement strategies. The technology holds particular promise for hybrid breeding in both field crops and horticultural species.

Conclusion

Reverse breeding represents a novel and innovative approach that challenges the traditional direction of plant breeding. By enabling the reconstruction of parental lines from elite heterozygous plants, it provides a powerful tool for hybrid development and genetic research. The technology offers significant advantages in preserving superior genetic combinations, accelerating breeding programs and improving breeding precision. Although technical challenges related to recombination suppression and haploid production remain, continued advances in biotechnology are expected to overcome these limitations. As modern agriculture seeks faster and more efficient breeding solutions, reverse breeding has the potential to play an increasingly important role in the development of superior crop varieties and sustainable agricultural production.

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CRISPR-Cas Genome Editing: Revolutionizing Precision Breeding in Agriculture

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Abstract

The growing demand for food, coupled with climate change, emerging pests and diseases, and shrinking agricultural resources, has intensified the need for innovative crop improvement technologies. Conventional breeding methods have contributed significantly to agricultural development, but they are often time-consuming and less precise. CRISPR-Cas genome editing has emerged as a groundbreaking technology that enables targeted modifications in plant genomes with unprecedented accuracy and efficiency. By allowing precise alterations of specific genes, CRISPR-Cas has revolutionized plant breeding and biotechnology. The technology has been successfully employed to improve yield, disease resistance, nutritional quality, and tolerance to abiotic stresses in several crop species. This article discusses the concept, mechanism, applications, challenges, and future prospects of CRISPR-Cas genome editing and its transformative role in precision breeding and sustainable agriculture.

Introduction

Agriculture is facing immense challenges in meeting the food requirements of a rapidly growing global population. Climate change, declining natural resources, evolving pathogens, and increasing environmental concerns demand the development of crop varieties that are more productive, resilient, and sustainable. Plant breeding has historically played a crucial role in improving crop performance; however, conventional breeding approaches often require many years to develop improved cultivars and may involve the transfer of unwanted traits. Advances in molecular biology have led to the development of genome editing technologies that enable precise modifications of plant DNA. Among these technologies, CRISPR-Cas has emerged as the most widely adopted and versatile genome editing tool. Its simplicity, accuracy, and cost-effectiveness have transformed crop improvement programs and opened new opportunities for precision breeding. Today, CRISPR-Cas is considered one of the most promising technologies for addressing global agricultural challenges and ensuring future food security.

Concept of CRISPR-Cas Genome Editing

CRISPR, which stands for Clustered Regularly Interspaced Short Palindromic Repeats, is

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a natural defense mechanism found in bacteria and archaea. Scientists have adapted this system into a powerful genome editing tool capable of modifying specific DNA sequences in plants, animals, and microorganisms. The CRISPR-Cas system functions like molecular scissors that can identify and cut a targeted DNA sequence within the genome. Once the DNA is cut, natural cellular repair mechanisms modify the sequence, allowing researchers to insert, delete, or alter specific genes. Unlike conventional breeding methods that rely on random genetic variation, CRISPR-Cas enables precise and targeted genetic modifications. This precision significantly accelerates crop improvement and reduces the time required to develop superior varieties.

Mechanism and Components of CRISPR-Cas Genome Editing

The CRISPR-Cas system consists of several components that work together to identify and modify specific DNA sequences.

Guide RNA (gRNA): Guide RNA is designed to recognize a specific DNA sequence within the plant genome. It acts as a navigation system that directs the editing machinery to the desired target site. Major functions include:

- ✓ Identification of target genes.
- ✓ Accurate targeting of DNA sequences.
- ✓ Increased editing precision.
- ✓ Reduced off-target modifications.

The specificity of guide RNA determines the accuracy of genome editing.

Cas Protein: Cas proteins function as molecular scissors that cut DNA at the target location identified by the guide RNA. Cas9 is the most widely used genome editing enzyme. Major advantages include:

- ✓ Precise DNA cleavage.
- ✓ High editing efficiency.
- ✓ Versatility across crop species.
- ✓ Ease of genetic modification.

The Cas enzyme creates a break in the DNA, enabling subsequent genetic modifications.

DNA Repair Mechanisms: Following DNA cleavage the plant's natural repair system repairs the break. This repair process can introduce targeted mutations or facilitate precise genetic modifications. Major outcomes include:

- ✓ Gene knockout.
- ✓ Gene insertion.
- ✓ Gene replacement.
- ✓ Trait modification.

These repair mechanisms form the basis for developing improved crop varieties with desired characteristics.

Applications in Crop Improvement

CRISPR-Cas genome editing has become a powerful tool for enhancing agricultural productivity and sustainability.

Development of Disease-Resistant Crops: Plant diseases cause substantial yield losses worldwide and threaten food security. CRISPR-Cas enables targeted modification of susceptibility genes, enhancing resistance against bacterial, fungal, and viral pathogens. Several crops have been successfully edited to improve disease resistance, reducing

dependence on chemical pesticides and improving crop protection.

Improvement of Abiotic Stress Tolerance: Climate change has increased the occurrence of drought, salinity, heat stress, and flooding. CRISPR-Cas allows breeders to modify genes associated with stress tolerance, enabling crops to perform better under adverse environmental conditions. Enhanced tolerance to abiotic stresses contributes to stable crop production and agricultural resilience.

Enhancement of Yield and Nutritional Quality: Genome editing has been used to improve important agronomic traits such as grain size, plant architecture, flowering time, and nutrient content. Researchers have successfully developed crops with improved productivity and enhanced nutritional quality. Such improvements contribute to food security and better human nutrition.

Accelerating Precision Breeding: Traditional breeding often requires multiple generations to introduce and stabilize desired traits. CRISPR-Cas enables direct modification of target genes, significantly reducing breeding time. The technology can also be integrated with genomic selection, speed breeding, and other advanced breeding tools to accelerate crop improvement programs.

Challenges and Limitations

Despite its tremendous potential, CRISPR-Cas genome editing faces several challenges. One of the major concerns is the possibility of off-target effects, where unintended genetic modifications may occur. Although advancements in guide RNA design have improved precision, ensuring complete accuracy remains an important area of research. Regulatory policies governing genome-edited crops also vary among countries, creating uncertainty regarding commercialization and international trade. Public perception and acceptance of genome-edited crops continue to influence adoption in many regions. Furthermore, successful genome editing requires specialized expertise, advanced laboratory facilities, and efficient transformation systems, which may not be readily available in all breeding programs. Addressing these challenges will be crucial for the widespread implementation of CRISPR-based technologies in agriculture.

Future Prospects

The future of CRISPR-Cas technology in agriculture is highly promising. Continuous improvements in genome editing tools are enhancing editing accuracy, efficiency and versatility. Emerging technologies such as base editing, prime editing, and multiplex genome editing are expanding the range of possible genetic modifications. Integration of CRISPR-Cas with artificial intelligence, genomic selection, and speed breeding is expected to further accelerate crop improvement. Researchers are increasingly focusing on developing climate-resilient, nutrient-rich, and disease-resistant crops to address future agricultural challenges. As regulatory frameworks become clearer and public awareness improves, CRISPR-Cas is likely to become a central component of next-generation breeding programs worldwide.

Conclusion

CRISPR-Cas genome editing has revolutionized modern plant breeding by enabling precise, efficient, and targeted genetic modifications. The technology offers unprecedented opportunities to improve crop productivity, enhance nutritional quality, strengthen resistance to diseases, and increase tolerance to environmental stresses. Compared with conventional breeding methods, CRISPR-Cas significantly accelerates the development of improved crop varieties while maintaining high precision. Although challenges related to regulation, public acceptance, and technical limitations remain, ongoing scientific advancements continue to expand its potential applications. As agriculture seeks sustainable solutions to meet future food demands, CRISPR-Cas genome editing will play a pivotal role in shaping the future of precision breeding and global food security.

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High-Throughput Phenotyping: Bridging Genomics and Crop Improvement

Anupriya Rana, Abhishek Kumar Suman and Preeti Thakur

Abstract

The rapid advancement of genomics has revolutionized plant breeding by enabling the identification of genes and molecular markers associated with important agronomic traits. However, the ability to measure plant traits accurately and efficiently remains a major challenge in crop improvement programs. High-throughput phenotyping (HTP) has emerged as a powerful technology that enables rapid, precise, and non-destructive measurement of plant characteristics on a large scale. By integrating advanced imaging systems, sensors, robotics, drones, and artificial intelligence, HTP facilitates the collection of large amounts of phenotypic data under both controlled and field conditions. This technology is helping bridge the gap between genomics and crop improvement by accelerating trait discovery, genetic analysis, and breeding decisions. High-throughput phenotyping is increasingly becoming a cornerstone of modern crop improvement programs aimed at enhancing productivity, resilience, and sustainability.

Introduction

Plant breeding has traditionally relied on phenotyping, the process of measuring observable plant characteristics such as plant height, flowering time, biomass, yield and stress responses. Phenotypic information is essential because it reflects the interaction between genotype and environment and ultimately determines crop performance. While genomic technologies have advanced rapidly over the past two decades, phenotyping has often remained a bottleneck in breeding programs. Modern sequencing technologies can generate vast amounts of genetic information, but the efficient measurement of complex plant traits has lagged behind. Conventional phenotyping methods are labor-intensive, time-consuming, and often subjective, limiting the speed and precision of breeding efforts. To overcome these limitations, researchers have developed high-throughput phenotyping systems that enable rapid and automated collection of plant trait data. These technologies are transforming crop improvement by providing accurate phenotypic information that can be integrated with genomic data to accelerate breeding progress.

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Concept of High-Throughput Phenotyping: High-throughput phenotyping refers to the automated and large-scale measurement of plant traits using advanced sensing technologies and computational tools. The objective is to collect precise phenotypic data rapidly and efficiently across large breeding populations. Unlike traditional phenotyping methods, which often involve manual observations, high-throughput phenotyping utilizes imaging systems, sensors, drones, robotics, and machine learning algorithms to monitor plant growth and development. These technologies enable continuous and non-destructive assessment of plant traits throughout the crop life cycle. The integration of phenotypic and genomic information allows breeders to better understand trait inheritance and improve selection efficiency, thereby accelerating crop improvement programs.

Components and Technologies of High-Throughput Phenotyping

Imaging Technologies: Imaging systems form the foundation of most high-throughput phenotyping platforms. Different imaging techniques capture information related to plant growth, morphology, and physiological responses. Major imaging technologies include:

- ✓ RGB imaging for plant architecture and growth analysis.
- ✓ Thermal imaging for temperature and stress detection.
- ✓ Hyperspectral imaging for physiological assessment.
- ✓ Fluorescence imaging for photosynthetic activity evaluation.

These technologies enable detailed monitoring of plant performance without damaging the crop.

Sensor-Based Phenotyping: Various sensors are used to measure environmental and plant-related parameters. These sensors provide real-time information regarding crop status and field conditions. Important applications include:

- ✓ Monitoring soil moisture.
- ✓ Assessing canopy temperature.
- ✓ Measuring plant water status.
- ✓ Evaluating nutrient deficiencies.

Sensor technologies improve the accuracy and efficiency of phenotypic data collection.

Unmanned Aerial Vehicles (UAVs) and Drones: Drones have become valuable tools for field phenotyping because they can rapidly collect data over large agricultural areas. Equipped with cameras and sensors, UAVs provide high-resolution images and environmental information. Major advantages include:

- ✓ Rapid field coverage.
- ✓ High-resolution data acquisition.
- ✓ Reduced labor requirements.
- ✓ Real-time crop monitoring.

The use of drones has significantly expanded the scope of field-based phenotyping.

Applications in Crop Improvement

Accelerating Breeding Programs: High-throughput phenotyping enables breeders to evaluate thousands of plants quickly and accurately.

This allows faster identification of superior genotypes and improves selection efficiency. Large breeding populations can be screened within a shorter period, reducing the time required for variety development.

Identification of Stress-Tolerant Genotypes: Climate change has increased the frequency of drought, heat stress, salinity and other environmental challenges. High-throughput phenotyping facilitates the rapid detection of plant responses to these stresses.The technology enables breeders to identify stress-tolerant genotypes with greater precision and efficiency than traditional methods.

Integration with Genomics and Precision Breeding: One of the most significant contributions of high-throughput phenotyping is its ability to complement genomic technologies. Accurate phenotypic data enhance genome-wide association studies, genomic selection, quantitative trait locus mapping, and marker-assisted breeding. This integration strengthens the relationship between genotype and phenotype, enabling more effective breeding decisions.

Monitoring Crop Growth and Productivity: High-throughput phenotyping provides continuous information regarding plant growth, biomass accumulation, canopy development, and yield-related traits. Such information supports both research and breeding programs aimed at improving crop productivity.The ability to monitor crops throughout their growth cycle improves understanding of plant performance under diverse environmental conditons.

Functional Genomics and Gene Discovery: The technology plays an important role in functional genomics by enabling detailed characterization of plant responses to genetic modifications. Researchers can evaluate the effects of specific genes on plant growth, physiology, and stress responses.This accelerates the identification of genes associated with important agronomic traits and supports precision breeding efforts.

Challenges and Limitations

Despite its enormous potential, high-throughput phenotyping faces several challenges. The establishment and maintenance of advanced phenotyping platforms often require substantial financial investment, making adoption difficult for many research institutions and breeding programs. Large volumes of data generated by imaging systems and sensors demand sophisticated computational infrastructure and bioinformatics expertise for storage, processing and interpretation. Environmental variability under field conditions can also affect data quality and consistency. Furthermore, the integration of phenotypic information with genomic datasets remains complex and requires interdisciplinary collaboration among breeders, geneticists, engineers, and data scientists. Addressing these challenges will be essential for maximizing the impact of high-throughput phenotyping in crop improvement.

Future Prospects

The future of high-throughput phenotyping is closely linked to advances in artificial intelligence,

machine learning, robotics, and remote sensing technologies. Improvements in sensor accuracy and data analytics are expected to enhance the precision and efficiency of phenotypic measurements. The increasing availability of drones, autonomous vehicles, and cloud-based computational platforms will make phenotyping more accessible to breeding programs worldwide. Integration of high-throughput phenotyping with genomics, genome editing, and predictive breeding approaches will further accelerate the development of superior crop varieties. As agriculture faces increasing demands for productivity and sustainability, high-throughput phenotyping is expected to become a fundamental component of next-generation breeding systems.

Conclusion

High-throughput phenotyping has emerged as a transformative technology that bridges the gap between genomics and crop improvement. By enabling rapid, accurate and large-scale measurement of plant traits, it enhances the efficiency of breeding programs and supports the development of improved crop varieties. The technology has significant applications in stress tolerance screening, trait discovery, functional genomics, and precision breeding. Although challenges related to cost, data management, and technical complexity remain, continuous technological advancements are expanding its accessibility and effectiveness. As modern agriculture increasingly relies on data-driven breeding strategies, high-throughput phenotyping will play a pivotal role in improving crop productivity, resilience, and global food security.

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Pangenomics: Exploring the Hidden Genetic Diversity of Crop Species

Anupriya Rana and Rivanshu Dhull

Abstract

Genetic diversity is the foundation of crop improvement and agricultural sustainability. Traditional genome sequencing approaches have provided valuable insights into crop genetics; however, a single reference genome often fails to capture the complete genetic variation present within a species. Pangenomics has emerged as a transformative approach that explores the entire genetic repertoire of a species by analyzing multiple genomes simultaneously. By identifying both shared and unique genes among individuals, pangenomics reveals hidden genetic diversity that can be utilized for crop improvement. This approach has enhanced our understanding of trait variation, adaptation, evolution, and breeding potential in crop plants. Pangenomics is increasingly being used to identify valuable genes associated with yield, disease resistance, stress tolerance, and nutritional quality. This article discusses the concept, components, applications, challenges, and future prospects of pangenomics and its significance in modern crop improvement programs.

Introduction

Crop improvement relies heavily on the availability and utilization of genetic diversity. For decades, plant breeders and geneticists have used conventional breeding, molecular markers, and genome sequencing to identify beneficial traits and develop improved varieties. The sequencing of reference genomes has significantly advanced our understanding of plant genetics and provided valuable resources for crop improvement. However, a single reference genome represents only one individual and often overlooks substantial genetic variation present within a species. Many important genes associated with adaptation, disease resistance, and productivity may be absent from the reference genome. As a result, breeders may fail to capture the full range of useful genetic diversity available in crop populations. Pangenomics has emerged as a powerful solution to this limitation. By analyzing multiple genomes from diverse individuals, pangenomics provides a more comprehensive view of genetic variation and enables researchers to uncover hidden genes and structural variations that contribute to important agronomic traits.

Concept of Pangenomics

Pangenomics refers to the study of the complete set of genes present within a species. Instead of relying on a single reference genome,

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pangenomic analysis combines genomic information from multiple individuals to capture the entire spectrum of genetic diversity. The concept was first introduced in microbial genomics and has since been widely adopted in plant research. A pangenome includes all genes present across different individuals within a species, providing a broader understanding of genetic variation and evolutionary processes. By incorpor-ating genomes from diverse cultivars, landraces, and wild relatives, pangenomics enables researchers to identify previously unknown genes and genetic variations that may be valuable for crop improve-ment.

Components of a Pangenome

A pangenome is generally divided into differ-ent categories based on gene distribution among individuals.

Core Genome: The core genome consists of genes that are present in all individuals of a species. These genes are essential for basic biological functions and survival. Major characteristics include:

- ✓ Conserved across all genotypes.
- ✓ Responsible for fundamental cellular processes.
- ✓ Essential for growth and development.
- ✓ Relatively stable during evolution.

The core genome represents the common genetic foundation shared by all members of a species.

Dispensable Genome: The dispensable genome contains genes that are present in some individuals but absent in others. These genes often contribute to adaptation and phenotypic variation.

Important features include:

- ✓ Variable among genotypes.
- ✓ Associated with environmental adaptation.
- ✓ Contribute to agronomic diversity.
- ✓ Influence stress responses and productivity.

These genes often provide valuable resources for breeding programs.

Unique or Private Genes: Unique genes are found only in specific individuals or populations. Although present in limited genotypes, they may play important roles in adaptation and trait expression. Major advantages of studying unique genes include:

- ✓ Discovery of novel traits.
- ✓ Identification of rare alleles.
- ✓ Improved understanding of genetic diversity.
- ✓ Utilization of untapped breeding resources.

Such genes frequently originate from land-races and wild relatives that possess valuable adaptive characteristics.

Applications in Crop Improvement

Pangenomics has become an important tool for modern plant breeding and genetic research.

Discovery of Novel Genes: One of the most significant contributions of pangenomics is the identification of genes that are absent from reference genomes. These genes may control important agronomic traits that were previously overlooked. Researchers have discovered novel genes associated with disease resistance, nutrient use efficiency, and environmental adaptation through pangenomic studies.

Enhancing Disease Resistance Breeding: Plant

diseases continue to cause major losses in agricultural production. Pangenomic analysis helps identify resistance genes distributed among different genotypes, including wild relatives and traditional varieties.The identification of diverse resistance genes enables breeders to develop crop varieties with broader and more durable resistance against pathogens.

Improving Abiotic Stress Tolerance: Climate change has increased the frequency of drought, salinity, heat stress, and flooding. Pangenomics helps uncover genetic variations associated with tolerance to these environmental stresses.By identifying stress-responsive genes, breeders can develop climate-resilient varieties capable of maintaining productivity under challenging conditions.

Accelerating Precision Breeding: The availability of comprehensive genetic information enhances the efficiency of modern breeding programs. Pangenomic data support marker-assisted selection, genomic selection, and genome editing by providing a broader understanding of gene diversity and trait architecture.This enables breeders to make more informed decisions and improve the precision of crop improvement efforts.

Conservation and Utilization of Genetic Resources: Pangenomics provides valuable insights into the genetic diversity preserved in germplasm collections, landraces and wild relatives. Understanding this diversity facilitates the effective conservation and utilization of genetic resources for future breeding programs. The approach helps identify unique genetic variants that may become important for addressing future agricultural challenges.

Challenges and Limitations

Despite its enormous potential, pangenomics faces several challenges. Constructing a comprehensive pangenome requires sequencing and analyzing a large number of genomes, which can be costly and computationally demanding. The management and interpretation of massive genomic datasets require advanced bioinformatics tools and specialized expertise. In addition, integrating pangenomic information into practical breeding programs remains a complex task, particularly in crops with large and highly repetitive genomes. Standardization of analytical methods and data-sharing platforms is also necessary to ensure efficient utilization of pangenomic resources. Addressing these challenges will be essential for maximizing the benefits of pangenomics in crop improvement.

Future Prospects

The future of pangenomics is closely linked to advances in sequencing technologies, computational biology, and artificial intelligence. The decreasing cost of genome sequencing is enabling researchers to analyze larger and more diverse populations than ever before. Future pangenome projects are expected to include thousands of genomes, providing unprecedented insights into crop diversity and evolution. Integration of pangenomics with genome editing, genomic selection, and high-throughput phenotyping will accelerate the develop-

ment of superior crop varieties. As breeders seek to improve productivity, resilience, and sustain-ability, pangenomics will become an increasingly important resource for identifying and utilizing beneficial genetic variation.

Conclusion

Pangenomics has revolutionized our understanding of crop genetic diversity by moving beyond the limitations of single reference genomes. By capturing the complete genetic repertoire of a species, it reveals hidden genes and structural variations that contribute to important agronomic traits. The approach has significant applications in gene discovery, disease resistance breeding, stress tolerance improvement, and conservation of genetic resources. Although challenges related to data generation, analysis, and implementation remain, continued technological advancements are rapidly expanding the potential of pangenomics. As agriculture faces growing demands for sustainable and resilient crop production, pangenomics will play a pivotal role in unlocking the full potential of crop genetic diversity and shaping the future of plant breeding.

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Speed Breeding: Accelerating Crop Improvement for Future Food Security

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Abstract

The growing global population, changing climate, and increasing demand for food require the rapid development of improved crop varieties. Conventional plant breeding often takes several years to develop and release a new variety, limiting the speed at which breeders can respond to emerging agricultural challenges. Speed breeding has emerged as a revolutionary approach that accelerates plant growth and shortens generation time through controlled environmental conditions. By extending photoperiods and optimizing temperature, light intensity, and growth conditions, speed breeding enables multiple crop generations within a single year. This technology has significantly enhanced breeding efficiency and supports the rapid development of high-yielding, disease-resistant, and climate-resilient cultivars. The integration of speed breeding with modern genomic tools is transforming crop improvement programs worldwide and contributing to future food security.

Introduction

Agriculture faces unprecedented challenges in the twenty-first century. Rapid population growth, climate change, emerging pests and diseases, shrinking arable land, and increasing food demand have intensified the need for faster crop improvement strategies. Plant breeding plays a crucial role in developing superior crop varieties that can withstand biotic and abiotic stresses while maintaining high productivity. However, conventional breeding programs often require six to twelve years to develop and release a new cultivar due to the long generation cycles of many crops. The need to accelerate genetic gain has led researchers to explore innovative breeding technologies capable of shortening breeding cycles. Among these innovations, speed breeding has gained considerable attention as a practical and efficient method for reducing generation time and increasing breeding efficiency. By manipulating environmental conditions to promote rapid plant growth and early flowering, speed breeding allows breeders to advance several generations within a year, significantly reducing the time required for variety development.

Concept of Speed Breeding

Speed breeding is a crop improvement technique that accelerates plant growth and development by providing optimized environmental conditions such as extended photoperiods, controlled temperature, and appropriate light intensity.

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The primary objective is to shorten the time between planting and seed harvest, thereby increasing the number of generations that can be grown annually. Unlike conventional breeding, where crops are grown under natural environmental conditions, speed breeding utilizes controlled environments such as growth chambers, greenhouses, and specialized facilities. Under these conditions, plants complete their life cycles much faster, enabling breeders to rapidly advance breeding populations and accelerate genetic improvement. The concept has been successfully applied in several important crops, including wheat, barley, chickpea, pea, canola, rice, and various horticultural crops. Its ability to reduce breeding time has made it an important tool for modern crop improvement programs.

Principles and Components of Speed Breeding

Extended Photoperiods: One of the key components of speed breeding is the use of extended light periods. Plants are exposed to longer durations of light, often ranging from 20 to 22 hours per day, followed by a short dark period. The benefits of extended photoperiods include:

- ✓ Faster plant growth and development.
- ✓ Earlier flowering and seed production.
- ✓ Reduced generation time.
- ✓ Increased number of breeding cycles per year.

Extended lighting allows plants to photosynthesize for longer periods, promoting rapid growth and accelerating reproductive development.

Controlled Environment Conditions: Speed breeding relies on carefully controlled environmental factors to maximize plant performance. Growth chambers and greenhouses are used to maintain optimal temperature, humidity, and light intensity throughout the crop growth cycle. Important advantages include:

- ✓ Uniform crop growth.
- ✓ Reduced environmental variability.
- ✓ Enhanced breeding precision.
- ✓ Improved seed production efficiency.

The ability to regulate environmental conditions ensures consistent plant development and facilitates year-round breeding activities.

Rapid Generation Advancement: The ultimate goal of speed breeding is to achieve rapid generation advancement. By shortening the period from seed germination to seed harvest, breeders can grow multiple generations annually. Major benefits include:

- ✓ Faster fixation of desirable traits.
- ✓ Accelerated selection processes.
- ✓ Reduced breeding cycle duration.
- ✓ Increased genetic gain per unit time.

In several crops, speed breeding has enabled the production of four to six generations per year, compared with one or two generations under conventional field conditions.

Applications in Crop Improvement

Accelerating Variety Development: One of the most significant applications of speed breeding is the rapid development of improved crop varieties. The technology allows breeders to advance segregating populations quickly and identify superior genotypes

in a shorter period. By reducing the breeding cycle, speed breeding accelerates the release of varieties with improved yield potential, stress tolerance, and disease resistance.

Integration with Modern Breeding Technologies: Speed breeding complements several modern breeding approaches, including marker-assisted selection, genomic selection, and genome editing. The combination of these technologies enables faster identification, selection, and advancement of desirable genotypes. The integration of speed breeding with molecular breeding tools significantly enhances breeding efficiency and accelerates genetic improvement.

Development of Climate-Resilient Crops: Climate change has increased the frequency of drought, heat stress, flooding, and emerging diseases. Developing climate-resilient crop varieties has become a major priority for breeding programs worldwide. Speed breeding facilitates rapid screening and selection of genotypes under controlled stress conditions. This allows breeders to identify and develop varieties capable of adapting to changing environmental conditions.

Genetic Research and Functional Genomics: Beyond breeding applications, speed breeding has become an important tool in plant research. Researchers use the technology to study gene function, validate molecular markers, and investigate trait inheritance within a shorter time frame. Rapid generation turnover enables scientists to conduct experiments more efficiently and accelerate discoveries in plant genetics and genomics.

Challenges and Limitations

Despite its numerous advantages, speed breeding faces several challenges that may limit widespread adoption. The establishment of controlled-environment facilities requires substantial investment in infrastructure, lighting systems, and environmental control equipment. Energy costs associated with maintaining extended photoperiods can also be significant. Furthermore, not all crop species respond equally to speed breeding protocols, and some crops may require species-specific optimization. There is also a risk that artificial growth conditions may not fully replicate field environments, potentially affecting the expression of certain traits. Therefore, field evaluation remains essential before the release of improved varieties. Technical expertise and proper facility management are also necessary to ensure successful implementation of speed breeding programs.

Future Prospects

The future of speed breeding is highly promising as plant breeding continues to embrace advanced technologies. Integration with genomic selection, CRISPR-Cas genome editing, high-throughput phenotyping, and artificial intelligence is expected to further enhance breeding efficiency. Improvements in LED lighting systems and controlled-environment technologies are making speed breeding more affordable and energy-efficient. As climate change intensifies the need for rapid crop improvement, speed breeding is likely to become a

standard component of modern breeding programs. The technology will play a crucial role in developing high-yielding, stress-tolerant, and nutritionally improved crop varieties capable of meeting future agricultural demands.

Conclusion

Speed breeding has emerged as a transformative technology in modern plant breeding, enabling the rapid development of improved crop varieties through accelerated generation advancement. By optimizing environmental conditions and shortening breeding cycles, it significantly increases breeding efficiency and genetic gain. The technology has demonstrated immense potential in variety development, genetic research, climate-resilient breeding, and integration with advanced molecular tools. Although challenges related to infrastructure costs and species-specific responses remain, ongoing technological advancements are expected to enhance its accessibility and effectiveness. As global agriculture faces increasing challenges, speed breeding will play a vital role in accelerating crop improvement and strengthening future food security.

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Climate Change Adaptation Using Artificial Intelligence

Neha Kumari and Manjeet Kaur

Abstract

This document explores the transformative role of Artificial Intelligence (AI) as a critical pillar in global climate adaptation strategies. As the IPCC warns of catastrophic temperature rises, AI technologies including machine learning, deep learning, and computer vision are being deployed to mitigate the unavoidable impacts of climate change. The synthesis highlights how AI supercharges climate modelling, enabling high-resolution local predictions and extending life-saving early warning windows for extreme weather events. Key applications are examined across several vital sectors: in agriculture, AI-driven precision tools optimize resource use and accelerate the breeding of resilient crop varieties; in energy, machine learning balances the intermittency of renewables to stabilize smart grids; and in urban planning, "digital twins" allow for the simulation of climate-resilient infrastructure. Despite its potential, the document cautions against significant hurdles, specifically the "data gap" in the Global South and the risk of widening technological inequality. It concludes that while AI is not a panacea, its thoughtful and equitable integration into policy and governance is essential for enhancing human ingenuity and ensuring a livable planet in the face of the twenty-first century's greatest challenge.

Introduction: The Climate Crisis and the Need for Intelligent Solutions

The climate crisis stands as the defining challenge of the twenty-first century. Rising global temperatures, accelerating sea-level rise, intensifying extreme weather events, and mounting threats to biodiversity are no longer distant projections they are present-day realities reshaping lives on every continent. The Intergovernmental Panel on Climate Change (IPCC) has made it unequivocally clear: without immediate and sweeping action, average global temperatures could rise by more than 2.5°C above pre-industrial levels by the end of this century, with catastrophic consequences. Adaptation the process of adjusting to the current and anticipated effects of climate change has emerged as an indispensable pillar of climate policy alongside mitigation. While mitigation seeks to reduce greenhouse gas emissions and slow the pace of warming, adaptation acknowledges that a certain degree of climate change is already locked into the Earth system and those communities, ecosystems, and economies must build resilience to survive and thrive in a changing world. It is in this urgent context that Artificial Intelligence

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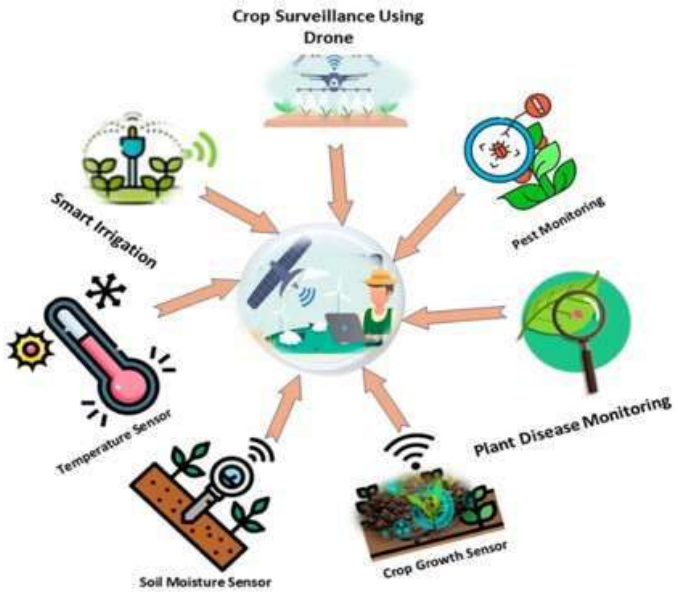
(AI) has emerged as one of the most promising technological tools available to scientists, policy-makers and communities. AI encompasses a broad suite of technologies including machine learning, deep learning, computer vision, and natural language processing that enable computers to learn from data, identify patterns, and make predictions at scales and speeds far beyond human capability. Applied to climate adaptation, AI is transforming how we model climate futures, manage natural resources, protect vulnerable populations and design resilient infra-structure.

Figure 1: AI-powered satellite monitoring systems analyze Earth's climate systems in real time enabling unprecedented predictive capabilities.

AI in Climate Modeling and Prediction: Super-charging Climate Models: Traditional climate models, while scientifically robust, are computati-onally expensive and often struggle to capture local-scale climate dynamics with sufficient precision. AI is fundamentally transforming this domain. Deep learning models can now be trained on decades of historical climate data to produce high-resolution predictions of temperature, precipitation, drought probability, and storm frequency with remarkable accuracy often in a fraction of the time required by conventional physics-based models. Google Deep Mind's Graph Cast, for instance, demonstrated that an AI model trained on ERA5 reanalysis data could outperform the European Centre for Medium-Range Weather Forecasts' operational model on 90% of test variables. This represents a quantum leap in weather forecasting one that can directly save lives by extending the reliable forecast window from days to weeks.

Extreme Weather Early Warning Systems: AI is proving especially valuable in predicting extreme weather events the kind that is becoming more frequent and intense as the climate warms. Machine learning algorithms can now analyse atmospheric data from satellites, ocean buoys, and ground stations to predict the formation, trajectory, and intensity of hurricanes, monsoons and heat waves with unpreced-ented precision. IBM's AI-powered weather fore-casting platform, used across more than 200,000 weather stations globally, provides hyper local forecasts that help farmers, utilities, and emergency managers make better decisions days in advance. In flood-prone regions of South and Southeast Asia, AI-driven early warning systems are giving commun-ities critical time to evacuate. Google's Flood Forecasting Initiative, launched in partnership with national meteorological agencies, uses deep learning to predict river flooding up to seven days ahead. Covering over 460 million people across 80 countries, the system have already demonstrated its capacity to reduce flood- related casualties significantly.

AI-Driven Adaptation in Agriculture and Food Security: Precision Agriculture under Climate Stress: Agriculture is among the sectors most vulnerable to climate change. Shifting precipitation patterns, prolonged droughts, soil degradation, and unpredictable growing seasons are already threatening food security for billions of people. AI-powered precision agriculture is helping farmers adapt by delivering data-driven insights that optimize resource use and maximize yields even under adverse conditions. Remote sensing satellites equipped with multispectral cameras, combined with AI image analysis, can monitor crop health, detect pest infestations, identify soil moisture deficits, and predict yield outcomes at the field level. Platforms such as Climate Corporation's Field View and Israel-based CropX integrate these capabilities with local weather forecasting to provide farmers with actionable, real-time recommendations on irrigation, fertilization, and harvesting schedules.



Crop Breeding and Genetic Adaptation: AI is also accelerating the development of climate-resilient crop varieties. Machine learning algorithms can analyse vast genomic datasets to identify genetic traits associated with heat tolerance, drought resistance and disease immunity. International agricultural research centres, including CGIAR institutions, are using AI to screen thousands of crop varieties rapidly, dramatically compressing the timeline for developing and deploying improved seeds to smallholder farmers in climate-vulnerable regions. In sub-Saharan Africa, where climate variability poses an existential threat to rainfed agriculture, AI-powered advisory services delivered via mobile phones are helping millions of small-holder farmers make smarter planting and manage-ment decisions. The FAO's Hand-in-Hand Digital Village initiative and Kenya's I Shamba platform exemplify this trend, combining AI analytics with accessible mobile delivery to reach farmers in remote, resource-scarce communities.

AI in Energy Transition and Urban Resilience: Optimizing Renewable Energy Systems: Transitioning from fossil fuels to renewable energy is the cornerstone of climate mitigation, but AI is proving equally vital to climate adaptation within the energy sector. The intermittent nature of solar and wind power outputs that fluctuate with weather conditions has traditionally posed challenges for grid stability. AI is solving this problem by accurately forecasting energy production and demand, enabling grid operators to balance supply seamlessly. Deep Mind's AI system, deployed in partnership with

Google's wind energy portfolio, demonstrated that machine learning could increase the value of wind energy by approximately 20% by predicting power output 36 hours in advance and committing to electricity delivery schedules. Similar AI optimization systems are now being deployed in smart grids across Europe, North America and China, integrating distributed renewable sources while minimizing waste and reducing the need for fossil fuel backup generation.

Climate-Resilient Urban Infrastructure: Cities, home to over half the world's population, are on the front lines of climate adaptation. Rising urban heat island effects, flash flooding, coastal inundation, and strained infrastructure are among the most pressing challenges. AI is enabling city planners and managers to design and operate more resilient urban systems. AI-powered digital twins virtual replicas of entire cities allow planners to simulate the impacts of extreme weather events on transportation networks, water systems, buildings, and energy grids before they occur. Singapore's Virtual Singapore platform and Rotterdam's climate adaptation models are pioneering examples. By testing adaptation interventions in the virtual realm, cities can make evidence-based investments in green infrastructure, flood barriers, and resilient building codes.

Challenges, Equity and the Path Forward: Data Gaps and Model Bias: Despite its enormous promise, AI-driven climate adaptation faces significant challenges that must be honestly confronted. Chief among these is the problem of data availability and quality. AI models are only as good as the data on which they are trained and many of the region's most vulnerable to climate change, particularly in the Global South, remain severely underrepresented in climate datasets. These risks creating AI systems that perform well in data-rich environments while failing precisely where the need is greatest.

The Equity Imperative: There is a profound risk that AI-driven climate adaptation could exacerbate existing inequalities rather than reduce them. Advanced AI systems require significant computational infrastructure, technical expertise, and financial investment. Without deliberate, equity-centered policy interventions including technology transfer open-source initiatives and capacity-building programs the benefits of AI adaptation may accrue primarily to wealthy nations and communities while vulnerable populations are left behind. International frameworks such as the Paris Agreement's adaptation provisions, the Kunming-Montreal Global Biodiversity Framework, and the UNFCCC's work program on loss and damage must explicitly address the equitable deployment of AI tools. Multilateral institutions, including the World Bank, UNDP, and regional development banks, have critical roles to play in financing AI adaptation capacity in least developed countries.

Ethical AI and Governance: AI systems deployed in high-stakes climate adaptation contexts must be transparent, accountable, and free from algorithmic bias. When AI models inform decisions about flood evacuation routes, drought relief allocation or clima-

te refugee assistance, the stakes of errors or biases are human lives. Robust governance frameworks combining technical standards, regulatory oversight, and community participation are essential to ensuring that AI serves as a tool of climate justice rather than a driver of new forms of exclusion.

Conclusion

Artificial intelligence is not a silver bullet for the climate crisis. It cannot substitute for the fundamental political will and systemic changes needed to slash greenhouse gas emissions and build equitable, sustainable economies. But deployed thoughtfully and equitably, AI represents a genuinely transformative set of tools that can help humanity navigate the profound challenges of a warming world. From early warning systems that save lives in flood-prone deltas, to precision agriculture platforms that sustain food security under drought, to smart grids that accelerate the renewable energy transition, AI is already demonstrating its value as an instrument of climate adaptation. The imperative now is to scale these solutions rapidly, govern them wisely, and ensure that their benefits reach every corner of a planet that urgently needs every advantage available. The climate crisis demands the full mobilization of human ingenuity and artificial intelligence, at its best, is a powerful amplification of that ingenuity. The decisions we make in the coming decade about how to develop, deploy, and democratize AI for climate adaptation will help determine whether our civilization can successfully navigate the greatest challenge it has ever faced.

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AI-Driven Decision Support System in Agriculture

Niyanza K. P. and Manjeet Kaur

Abstract

The increasing demand for food production, coupled with challenges such as climate variability, inefficient resource use, and crop diseases, necessitates the adoption of advanced technologies in agriculture. This study proposes an AI-driven Decision Support System (DSS) to enhance farm-level decision-making through data-driven insights. The system integrates soil sensors, remote sensing technologies, and machine learning algorithms to collect and analyze real-time data on soil conditions, weather patterns, and crop health. Based on this analysis, it provides precise recommendations for crop selection, irrigation scheduling, fertilizer application, and early disease detection. The proposed system improves agricultural productivity by optimizing the use of inputs such as water, nutrients, and pesticides, thereby reducing costs and minimizing environmental impact. It also supports precision agriculture by delivering location-specific solutions and enabling predictive analysis for better planning and risk management. However, challenges such as high initial investment, lack of technical expertise, data reliability issues, and inadequate rural infrastructure may limit its widespread adoption. Overall, the AI-driven DSS offers a promising approach to achieving sustainable agriculture, improved productivity, and long-term food security.

Introduction

Agriculture plays a vital role in ensuring food security and supporting economic development across the world. With the increasing global population, the demand for food production is rising rapidly, placing significant pressure on farmers to improve productivity and efficiency. However, farmers face numerous challenges such as improper crop selection, inefficient fertilizer usage, plant diseases, and changing climatic conditions, which can negatively impact agricultural output. Traditional farming methods often rely on experience and manual observation, which may not always provide accurate results. In recent years, artificial intelligence (AI) has emerged as a powerful tool in agriculture, enabling data-driven decision-making and improving farming practices. AI techniques can analyze large amounts of data related to soil, weather, and crop conditions to provide accurate recommendations. This paper proposes an AI-driven decision support system that assists farmers in selecting suitable crops, optimizing fertilizer usage, and detecting plant diseases at an early stage. The objective of this study is to enhance agricultural

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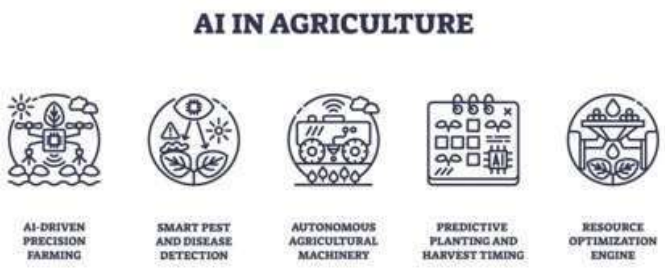
productivity, reduce resource wastage, and promote sustainable farming practices through the use of intelligent technologies.

Overview of AI-Driven Decision Support System

An AI-driven decision support system (DSS) is designed to assist farmers in understanding agricultural problems and making effective, data-driven decisions. It integrates advanced technologies such as soil sensors, remote sensing (including satellite and drone imagery) and artificial intelligence to collect, analyze and interpret agricultural data. These systems monitor key parameters such as soil moisture, temperature, pH levels, and nutrient content, along with environmental factors like weather conditions and crop health. By processing this data using machine learning algorithms, the system can generate accurate recommendations related to crop selection, irrigation scheduling, fertilizer application, and disease management. For example, it can suggest the most suitable crop based on soil and climate conditions or alert farmers to early signs of plant stress or disease.

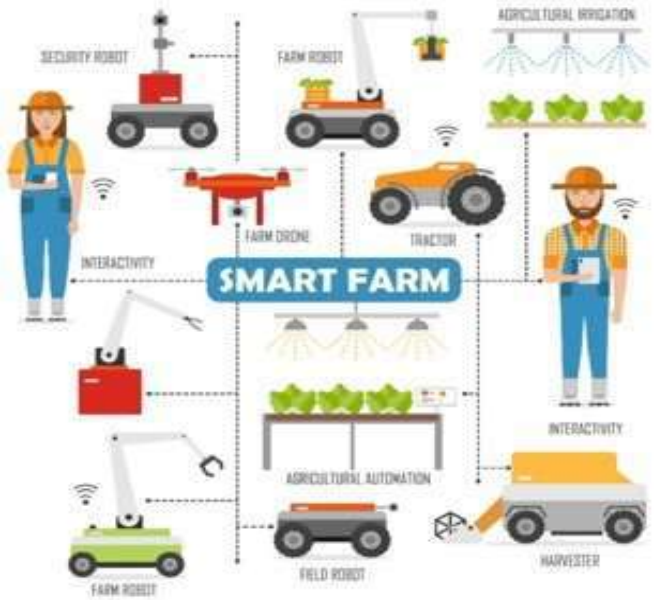


With the growing global demand for food and the increasing pressure on natural resources, such systems play a crucial role in improving agricultural productivity and efficiency. They help farmers optimize resource usage, reduce costs, minimize risks and adopt sustainable farming practices, ultimately contributing to enhanced yield and long-term agricultural development.

Working of the system

The system operates by collecting real-time data from multiple sources to provide accurate and timely agricultural insights. Soil sensors are deployed in the field to continuously measure important parameters such as soil moisture, temperature, pH level, and nutrient content, including nitrogen (N), phosphorus (P), and potassium (K). These sensors help in understanding the current condition of the soil and its suitability for different crops. In addition to ground-level data, remote sensing technologies such as satellites and drones are used to capture high-resolution images and monitor crop health, weather patterns, and environmental conditions over large areas. These technologies can detect variations in plant growth, water stress, and early signs of disease that may not be visible to the human eye. The collected data is then transmitted to a central system where it undergoes preprocessing, including cleaning and normalization, to ensure accuracy and consistency. Machine learning algorithms are applied to analyze patterns, identify trends, and make predictions based on historical and real-time data. These models are trained to recognize relationships between soil conditions, climate factors, and crop performance. Based on this analysis, the system generates actionable recommendations for farmers. These include selecting the most suitable crops for a given environment, optimizing irrigation schedules

to conserve water, recommending appropriate fertilizers in precise quantities, and detecting plant diseases at an early stage through image analysis. By providing timely and data-driven suggestions, the system enables farmers to make informed decisions, improve productivity, and reduce resource wastage.



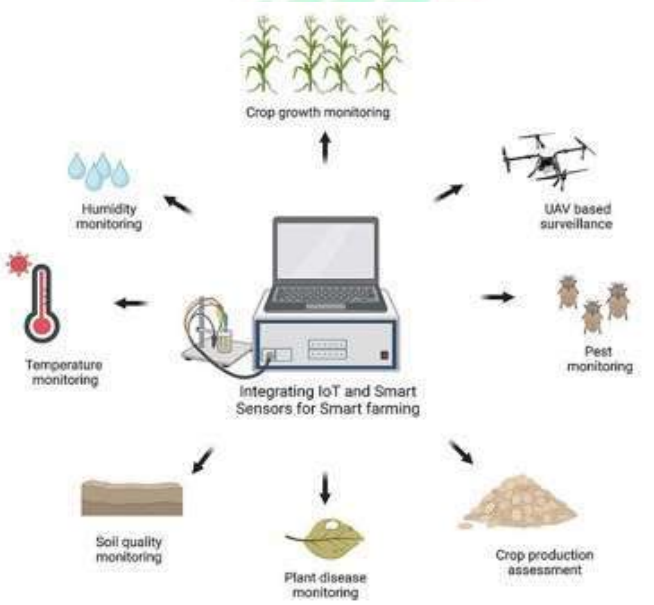
Application and examples

The system can be applied in a wide range of agricultural scenarios, enabling farmers to make timely and informed decisions. For instance, if soil moisture levels are low, the system can recommend optimal irrigation timing and quantity, helping conserve water while ensuring proper crop growth. If nutrient deficiency is detected through soil analysis, it can suggest specific fertilizers and appropriate dosages to restore soil health. In cases where leaf images show early signs of disease, the system can accurately identify the type of disease and recommend suitable treatment methods, such as targeted pesticide application or organic remedies. Additionally, the system can assist in crop selection by analyzing soil properties and climatic conditions, ensuring that farmers choose crops best suited to their land. The system can also predict weather-related risks, such as drought or heavy rainfall, and provide alerts to help farmers take preventive measures. It can monitor crop growth stages and recommend actions like timely harvesting to avoid losses. Furthermore, by analyzing historical data and yield patterns, the system can guide farmers in planning crop rotation and improving long-term soil fertility. These applications enable farmers to take proactive and data-driven actions, reducing crop loss, minimizing resource wastage, lowering production costs, and significantly improving overall productivity and sustainability in agriculture.

Benefits of the system

The AI-driven decision support system offers numerous benefits that significantly enhance modern agricultural practices. It improves crop yield by providing accurate and data-driven recommendations based on real-time analysis of soil and environmental conditions. By optimizing the use of resources such as water, fertilizers, and pesticides, the system helps reduce wastage, lower input costs, and minimize environmental impact. The system also enables early detection of plant diseases through image analysis and continuous monitoring, allowing farmers to take timely preventive measures and avoid large-scale crop losses. In addition, it supports precision agriculture by delivering location-specific recommendations, ensuring that each part of the field is managed according to its unique requirements.

Furthermore, the system reduces dependency on guesswork and traditional methods by promoting scientific decision-making. It saves time and labor by automating monitoring and analysis processes. The use of predictive analytics also helps farmers anticipate weather changes, pest attacks, and yield outcomes, enabling better planning and risk management. Overall, the system enhances productivity, improves profitability, supports sustainable farming practices, and contributes to long-term agricultural development.



Challenges and limitations

Despite its numerous advantages, the AI-driven decision support system faces several challenges that can limit its widespread adoption. One of the primary concerns is the high initial cost of implementation, including expenses for sensors, drones, software systems, and infrastructure, which can be difficult for small-scale and marginal farmers to afford. Another major challenge is the lack of technical knowledge and training among farmers. Many farmers may not be familiar with advanced technologies such as artificial intelligence, data analytics, or digital tools, which can hinder effective usage of the system. Additionally, the system relies heavily on the availability of accurate and high-quality data. Inaccurate or incomplete data can lead to incorrect recommendations, affecting crop outcomes. Infrastructure-related issues such as poor internet connectivity, especially in rural areas, can disrupt real-time data transmission and system performance. Sensor malfunctions, maintenance requirements, and power supply limitations can further impact reliability. Data privacy and security concerns also arise when large amounts of agricultural data are collected and stored. Moreover, the system may require continuous updates and model improvements to adapt to changing environmental conditions and crop patterns. Without proper support and maintenance, the effectiveness of the system may decline over time. Addressing these challenges through cost reduction, farmer training programs, improved infrastructure, and robust system design is essential for ensuring the successful adoption and long-term sustainability of AI-driven agricultural systems.

Conclusion

In conclusion, the AI-driven decision support system presents an effective solution to the challenges faced in modern agriculture. By integrating technologies such as sensors, remote sensing, and machine learning, the system enables farmers to make accurate and data-driven decisions

related to crop selection, fertilizer usage, irrigation, and disease management. The system significantly improves agricultural productivity by optimizing resource utilization, reducing wastage, and enabling early detection of plant diseases. It also supports precision agriculture by providing location-specific recommendations, thereby enhancing efficiency and sustainability. Although certain challenges such as high implementation costs, lack of technical knowledge, and infrastructure limitations exist, these can be addressed through proper training, technological advancements, and supportive policies. Overall, the adoption of AI-driven decision support systems has the potential to transform agriculture into a more efficient, sustainable, and intelligent sector, ensuring better productivity and long-term food security.

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Role of Millipedes in Sustainable Agriculture: A Maharashtra Perspective

Yashwant Patne and Ravi Barde

Abstract

Millipedes play a crucial role as soil-dwelling arthropods, significantly contributing to sustainable agriculture and ecosystem stability. These creatures are actively involved in decomposition, nutrient recycling, soil aeration, and maintaining soil fertility. By consuming decaying plant matter and organic residues, millipedes speed up the decomposition process and enhance nutrient availability in agricultural soils. Their actions promote microbial activity, humus formation, and improve soil structure, which in turn supports healthy crop growth. In Maharashtra and other regions of India, millipedes are frequently found in moist soils, agricultural fields, forest litter, and compost-rich environments, particularly during the monsoon season. Despite their ecological significance, the diversity of millipedes is threatened by excessive pesticide use, habitat destruction, soil pollution, and climate change. Preserving soil biodiversity and adopting eco-friendly agricultural practices are vital for maintaining healthy agroecosystems. This article emphasizes the ecological importance of millipedes and their role in promoting sustainable agriculture in India.

Introduction

Soil is one of the most critical components in the sustainability of agriculture and ecosystems. Bacteria, fungi, protozoa, earthworms, insects and soil arthropods are all examples of beneficial organisms in healthy soil that help maintain soil fertility and cycling of nutrients. In these, the millipedes are ecologically significant decomposers which play key roles in terrestrial systems. Millipedes are in the phylum Arthropoda and belong to the class Diplopoda, and are defined by elongated segmented bodies and two pairs of legs on most segments. They have been found mostly in wettish places like forest litter, compost heaps, grasslands and in farms. These organisms are generally found under stones, leaf litter, decaying wood and moist soil, but will become active when conditions are humid and during enlightenment during the day. Millipedes help to decompose and recycle nutrients by eating dead plant matter and decomposing organic matter as shown in Figure 1. Their feeding activity broken down the coarse litter into smaller pieces, which can be broken down by microorganisms later. This process leads to better nutrient assimilation and helps maintaining fertile soils (Mahure and Zilpe, 2026). Sustainable agriculture became an important topic recently because of concerns about damage to the soil, chemical contamination and reduction in

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biodiversity. Soil organisms such as millipedes are now recognized as important components of sustainable farming systems because they naturally improve soil health and ecosystem productivity.

Fig. 1: Millipedes as hidden Allies of Soil Health

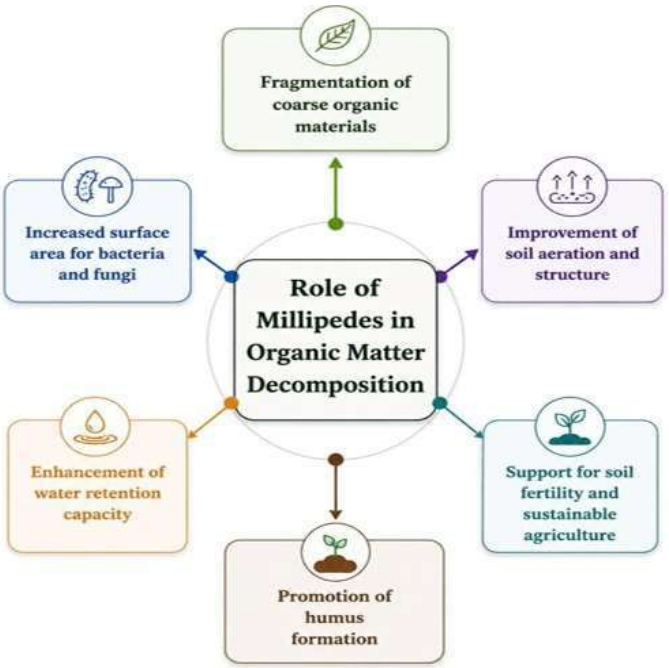
Diversity and Distribution of Millipedes

Millipedes are distributed widely throughout tropical, subtropical, and temperate regions of the world. India possesses rich millipede diversity due to its varied climatic conditions, vegetation types, and ecological habitats. In Maharashtra, millipedes are commonly observed in forest ecosystems, grasslands, compost-rich habitats, and agricultural fields, particularly during the rainy season. The diversity and abundance of millipedes are influenced by environmental factors such as soil moisture, organic matter content, temperature, vegetation type, and habitat conditions. Areas rich in decomposing organic matter generally support higher millipede populations because they provide suitable food and shelter. Different species of millipedes exhibit variations in colour, size, and ecological adaptation. Some species prefer moist forest litter, whereas others are commonly found in cultivated agricultural soils. Their occurrence often indicates healthy soils rich in organic matter and microbial activity. Studies on millipede diversity have shown that soil organisms respond significantly to ecological conditions and habitat quality (Shaikh *et al*., 2025). Millipedes are also considered useful biological indicators because their abundance reflects soil fertility and environmental stability. Agricultural ecosystems with reduced chemical disturbance and higher organic content generally support greater diversity of soil macrofauna.

Role of Millipedes in Organic Matter Decomposition

An important ecological process is decomposition which helps to decompose dead organic material and convert it into simple nutrients for the plants. Millipedes are one of the key decomposing organisms involved in the process. They feed on decaying twigs, fallen leaves, crop residues and other decomposing organic materials with the soil ecosystem. As millipedes feed, they can break down large pieces of organic matter into smaller fragments and thus increase the surface area for microbial processing. These particles are further decomposed by bacteria and fungi, which release nutrients including nitrogen, phosphorus, and potassium into the soil. This process helps in nutrient cycling and contributes to soil fertility. Humus formation is also a result of organic matter decomposition. It adds water retention and improves the aeration of the soil, while also improving its overall structure. Humus-rich soils are more fertility and sustainable agricultural. Millipedes help in the decomposition of residues and organic waste materials from crops on farmland. They carry out ecological activities that prevent the accumulation of undecomposed litter and

stimulate natural nutrient recycling. In the context of soil and climate studies, millipedes are important decomposers that have been implicated in nutrient cycling and improving soil structure (Shaikh *et al*., 2025).



Contribution to Soil Fertility and Soil Structure

Through nutrient cycling and soil structure alteration, millipedes play a direct role in soil fertility. The way they move through the upper layers of soil increase aeration and helps water get into the soil. More aeration ensures root development and increases microbial respiration. Millipede faecal pellets contain a mixture of partially decayed organic matter and beneficial microorganisms. These pellets favour soil aggregation and thereby enhance the texture of soils. Soils that are assembled resemble well-aggregated soils which hold greater water, have more nutrients, and resist erosion. Millipedes, too, play a role in the soil ecosystem as potential determinants of microbial populations. The feedings catalyze microbial decay and promote mineralization processes. Higher microbial activity enhances the availability of mineral nutrients essential for plants' growth. Thus, soils with high soil macrofauna presence seem to be more biologically active and ecologically stable. Responses to millipedes and microorganisms may maintain fertile soils for sustainable crop production (Mahure and Zilpe, 2026). Numerous research investigations demonstrated a positive correlation between millipede abundance and soil organic matter or vegetation quality (Suriel *et al.*, 2025). Hence, conservation of soil biodiversity should be a requisite for preserving stable and resilient agro-ecosystems.

Ecological Importance in Agricultural Ecosystems

Millipedes play an important ecological role in maintaining balance within agricultural ecosystems. Their decomposition activities help recycle nutrients naturally and reduce dependence on chemical fertilizers. They also support soil biological activity and improve ecosystem functioning. Healthy populations of soil organisms contribute to ecosystem resilience under changing environmental conditions. Agricultural soils rich in organic matter and biodiversity are generally more resistant to erosion, nutrient loss, and climatic stress. Millipedes also participate in terrestrial food webs and serve as prey for birds, reptiles, amphibians, and predatory invertebrates. Thus, they contribute to maintaining ecological interactions and biodiversity within ecosystems.

Traditional agricultural practices involving composting, organic manures, mulching, and crop residue retention often support diverse soil fauna including millipedes. Such eco-friendly practices improve soil health while conserving beneficial organisms. Although a few millipede species may occasionally damage seedlings under unfavourable conditions, their ecological benefits are generally much greater than their harmful effects. Most species contribute positively to decomposition and nutrient recycling processes.

Millipedes and Sustainable Agriculture

Sustainable agriculture aims to maintain long-term productivity while minimizing environmental damage and conserving natural resources. Soil biodiversity forms the foundation of sustainable farming systems, and millipedes represent an important component of this biological diversity. Organic farming practices encourage the growth of beneficial soil organisms by increasing organic matter and reducing chemical disturbances. Compost application, mulching, crop rotation, and minimum tillage create favourable habitats for millipedes and other decomposers. Millipedes contribute indirectly to sustainable agriculture by improving nutrient availability, soil structure, moisture retention, and microbial activity. Their ecological functions help reduce dependence on synthetic fertilizers and improve soil productivity naturally. Conservation agriculture practices such as residue retention and reduced tillage also help maintain soil biodiversity. Excessive ploughing and indiscriminate pesticide application can destroy soil habitats and reduce populations of beneficial organisms. Millipedes therefore play an important role in maintaining healthy soils and supporting environmentally sustainable agricultural systems in India.

Threats to Millipede Diversity

Millipedes, despite being an important ecological component have high environmental threats. Soil biodiversity and millipede populations are also negatively impacted by habitat destruction, urbanization, industrialization and deforestation with the excessive use of pesticides. In chemical-intensive agriculture, soil biological activity is reduced and natural decomposition processes are disrupted. Crop residues are burned, and removal of organic litter means less food for decomposer organisms. And climate change is a third major threat to millipede diversity. Increasing temperatures, irregular rainfall patterns and extended periods of drought result in a depletion of the moisture content within soils needed for millipede survival and activity. Conservation of soil biodiversity does not receive the same level of attention as that of other species due to lack of awareness.

Conservation and Management

Ensuring the survival of millipedes is essential for the health of soil ecosystems and the long-term viability of agricultural productivity. Agricultural practices should aim to protect soil biodiversity and reduce environmental impact. The following approaches can support the conservation of millipede populations:

- ✓ Curtailing the excessive application of pesticide
- ✓ Advocating for organic farming methods
- ✓ Preserving crop residues and organic substances
- ✓ Sustaining soil moisture through the use of mulch
- ✓ Limiting tillage and soil disruption
- ✓ Protecting natural habitats and forest ecosystems
- ✓ Enhancing awareness of the importance of conserving soil biodiversity

Furthermore, conducting more research into the ecology, taxonomy, and distribution of Indian millipedes is crucial to fully grasp their contribution to ecosystem health and sustainable agriculture.

Conclusion

Millipedes play a crucial role as soil macroarthropods, significantly aiding in decomposition, nutrient cycling, soil fertility, and ecosystem stability. Their presence enhances soil structure, boosts microbial activity, and increases nutrient availability, thereby promoting sustainable agricultural productivity. In India, especially in Maharashtra, millipedes are a vital part of soil biodiversity found in forests, grasslands, compost-rich areas, and agricultural systems. Preserving these beneficial decomposers is vital for maintaining healthy soils and ecological balance. Eco-friendly farming methods such as organic agriculture, mulching, retaining crop residues, and minimizing pesticide use can help protect millipede diversity and naturally enhance soil health. Raising awareness about the ecological significance of millipedes will aid in biodiversity conservation and support sustainable agriculture in the future.

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Therapeutic Properties of Opium Poppy

D. Kasthuri Santira Kumari, Uzlifat Zahoor Tak and Sayan Deb

Introduction

Papaver somniferum L. also known as "opium poppy" or "sleep-bringing poppy" is widely grown as an ornamental flower throughout Asia, Europe and America. Australia, Turkey and India are the major producers of opium poppy (Luqman, 2011). The genus *Papaver* is a member of the Papaveraceae family, Papaveroideae subfamily, Ranunculales order, Angiosperms clade, and Plantae kingdom. With over 40 genera and 800 species, the Papaveraceae is a worldwide family that thrives in both tropical and alpine environments (Egan *et al*. 2011). While the term "opium" refers to the air-dried latex extracted from *Papaver somniferum* L., one of the most beneficial plant species in the Papaveraceae family, the word "poppy" has been used for numerous species of this family. The fluid, milky latex of vessels characterizes all portions of plants in this genus, with the exception of seeds. There are over 240 species in the family, 170 of which are in the genera Papaver and Papaveroideae include over 100 species. At the tribal level, Romneyeae (two genera) have been distinguished from Papaverae due to their distinct milky latex and water-like colorless juice, respectively.

Genus species *Papaver* are divided into nine divisions based on their life cycle and associated traits. The most advanced annual Papaver section is made up of the opium poppy and three other species (*P. glaucum, P. gracile* and *P. decaisnei*).

Poppy plants do not need fertilizer or manure but requires a well-drained sunny site, free of weeds. Being an easily grown garden plant having bright colored flowers in all shades of pink, red, lilac, orange, yellow, purple or white with dark shades at the base. The leaves are alternate, simple, clasping and toothed. The fruits are rounded capsule topped with the stigma discover small holes. The liquid (milky latex) obtained after lancing of the capsule

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contains opiates which are dried to produce raw opium, used for producing medicinal drugs such as codeine and morphine. Scraped out of the pod, the white liquid turns black on exposure to air, is the raw product used to make opiates and after the extraction purified to alkaloids. Opium produces natural opiates, largely used for manufacture of many alkaloids including morphine, codeine, narcotine, laudenine, papaverine etc. Alkaloids present in poppy can be of two different types; Phenanthrenes (morphine, codeine, and thebaine) that acts on the nervous system and are addictive to the human body and Isoquinolines such as papaverine and noscapine, non-addicting and relax muscle groups. The deadly and highly addictive drugs heroin and dimorphine, which are forbidden in several nations, are also derived from opium. The most well-known drugs are opiates, of which codeine and morphine are the most commonly used. When it comes to pain relief, morphine is more potent than codeine, which is a milder variant of morphine. Certain commercial goods, such Turkish, Chinese, Egyptian, Persian, and Indian opium, vary in quality and appearance and are often smoked as intoxicants. Small, black, dark blue, or yellow-white seeds are easily scattered by the wind, edible, and delicious. They are used in baked goods and confections and are marketed by seed businesses and nurseries all over the world.

Traditional Uses: The long-standing literary history of the usage of opium poppies in diverse cultures and traditions has undergone several changes over time (Page, 2005). The opium poppy was cultivated in the ancient Egyptian, Mesopotamian, and Persian civilizations. Fossilized evidence indicates that man may have used it more than 30,000 years ago, and the first recorded mention of it dates back to 4,000 BC in a Sumerian document. Poppies have been cultivated as attractive plants in Mesopotamia since 5000 BC, according to records. Remains of poppies have also been discovered in Egyptian tombs and at the Kalapodi and Kastanas sites. Theophrastus and Dioscorides (c. 77 AD) described an extract of the complete herb made from the capsules alone. Since the Neolithic era, poppies have been grown for food, ceremonial, and anesthetic. An Egyptian papyrus dated 1500 BC lists poppies as medicinal plants with significant therapeutic qualities. Priest-physicians encouraged the domestic use of opium concoctions throughout Egyptian society. Thebacium was the name given to these cures because of the extremely powerful poppies that were produced close to Thebes, the capital. Opium items were interred alongside Egyptian pharaohs. Opium poppies were widely used by the Arabs, Assyrians, Egyptians, Greeks, Indians, Minoans, Persians, Romans, and Sumerians, enabling ancient surgeons to carry out surgical procedures. Opium poppies are mentioned in several of the most significant ancient medical works, including the Ebers Papyrus, Dioscorides, Galen, and Avicenna.

Therapeutic Uses: The biological activities of several parts or products of this species have been studied (Eryilmaz *et al.*, 2016), but the opium poppy's commercial significance primarily stems

from its medicinal qualities, which are caused by the production of several BIAs, which are made up of roughly 2500 different structures. A number of isolated BIAs exhibit potent pharmacological effects, including the antimicrobial agents sanguinarine, the cholesterol-lowering berberine, the muscle relaxant tubocurarine, the vasodilator papaverine, the cough suppressant and possible anticancer medication noscapine, and the narcotic analgesics codeine and morphine. The majority of these BIAs have been isolated from Papaver species, particularly *P. somniferum* as a commercial source. Poppy seeds are valued not just as an ornamental species but also in the culinary arts, baking, and oil manufacturing.

One of the most important species of houseplants is the opium poppy. In addition to a number of semi-synthetic compounds, such as oxycodone and buprenorphine, which are mostly produced from thebaine, opium poppies continue to be the most significant commercial natural source of medications, including codeine and morphine. (Dang *et al*., 2012). Poppy genotypes can be broadly categorized into three groups: industrial (grown for the purpose of extracting alkaloids from capsules); culinary (grown for the purpose of producing seeds and oil); and both industrial and culinary (grown for the purpose of extracting alkaloids from capsules and collecting seeds). The use of poppies and their secondary metabolites in pharmacology is the most significant use. It is helpful to distinguish between opiate and opioid words in scientific terminology. The first was used to identify the compounds present in poppies, but it eventually expanded to encompass any drugs that were either synthesized or directly generated from morphine and its derivatives. Therefore, wholly synthesized substances like fentanyl are not regarded as opioids, although morphine, heroin, codeine, and naloxone are. Opioids refer to all substances, endogenous (natural binders for opioid receptors) and exogenous that interact with opioid receptors. Opioids are also known as narcotic analgesics, but often the definition of narcotic (a sleep-inducing drug) is used as a synonym for abused drugs. The narcotic substance opium has several traditional medical use as a sedative and pain reliever. Numerous illnesses and conditions, such as cancer, pain, cough, spasm, diarrhea, fever, asthma, etc., have been treated with it. Opium poppies are surprisingly rarely used as medicines in South Asian mythology or religion. Opium and other intoxicants are used in rituals by adherents of shaktis, or divine energy. It is traditionally offered to visitors in North India as opium water. In 1967-1971, Hartwell describes opium as a treatment for cancer of the skin, stomach, tongue, uterus, breast cancer, ear, nose, and vaginal polyps, scleroses of the liver, spleen, and uterus, and tumors of the abdomen, bladder, eyes, liver, spleen, and uvula (Hartwell, 1967-1971). It is stated that the decoction of capsules and seeds can help with uterine cancer, poppy tincture can help with ulcers, and a plant boiled in oil can help with liver tumors and indurations. According to Egyptians, consuming opium makes one happier, more chatty, and more hardworking. Morphine, the

predominant alkaloid and an active ingredient found in opium poppy plant constitute 8-17% of the dry weight, although it may reach up to 26% in specially-bred cultivars or produce as low as 0.04%. Przemko and Norman cultivars of the opium poppy, produces two other alkaloids, thebaine and oripavine, used in the manufacture of semi-synthetic and synthetic opioids like oxycodone and etorphine and some other drugs. Papaverine, also an alkaloid found in opium poppy, is used primarily in the treatment of both vascular and visceral spasm (especially of heart and brain), and sometimes for the treatment of erectile dysfunction.

Benefits of Opium poppy as food commodity and nutraceutical: Poppy seed and oil are two dietary items derived from opium poppies. The poppy plant yields a large number of tiny white, creamy, or black seeds that have very little opiate content, and the oil that is derived from them has even less. There are commercial applications for both the oil and the seed residue. Seeds can be crushed into flour, added to sauces as thickening or flavoring agents, used in salad dressings, and utilized as frying oil. A traditional sedative drink is occasionally made by infusing mature poppy heads. The seeds can be boiled in water with salt, oil, and rice to give it a nutty taste. To make curry, the seeds can be crushed, dry roasted, and combined with tamarind. The seeds create a distinctive, thick, creamy, and nut-like curry base when combined with crushed coconut. In addition to being edible, seeds are used in many different dishes, particularly baked goods and confections. They are used to rolls, breads, and cakes, as well as dusted on desserts. In addition to being used to make paints, varnishes, and soaps, poppy seed is a source of drying oil (44-50%), and its oil cakes are fed to cattle (Krist *et al*., 2005). Other uses of opium poppy includes: white seeds used for the preparation of emulsions, bluish-black varieties used for baking, stems used for making straw, poppy seed meal for extracting lecithin, oil is very good for lighting as it burns longer, flower for making opium tea with high morphine content, seedlings eaten as a potherb and seed pods are also sold for dried flower arrangements.

Conclusion

Since ancient times, opium poppy (*Papaver somniferum* L.) is known for its medicinal properties, related to its secondary metabolite content. Its most important secondary metabolites, called benzylisoquinoline alkaloids (BIAs), are still essential in pharmaceutical field. Few of them, like morphine, have specific clinical application but also effects on CNS. Not all poppy cultivars are able to biosynthesize morphine in high amount, making this plant useful for other purposes like food uses.Man may have used opium poppies more than 30,000 years ago, according to fossilized evidence, and Sumerian texts from 4,000 BC contain the first known written mention of the plant. Opium was made from the juice of unripe seed capsules or air-dried milky latex in traditional medicine to treat a variety of illnesses. Because it contains opiates (morphine, codeine, narcotine, laudenine, papaveri-

ne, oripavine) that can lessen spasm, pain, excitement, change behavior, induce sleep, and help eliminate anxiety, it is frequently used for medical purposes.

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Saccharomyces cerevisiae: A Versatile Microbe in Industrial Biotechnology

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Abstract

Saccharomyces cerevisiae, commonly designated baker's or brewer's yeast, occupies an unrivaled position in industrial biotechnology as the most extensively characterized and industrially deployed eukaryotic microorganism. Its genetic tractability, robust fermentative metabolism, GRAS (Generally Recognized as Safe) status, and capacity for post-translational protein modification have collectively established it as the preferred cellular chassis for applications spanning biofuel production, pharmaceutical protein synthesis, food fermentation, and emerging synthetic biology platforms. According to Grand View Research, 2023, the global fermentation-derived products market projected to exceed USD 1.3 trillion by 2030, S. cerevisiae remains at the productive center of this expansion. This article provides an integrated review of S. cerevisiae's biological attributes, metabolic capabilities, and industrial applications, incorporating recent advances in metabolic engineering, adaptive laboratory evolution, and CRISPR-based genome editing, while addressing persistent challenges of strain robustness, inhibitor tolerance and regulatory compliance.

Introduction

The history of human civilization is inseparably interwoven with the metabolic activities of *Saccharomyces cerevisiae*. Long before its scientific characterization by Emil Christian Hansen in 1883, this unicellular fungus had been exploited for millennia in bread leavening, wine fermentation, and beer brewing constituting arguably the oldest biotechnological relationship between humans and a microorganism. Yet the contemporary relevance of *S. cerevisiae* extends far beyond its artisanal origins. In the twenty-first century, it functions as a programmable biological factory, a model eukaryote for fundamental cell biology research, and a frontline platform for the synthesis of complex molecules that underpin the pharmaceutical, nutraceutical, and bioenergy sectors. *S. cerevisiae* is a non-pathogenic, facultatively anaerobic ascomycete yeast that reproduces vegetatively by budding and sexually through the formation of ascospores. It exhibits a biphasic life cycle, alternating between haploid and diploid phases, which facilitates both classical genetic crossing and modern molecular manipulation. Its cellular diameter ranges from 5 to 10 µm,

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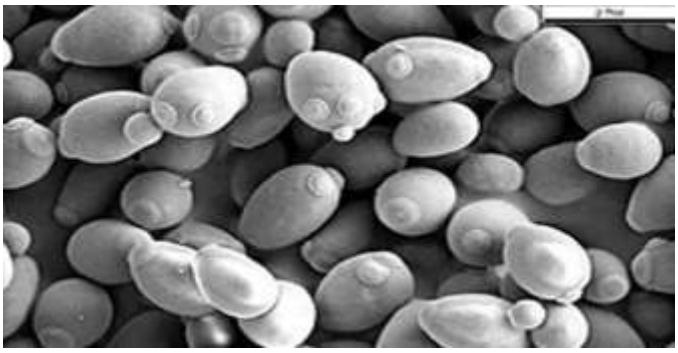
with a generation time of approximately 1.5-2 hours under optimal aerobic conditions (28-32°C, pH 4.5-6.5). It ferments glucose to ethanol with a theoretical yield of 51.1% (w/w), tolerates ethanol concentrations exceeding 14% (v/v), and withstands osmotic and oxidative stresses encountered in industrial fermenters (Bhatt *et al*., 2021). Its fully sequenced 12.1 Mb genome, the first eukaryotic genome to be completely sequenced in 1996, encodes approximately 6,000 open reading frames, the majority of which have been functionally annotated, providing an unparalleled scaffold for systems-level metabolic design. Concurrently, the emergence of CRISPR-Cas9-mediated genome editing, automated high-throughput screening, and machine learning-guided strain optimization has exponentially expanded the industrial utility of this organism. Despite its dominance, *S. cerevisiae* is not without industrial limitations. Its native inability to efficiently ferment pentose sugars (xylose, arabinose) from lignocellulosic biomass, susceptibility to fermentation inhibitors such as furfural and hydroxymethylfurfural (HMF), and constrained secretory pathway capacity for heterologous proteins represent persistent bottlenecks that active research continues to address (Kwak and Jin, 2017).



This review synthesizes current knowledge across the biological, metabolic engineering and application dimensions of *S. cerevisiae*, with emphasis on developments reported since 2017.

Industrial Applications

Overview of Industrial Sectors: The industrial footprint of *S. cerevisiae* spans multiple high-value sectors, from traditional fermentation industries to cutting-edge synthetic biology platforms. Table 1 summarizes its primary applications alongside key output metrics and recent literature references.

Bioethanol and Biofuel Production: The most volumetrically significant industrial application of *S. cerevisiae* is first-generation bioethanol production, wherein glucose and sucrose derived from sugarcane, corn, or sugar beet are fermented to ethanol at industrial efficiencies approaching the theoretical maximum of 0.511 g ethanol g^{-1} glucose (Bhatt *et al*., 2021). Brazil and the United States collectively produced approximately 105 billion liters of fuel ethanol in 2022, the vast majority employing *S. cerevisiae*-based fermentation processes.

Table 1: Industrial Applications of *Saccharomyces cerevisiae* across Biotechnology Sectors

Industrial Sector	Application	Key Product / Output	Reference
Biofuels	Bioethanol fermentation	Ethanol yield up to 51.1 g L^{-1}	Bhatt *et al*., 2021
Pharmaceuticals	Heterologous protein expression	Insulin, HBsAg vaccine	Nielsen *et al*., 2022
Food & Beverage	Fermentation of bread, beer, wine	>150 billion USD market (2023)	-
Synthetic Biology	Metabolic pathway engineering	Artemisinic acid, lycopene	Ro *et al*., 2006
Nutraceuticals	Ergosterol & beta-glucan production	Beta-glucan: 30-65% cell wall DW	Tang *et al*., 2023
Environmental Biotech	Heavy metal bioremediation	Pb^{2+} removal: up to 89%	Vargas-García *et al*., 2022

In second-generation (2G) bioethanol production from lignocellulosic feedstocks, agricultural residues such as corn stover, sugarcane bagasse, and wheat straw, native *S. cerevisiae* strains are metabolically insufficient due to their inability to ferment xylose, the second most abundant sugar in plant biomass. Extensive metabolic engineering efforts, including the introduction of the xylose reductase/xylitol dehydrogenase (XR/XDH) path-way from *Scheffer-somyces stipiti*s or xylose isomerase from *Piromyces sp*., have yielded recombinant strains capable of co-fermenting glucose and xylose with ethanol yields of 0.43-0.47 g g^{-1} total sugars (Kwak and Jin, 2017). Adaptive laboratory evolution (ALE) strategies applied to these engineered strains have further improved xylose consumption rates by 30-45% over parental lines.

Pharmaceutical and Therapeutic Protein Production: *S. cerevisiae* was the first eukaryotic host approved by the U.S. FDA for the production of a recombinant human therapeutic protein insulin (Humulin®, 1982) and has since served as the production platform for the recombinant hepatitis B surface antigen (HBsAg) vaccine, which has immunized over 1.3 billion individuals globally (Nielsen *et al*., 2022). The yeast's secretory pathway can be engineered to direct heterologous proteins into the culture medium, simplifying downstream purification; however, hyperglycosylation via high-mannose N-linked glycans often compromises the pharmacokinetic profiles of therapeutic proteins and requires glycoengineering interventions. Humanized glycosylation pathways achieved through systematic deletion of yeast-specific mannosyltransferases and introduction of mammalian glycosyltransferases have been successfully implemented in industrial strains, bringing *S. cerevisiae*-derived glycoproteins closer to mammalian cell-culture standards (Nielsen *et al*., 2022).

Synthetic Biology and High-Value Metabolite Production: The reconstruction of complex natural product biosynthetic pathways in *S. cerevisiae* represents one of the most transformative develop-ments in synthetic biology over the past two decades. The landmark achievement of engineering *S. cerevisiae* strain EPY300 to produce artemisinic acid the precursor to the frontline antimalarial drug artemisinin at titers of 320 mg L^{-1} through mevalonate (MVA) pathway upregulation and heterologous expression of *Artemisia annua* cyto-chrome P450 enzymes (Ro *et al.,* 2006) demon-strated the species' capacity as a total biosynthetic

platform. Subsequent iterations of this strategy have delivered commercial-scale production via Sanofi. More recently, yeast cell factories have been engineered for the de novo synthesis of lycopene (yield: 2.37 g L^{-1}), cannabinoids including canna-bidiolic acid (CBDA; 8 mg L^{-1}) and monoterpenoid fragrance compounds valued at >USD 200 kg^{-1} in the flavor and fragrance industry (Tang *et al*., 2023).

Environmental Biotechnology: Beyond production biotechnology, *S. cerevisiae* has demonstrated significant potential in environmental remediation applications. Its high cell wall affinity for divalent heavy metal cations mediated by chitin, glucan, and mannoprotein components enables biosorption of lead (Pb^{2+}), cadmium (Cd^{2+}), and mercury (Hg^{2+}) from industrial effluents. Vargas-García *et al.* (2022) reported Pb^{2+} removal efficiencies of up to 89% using immobilized non-living yeast biomass at initial metal concentrations of 100 mg L^{-1}, with Langmuir maximum adsorption capacities of 68.4 mg g^{-1}. Surface display systems wherein metal-binding peptides such as metallothionein or phytochelatin synthase are tethered to the yeast cell wall via α-agglutinin anchors have further enhanced biosorption capacities by 2.3-fold compared to unmodified strains.

Challenges and Future Directions

In lignocellulosic biorefineries, the presence of fermentation inhibitors furfural, HMF, acetic acid, and phenolic compounds generated during biomass pretreatment severely impairs yeast viability and fermentation rates, with HMF concentrations as low as 5 mM reducing ethanol productivity by up to 35% (Bhatt *et al.,* 2021). Engineering inhibitor tolerance via overexpression of aldehyde detoxification enzymes (ADH6, ALD6) and ROS-scavenging systems has yielded partial improvements, though industrially sufficient tolerance across all inhibitor classes remains elusive. Protein secretion bottlenecks arising from ER folding stress, unfolded protein response (UPR) activation, and vacuolar degradation of secretory intermediates limit the titers of heterologous proteins achievable in *S. cerevisiae* to levels generally 10-100-fold below those attainable in *Pichia pastoris* (*Komagataella phaffii*) for certain proteins (Nielsen *et al*., 2022). Rational engineering of the secretory pathway, including HAC1 overexpression to pre-activate UPR and deletion of vacuolar proteases (PEP4, PRB1), has partially addressed this limitation. From a forward-looking perspective, the integration of *S. cerevisiae* into circular bioeconomy frameworks wherein it simultaneously valorizes agricultural waste streams, produces high-value compounds, and generates biogas from spent biomass represents a compelling systems-level opportunity. Synthetic consortia pairing *S. cerevisiae* with cellulolytic bacteria or other specialist yeasts for consolidated bioprocessing (CBP) of lignocellulose are under active development (Kwak and Jin, 2017). Additionally, the application of cell-free yeast extract systems for rapid prototyping of metabolic pathways prior to in vivo implementation is gaining traction as a complementary design tool (Bhatt *et al*., 2021).

Conclusion

Saccharomyces cerevisiae's century-spanning industrial legacy, far from being superseded by newer microbial platforms, has been fundamentally reinvigorated by the convergence of CRISPR genome editing, systems metabolic engineering, and synthetic biology. Its unparalleled genetic tractability, eukaryotic biochemical machinery, and GRAS status position it as the default chassis for an expanding portfolio of industrial biotechnology applications, from lignocellulosic biofuels and antimalarial precursors to therapeutic proteins and heavy metal bioremediation. Future priorities must include the development of thermo- and inhibitor-tolerant chassis strains for second-generation biorefineries, humanized glycoengineered platforms for next-generation biopharmaceuticals and validated synthetic consortia for consolidated bioprocessing.

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Spray Induced Gene Silencing for Crop Protection

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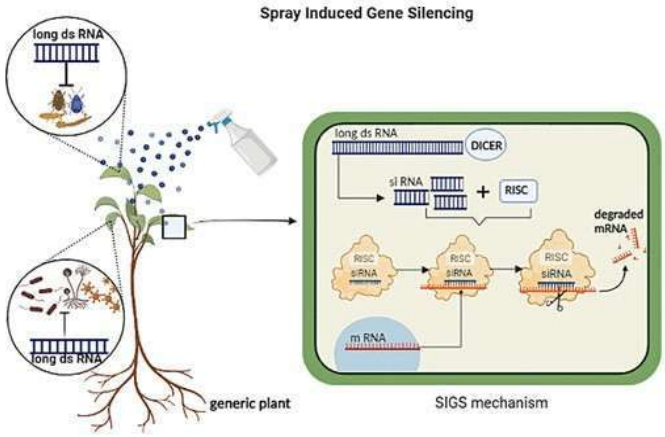
Spray-induced gene silencing (SIGS) is an emerging RNA-based technology that uses externally applied double-stranded RNA (dsRNA) or small interfering RNA (siRNA) to silence essential genes in plant pathogens and pests, thereby protecting crops without the need for genetic modification of the host plant. By leveraging the natural RNA interference (RNAi) pathway, SIGS offers a highly specific, flexible, and environmentally friendly alternative to conventional chemical pesticides, especially in an era of increasing regulatory pressure and public concern about pesticide residues and resistance (Wang and Jin, 2017).

Underlying science of SIGS: SIGS relies on the conserved RNAi machinery present in many fungi, oomycetes, insects, and nematodes. When dsRNA molecules are sprayed onto plant surfaces, they can be taken up by the pathogen or pest, processed by the enzyme Dicer into small interfering RNAs (siRNAs), and then loaded into the RNA-induced silencing complex (RISC). The RISC-bound siRNA guides the complex to the complementary messenger RNA (mRNA) of a target gene, leading to its degradation and consequent "silencing" of the gene product. If the targeted gene is essential for growth, development, or virulence, such as genes involved in cell-wall synthesis, nutrient uptake or toxin production, the pathogen or pest is weakened or killed, thereby preventing disease or infestation (Wang and Jin, 2017).



SIGS is conceptually related to host-induced gene silencing (HIGS), in which the plant itself is genetically engineered to produce hairpin RNAs that silence the same types of pathogen or pest genes. However, unlike HIGS, SIGS does not require genetic transformation of the crop, making it potentially faster to deploy across different species and more acceptable in regions with strict rules on genetically modified organisms (GMOs). Instead, the silencing triggers are produced *in vitro* (often via *in vitro* transcription or bacterial fermentation) and then formulated as a sprayable solution applied to leaves, stems, seeds, or even harvested produce.

Advantages for crop protection: SIGS offers several advantages over conventional synthetic pesticides. First, it is highly sequence-specific, meaning that carefully designed dsRNAs can target

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genes that are unique to a particular pest or pathogen, thereby minimising impacts on non-target organisms such as beneficial insects, pollinators, and soil microbes. This specificity reduces the risk of ecological disruption and aligns with integrated pest management (IPM) strategies that emphasize biological and ecological balance (Chen *et al*., 2025). Second, SIGS is non-transgenic at the crop level, which simplifies regulatory approval and consumer acceptance in many markets. Farmers can treat multiple crop species with the same RNA-based product without having to develop or deploy separate transgenic lines, and the technology can be rapidly adapted to new or evolving pest strains by simply redesigning the dsRNA sequence. This "agile" characteristic is particularly attractive in the face of climate-driven pest range shifts and emerging pathogens. Third, SIGS is considered environmentally sustainable because dsRNA is biodegradable and does not leave persistent residues in soil or water, unlike many broad-spectrum chemical insecticides and fungicides. Field-relevant studies have shown that topical dsRNA sprays can control key fungal pathogens (e.g., *Botrytis, Fusarium*), oomycete species (e.g., *Phytophthora*), and insect pests (e.g., aphids, beetles, stored-grain insects) at relatively low application rates, with efficacy comparable to or better than some chemical controls in model systems (Chen *et al*., 2025).

Mechanisms of uptake and delivery challenges: Despite its promise, SIGS faces several practical challenges, starting with how dsRNA molecules are taken up by the target organism. In many foliar-pathogenic fungi and oomycetes, dsRNA can be absorbed across the cell wall and plasma membrane, often facilitated by environmental RNAi-pathway components that are present in some microorganisms but not in others. Insects typically internalize dsRNA either by ingesting sprayed foliage or by direct cuticular absorption, after which the RNA is processed in midgut or systemic tissues. However, naked dsRNA is vulnerable to rapid degradation by environmental nucleases, UV light, and plant- and microbe-associated enzymes, which limits its persistence and field-level efficacy. To address this, researchers are developing advanced delivery formulations, including nano-carriers, lipid-based systems, chitosan polymers, and biocompatible clays that protect dsRNA from degradation and enhance its penetration into plant tissues or pest bodies. For example, nano based SIGS formulations have shown improved uptake and longer residual activity in greenhouse and laboratory trials, raising the possibility of fewer applications and lower total RNA inputs per hectare (Chen *et al*., 2025). Spray parameters also matter. Droplet size, spray volume, adjuvants, and timing relative to infection or pest colonization can all influence how much dsRNA reaches the target and how long it remains biologically active. Work on postharvest applications, such as protecting stored rice grains against the lesser grain borer (*Rhyzopertha dominica*), has demonstrated that spray-applied dsRNA can persist for at least 60 days in the grain

matrix, with measurable insect mortality and a substantial fraction of the initial dsRNA still detectable after storage. Such results highlight the potential for SIGS in both pre-harvest field management and postharvest storage systems.

Spectrum of targets and crops: SIGS has already been tested across a wide range of biotic threats, including fungi, oomycetes, insects, nematodes, and viruses, often in high-value or staple crops. For fungal diseases, studies have targeted genes essential for melanin biosynthesis, appressorium formation, or effector secretion in pathogens such as *Botrytis cinerea* (gray mold) and Fusarium species, resulting in reduced lesion expansion and disease severity on treated plants. In oomycetes like Phytophthora infestans, which causes late blight in potato and tomato, SIGS has been used to silence genes involved in pathogen motility, host penetration, or infection-related signaling, leading to improved disease control under controlled conditions. For insect pests, SIGS-based sprays have been applied to aphids, beetles, and lepidopteran larvae, with target genes often related to essential metabolic processes, moulting, or detoxification enzymes. By impairing these functions, the RNA-based treatment can reduce feeding damage, retard development, or increase mortality, effectively lowering pest pressure without broad-spectrum lethality to non-target insects. Viral pathogens represent another important frontier, because there are currently no widely adopted "pesticide-like" antiviral agents for crops. Recent work has shown that dsRNA targeting conserved regions of viral genomes can suppress viral replication and reduce symptom severity when applied as foliar sprays or through other contact routes, offering a non-transgenic strategy for managing crop viruses (Wang and Jin, 2017).

Regulatory, economic and scalability issues: The regulatory and economic landscape for SIGS is still evolving. In late 2023 the U.S. Environmental Protection Agency (EPA) approved Ledprona, the first sprayable dsRNA biopesticide, marking a significant milestone for SIGS as a commercially viable technology. This approval signals that RNA-based sprays can meet safety and efficacy standards comparable to conventional agrochemicals at least in some jurisdictions. However, regulatory frameworks differ globally, and questions about long-term environmental impacts, non-target effects, and potential for off-target RNAi remain active areas of research and policy discussion. From an economic standpoint, large-scale production of dsRNA remains a bottleneck. Traditional *in-vitro* transcription methods can be costly, and fermentation-based expression in bacterial or yeast systems must be optimised for yield, purity, and sequence fidelity. Recent advances in cost-effective dsRNA production, including improved cell-free systems and engineered microbial platforms, are beginning to reduce manufacturing expenses and could make SIGS more competitive with chemical pesticides, especially where resistance or residue concerns are acute. Scalability also depends on how well SIGS integrates with existing farm practices.

Farmers are more likely to adopt RNA-based sprays if they can be tank-mixed with fertilizers or other agrochemicals, applied with standard boom sprayers, and scheduled within familiar spray windows. Field-scale trials are therefore essential to validate not only biological efficacy but also practicality under real-world conditions, including variable weather, soil types, and pest complexes (Wang and Jin, 2017).

Nanotechnology and combinatorial approaches: A particularly promising direction is the combination of SIGS with nanotechnology. Nano-carriers can encapsulate dsRNA, forming protective "packets" that shield the RNA from degradation while facilitating uptake into plant tissues or pest cells. For example, nano bioconjugates made from biodegradable polymers, inorganic nanoparticles, or plant-derived materials have been tested as vehicles for dsRNA in tomato, wheat, and other species, yielding improved protection against fungi and insects compared with unformulated sprays.

Combinatorial strategies, such as mixing multiple dsRNA sequences targeting different genes in the same pest or pathogen, or pairing SIGS with low-dose chemical fungicides or insecticides, are also being explored. These combinations can enhance efficacy, delay resistance evolution, and reduce the total amount of active ingredients needed, contributing to more sustainable crop-protection programs. For instance, studies on postharvest protection of rice have shown that dsRNA sprays can achieve insect mortality levels comparable to higher rate chemical treatments, but with fewer applications and lower environmental load.

Future perspectives and integration into agriculture: Looking ahead, SIGS is likely to become an increasingly important component of precision agriculture and digital-farm platforms. Because dsRNA sequences can be rapidly redesigned, SIGS is well suited to "smart" crop-protection schemes that respond to real-time pest monitoring, weather forecasts, and genomic surveillance of pathogen populations. For example, if a new virulent strain of a fungal pathogen emerges, researchers can quickly design a new dsRNA sequence targeting a strain-specific gene and deploy it as a spray within a single growing season, far faster than breeding a resistant cultivar.

Integration with other biotechnological tools, such as gene editing to validate target genes or marker-assisted breeding to stack SIGS-compatible traits, can further broaden the utility of the technology. In developing regions, where access to proprietary seeds or complex biotech traits may be limited, SIGS offers a path to deploy RNA-based protection across multiple locally adapted varieties without requiring genetic modification of each cultivar. Nevertheless, responsible development is crucial. Robust biosafety assessments, transparent communication with growers and consumers, and clear labelling of RNA-based products will be necessary to maintain public trust and regulatory goodwill. Ongoing research should focus on improving delivery efficiency, extending field persi-

stence, minimising off-target effects, and reducing production costs, so that SIGS can transition from a promising laboratory tool to a mainstream, economically viable option for crop protection worldwide. Spray-induced gene silencing represents a powerful, RNA-driven paradigm for managing pests and diseases in agriculture. By harnessing the natural RNAi machinery of pathogens and pests, SIGS delivers a targeted, non-transgenic, and environmentally friendly alternative to many conventional pesticides. As delivery technologies, regulatory frameworks, and manufacturing methods mature, SIGS is poised to become a key pillar of sustainable crop-protection strategies in the twenty-first century.

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The Wild Safflower (*Carthamus oxyacantha* M. Bieb.): Ecological, Biological and Conservation Perspectives

Dhanshree M. Ridhorkar, Ajay Baldaniya and Nikhil Pawar

Abstract

Carthamus oxyacantha M. Bieb. (wild safflower), a thorny annual herb of the family Asteraceae, occupies a strategically critical position at the intersection of evolutionary plant biology, agroecosystem dynamics, and genetic resource conservation. Distributed across the semi-arid and disturbed landscapes of South Asia, Central Asia, and the Middle East, this species functions simultaneously as a crop wild relative (CWR) of cultivated safflower (*C. tinctorius* L.) and as an ecologically resilient ruderal colonizer. Despite its recognized value as a reservoir of stress-tolerance genes and bioactive phytochemicals, *C. oxyacantha* remains substantially underrepresented in mainstream conservation frameworks. The need for contemporary ecological, biological, and conservation knowledge on *C. oxyacantha*, integrating field data, molecular evidence, and phytochemical profiles to underscore the urgency of its systematic evaluation and protection in an era of accelerating climate change and genetic erosion must be studied.

Introduction

Carthamus oxyacantha M. Bieb., commonly designated as wild safflower or prickly safflower, is one such CWR of immense agronomic and ecological consequence. As the closest wild relative of the cultivated safflower (*Carthamus tinctorius* L.), an oilseed crop cultivated across more than 60 countries and valued for its high linoleic acid content (>70%), *C. oxyacantha* serves as a living bridge between domesticated germplasm and evolutionary heritage. The species is distributed predominantly across northern India, Pakistan, Afghanistan, Iran, Central Asia, and parts of the Mediterranean, where it thrives in disturbed soils, roadsides, fallow fields, and semi-arid scrublands. Despite its scientific significance, *C. oxyacantha* has attracted considerably less scholarly focus compared to other CWRs such as wild wheat or wild rice relatives. With growing evidence of its pharmacological potential, its role in agroecological weed dynamics, and its vulnerability to herbicide-driven habitat loss, an integrated, evidence-based review of *C. oxyacantha* becomes not merely timely but essential.

Taxonomy and Botanical Characteristics: *C.*

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oxyacantha belongs to the tribe Cardueae within the family Asteraceae. First formally described by Marschall von Bieberstein in 1808, the species has been synonymized in some regional floras as *Carduncellus oxyacantha*, reflecting ongoing taxonomic revision within the *Carthamus* complex. Molecular phylogenetic analyses, utilizing ITS and trnL-F chloroplast regions, confirm C. oxyacantha as a member of the diploid clade (2n = 24) most ancestrally related to *C. tinctorius*, likely representing its progenitor species. Morphologically, *C. oxyacantha* is a highly branched annual herb ranging from 20 to 90 cm in height, distinguished by deeply lobed, spiny-margined leaves, and yellow to pale-orange tubular florets enclosed within prominently spinescent involucral bracts.

Table 1: Taxonomic Classification of *Carthamus oxyacantha* M. Bieb.

Taxonomic Rank	Classification
Kingdom	Plantae
Order	Asterales
Family	Asteraceae
Genus	*Carthamus* L.
Species	*Carthamus oxyacantha* M. Bieb.
Common Name	Wild Safflower / Prickly Safflower
Chromosome No.	2n = 24

The achenes (cypselas) are white to creamy-brown, approximately 5-7 mm long, often lacking a pappus, a feature that distinguishes them from most other *Carthamus* species. The plant exhibits an indeterminate flowering pattern that extends the reproductive window across 6-10 weeks, conferring a fitness advantage in unpredictable environments.

Ecological Distribution and Habitat Dynamics: *C. oxyacantha* occupies a broad but discontinuous geographic range extending from the Indus Plains of Pakistan and northwestern India through Afghanistan, Iran, Turkmenistan, and into parts of Turkey and Greece. Species Distribution Modeling (SDM) using MaxEnt algorithms indicates that the species' core climatic niche is characterized by mean annual temperatures of 18-28°C, annual precipitation of 200-600 mm, and high solar radiation regimes typical of semi-arid steppe and Mediterranean-type biomes (Hosseini *et al*., 2020). Ecophysiological studies indicate that *C. oxyacantha* employs C_3 photosynthesis augmented by enhanced root hydraulic conductivity during water-deficit periods, allowing soil moisture extraction from depths of up to 1.2 meters (Basu *et al*., 2022). In heavily irrigated agroecosystems of the Punjab region, the plant functions as a competitive weed in wheat (*Triticum aestivum* L.) and chickpea (*Cicer arietinum* L.) fields, causing yield reductions of 18-35% at high infestation densities of >25 plants m^{-2} (Khan *et al*., 2022).

Biological Attributes and Genetic Significance

Reproductive Biology and Seed Ecology: *C. oxyacantha* is a predominantly outcrossing species with a self-incompatibility mechanism mediated by sporophytic pathways, promoting high levels of heterozygosity within populations. Pollination is largely entomophilous, with documented visits from Hymenoptera, Diptera and Lepidoptera. Seed dormancy is reported to be shallow, with germination rates

of 73-88% recorded under optimal temperature (20-25°C) and moisture conditions, while seeds retain viability in soil seed banks for up to 3-5 years. The species produces 50-150 seeds per plant under natural field conditions, with inter-population variability correlating strongly with soil fertility and precipitation patterns. Seed oil content ranges from 18 to 32%, with linoleic acid constituting 60-78% of total fatty acids, a profile closely approaching that of its cultivated counterpart, underscoring its value for biofortification programs (Basu *et al*., 2022).

Genetic Diversity and Crop Improvement Potential: Population-level genetic analyses using SSR (Simple Sequence Repeat) and RAPD markers across 42 accessions from Pakistan, India, and Iran demonstrated moderate to high genetic diversity (Shannon Index H = 0.34-0.52), with geographic distance and altitudinal gradient emerging as the primary drivers of population differentiation. Pre-breeding programs at ICARDA (International Center for Agricultural Research in the Dry Areas) and the National Bureau of Plant Genetic Resources (NBPGR), New Delhi, have employed *C. oxyacantha* germplasm to introgress alleles conferring resistance to Alternaria leaf spot (*Alternaria carthami*), Fusarium wilt, and aphid infestations into commercial safflower lines (Sharma & Rao, 2021). The species also harbors quantitative trait loci (QTL) associated with delayed leaf senescence and elevated carotenoid biosynthesis, traits with direct implications for both agronomic performance and nutritional quality (Basu *et al*., 2022).

Phytochemical Profile and Pharmacological Relevance: The pharmacological scrutiny of *C. oxyacantha* has intensified markedly over the past decade. Ethnobotanical surveys across Pakistan, Afghanistan, and Iran document its traditional use in treating inflammation, urinary tract disorders, hepatic ailments, and as a galactagogue (milk-inducing agent) in nursing mothers.

Table 2: Major Phytochemical Classes Identified in *Carthamus oxyacantha* and their Reported Biological Activities

Compound Class	Representative Compounds	Reported Activity
Flavonoids	Luteolin, Kaempferol	Antioxidant, Anti-inflammatory
Fatty Acids	Linoleic acid (72-80%)	Cardiovascular protection
Alkaloids	Serotobenine	Neuroprotective
Phenolics	Chlorogenic acid	Antimicrobial, Antioxidant
Terpenoids	β-sitosterol	Anti-cholesterol

Methanol and ethanol extracts of *C. oxyacantha* seeds and leaves have demonstrated IC_{50} values of 28.4-43.2 µg mL^{-1} in DPPH radical scavenging assays, with total phenolic contents ranging from 41.2 to 68.7 mg GAE g^{-1} dry weight: values comparable to *Carthamus tinctorius* petals. Anti-inflammatory activity assessed via COX-2 inhibition assays revealed significant downregulation at concentrations of 50-100 µg mL^{-1} attributable primarily to the flavonoid fraction.

Conservation Status, Threats and Challenges

Regional Conservation Status: The conservation status of *C. oxyacantha* has not been assessed by the IUCN Red List at the global level, representing a significant gap in international conservation policy. Regional assessments, however, paint a more nuan-

ced picture of localized vulnerability (Dempewolf *et al*., 2023).

Table 3: Conservation Status of *Carthamus oxyacantha* Across Key Range Countries

Region	Threat Level	Primary Threat	Source
Pakistan (Punjab)	Vulnerable	Herbicide drift	Khan *et al*., 2022
NW India	Near Threatened	Crop expansion	Sharma & Rao, 2021
Iran (Zagros)	Least Concern	Overgrazing	Hosseini *et al*., 2020
Central Asia	Data Deficient	Climate shift	Dempewolf *et al*., 2023

Major Threats

The primary threats confronting *C. oxyacantha* include: (i) intensive herbicide use in agricultural systems, particularly broad-spectrum ALS-inhibiting herbicides (e.g., clodinafop-propargyl, sulfosulfuron) that eliminate weedy Asteraceous populations in wheat fields without species selectivity (Khan *et al*., 2022); (ii) land conversion and monoculture expansion reducing the ruderal and marginal-land habitats the species depends upon; (iii) genetic erosion through unregulated collection and displacement by invasive exotic ruderals; and (iv) climate-driven phenological mismatches between flowering periods and pollinator activity windows, which may reduce reproductive success under warming scenarios (Hosseini *et al*., 2020).

Conservation Strategies and Future Directions

A multi-pronged conservation framework integrating both ex situ and in situ components is essential for the long-term security of *C. oxyacantha* genetic resources. On the ex situ front, systematic collection campaigns targeting priority regions of high allelic diversity: particularly the Baluchistan plateau, Zagros piedmonts, and Hindu Kush foothills, should be conducted before further habitat degradation. Collected accessions must be deposited in internationally accessible gene banks, including the Svalbard Global Seed Vault and FAO-registered national collections, with robust genomic passport data (Dempewolf *et al*., 2023). Agrienvironment schemes that economically incentivize farmers to tolerate low-density populations in field margins could simultaneously serve biodiversity and pollinator habitat objectives (Sharma and Rao, 2021). Additionally, the development of herbicide-tolerant CWR buffer zones around safflower cultivation areas would reduce genetic contamination risks between wild and cultivated *Carthamus* genotypes while preserving wild populations. From a research perspective, whole-genome sequencing of diverse *C. oxyacantha* accessions would dramatically accelerate the identification of functional genes for abiotic stress tolerance and disease resistance, facilitating targeted pre-breeding. Transcriptomic analyses under simulated drought and heat stress conditions have already identified 312 differentially expressed genes in preliminary studies (Basu *et al*., 2022), offering a molecular roadmap for precision introgression into commercial safflower.

Conclusion

Carthamus oxyacantha exemplifies the underappreciated biodiversity value of weedy, semi-arid taxa simultaneously a competitive agricultural weed and an irreplaceable reservoir of genetic and

phytochemical diversity. Climate change, agricultural intensification, and conservation underdocumentation collectively imperil this species despite its apparent regional ubiquity. Three conclusions emerge from the evidence: *C. oxyacantha* harbors untapped genetic and biochemical resources relevant to sustainable agriculture and pharmaceutical development; its populations face regionally differentiated yet globally significant threats requiring coordinated conservation response; and existing research remains fragmented, necessitating a collaborative, transnational agenda to realize its full potential as a model CWR. Future priorities must include population genomics, phylogeographic mapping, and climate-integrated conservation planning: ensuring this species endures not as a weed of forgotten margins, but as a living genetic legacy for plant breeders, ecologists, and pharmaceutical researchers alike.

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Forest Wealth, Tribal Wealth: The Importance of Non-Timber Forest Products in Local Economies

Gautam Dashrath Kelkar, Lalit Upadhyay and Dayanand Sai Painkra

Abstract

Non-Timber Forest Products (NTFPs) include a wide range of biological materials harvested from forests, excluding industrial round-wood. They provide crucial economic support for around 1.6 billion forest-dependent people worldwide, with a formal market value exceeding USD 88 billion annually, and potentially 2-3 times more through informal channels (FAO, 2020). NTFPs are particularly vital for indigenous and tribal communities in tropical regions, addressing food security, health, and income. This review explores the ecological diversity, economic contributions, conservation, and governance of NTFP-based economies, focusing on South Asia, the Amazon Basin, and Sub-Saharan Africa, using data from studies published between 2018 and 2024. The findings highlight ongoing inequities in NTFP value chains and the potential of community forest rights to enhance tribal welfare.

Introduction

Forests are vital ecosystems that provide far more than timber and carbon; they serve as essential sources of food, medicine, and cultural heritage for millions of people reliant on tropical and subtropical forests. Non-Timber Forest Products (NTFPs) include a variety of materials such as medicinal herbs, wild fruits, fungi, honey, and fibers, offering both subsistence and commercial value (Shackleton *et al.*, 2022). Although recognized in frameworks like the UN Sustainable Development Goals and the Kunming-Montreal Global Biodiversity Framework, NTFP-dependent communities often remain marginalized from the economic benefits of their labor and knowledge. Intermediary traders capture a significant portion of market profits, leaving primary collectors, often women and lower-income households, with minimal earnings (Rai and Sarkar, 2021). This review highlights the ecological, economic, and governance aspects of NTFP economies to support equitable policy reform.

Classification and Ecological Diversity of NTFPs

The Food and Agriculture Organization (FAO, 2020) defines Non-Timber Forest Products (NTFPs) as biological goods, excluding wood-derived from forests and trees. This includes produc-

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ts from plants, fungi, and animals, categorized by consumptive and non-consumptive uses. Tropical moist forests, covering about 1.8 billion hectares and home to over 50% of terrestrial species, offer the richest NTFP diversity. In India, the Ministry of Tribal Affairs recognizes 87 categories of Minor Forest Produce (MFP) under the Minimum Support Price scheme, sourced from over 3,000 plant species in tribal areas (FAO, 2020).

The phenological availability of NTFPs aligns closely with seasonal forest dynamics. Tribal communities have developed advanced Indigenous Ecological Knowledge (IEK) to manage harvests and extraction areas, a practice now seen as informal common-pool resource governance. However, disruptions from forest enclosure, tenure insecurity, and climate changes threaten both NTFP availability and the sustainability of these knowledge systems (Shackleton *et al*., 2022).

Economic Significance in Tribal and Local Economies

Household Income Contribution and Regional Profiles: The economic importance of NTFPs to tribal communities is both substantial and chronically underestimated in national accounts, which capture only formal market transactions. A comprehensive meta-analysis of 51 case studies across tropical forest regions found that NTFPs contribute 22-65% of total household income in forest-dependent families, with the highest shares, reaching 60-80%, recorded in communities lacking formal employment, irrigated agriculture, or government transfer mechanisms (Wunder *et al*., 2020). In India's tribal belt spanning Odisha, Jharkhand, Chhattisgarh, and Maharashtra, NTFPs support the livelihoods of over 100 million people, generating an estimated annual market value of USD 24 billion inclusive of informal subsistence flows (Sahu *et al*., 2022).

Tendu (*D. melanoxylon*) leaf alone generates seasonal employment for approximately 6 million tribal collectors across central India, with annual state procurement exceeding INR 35 billion (Sahu *et al*., 2022). In the Amazon, Brazil nut (*Bertholletia excelsa*) kernels, delivering 14-17 g of protein per 100 g and 100% of the daily selenium requirement in a single serving, represent both a critical nutritional resource and a commercially significant export commodity for remote extractivist communities beyond the reach of modern supply chains (Peres *et al*., 2021).

Gender Dimensions of NTFP Economies: NTFP collection is largely female labor, with women representing 60-80% of primary collectors in South Asia and Sub-Saharan Africa, but receiving only 30-45% of the proceeds due to exclusion from market transactions and governance (Rai and Sarkar, 2021).

Table 1: Classification of Major NTFP Categories with Representative Species and Primary Uses

NTFP Category	Representative Species / Products	Primary Use
Edible Plants & Fruits	Mahua (*Madhuca longifolia*), Amla (*Phyllanthus emblica*), Tendu (*Diospyros melanoxylon*)	Nutrition, food security, fermented beverages
Medicinal Plants	Ashwagandha (*Withania somnifera*), Giloy (*Tinospora cordifolia*), Neem (*Azadirachta indica*)	Traditional medicine, herbal commerce
Resins & Gums	Sal resin (*Shorea robusta*), Gum karaya (*Sterculia urens*), Frankincense (*Boswellia papyrifera*)	Industrial adhesives, food emulsifiers, export
Fibers & Canes	Bamboo (*Bambusa spp.*), Sabai grass (*Eulaliopsis binata*), Rattan (*Calamus spp.*)	Handicrafts, construction, textiles
Honey & Bee Products	Rock bee (*Apis dorsata*) honey, beeswax	Nutrition, cosmetics, traditional pharmacopoeia
Dyes & Tannins	Lac (*Kerria lacca*), Harda (*Terminalia chebula*)	Textile dyes, leather tanning, export trade

Table 2: Economic Contribution of NTFPs to Tribal Household Incomes across Selected Global Regions

Country / Region	Primary NTFP	Household Income Share	Annual Value (USD)
Odisha, India	Tendu leaves, Mahua	45-65%	~180 million yr^{-1}
Jharkhand, India	Lac, Sal seeds	38-52%	~140 million yr^{-1}
Congo Basin, DRC	Bush meat, wild fruits	60-80%	~1.1 billion yr^{-1}
Amazon Basin, Brazil	Brazil nuts, rubber	30-55%	~430 million yr^{-1}
Tigray, Ethiopia	Frankincense, honey	50-70%	~210 million yr^{-1}

Table 3: Key National Policy Frameworks for NTFP Management and their Impacts on Tribal Communities

Country / Framework	Key Provision	Impact on Tribal NTFP Rights
India: Forest Rights Act, 2006	Community Forest Resource (CFR) rights over NTFP collection, sale, and management	~50,000 CFR rights recognized; ~2.8 million individual titles issued by 2023
India: Van Dhan Scheme, 2018	Tribal cooperative clusters for value addition and marketing of 87 MFPs under MSP	~50,000 Van Dhan Vikas Kendras operative; USD 200 M+ in tribal income generated
Brazil: RESEX (Extractive Reserves)	Protected areas co-managed by extractivist communities for sustainable NTFP harvesting	>90 reserves covering 15.2 million ha; ~75,000 families supported

When women access markets directly, their incomes from NTFPs increase by 40-85%, improving household food security and child nutrition. Moreover, women possess more conservation-oriented traditional ecological knowledge regarding medicinal plants, which highlights the ecological and social cost of losing female knowledge (Rai and Sarkar, 2021).

NTFPs as Instruments of Forest Conservation

The conservation economics of non-timber forest products (NTFPs) are based on the idea that forests providing economic benefits to local communities are better protected than those where communities are excluded (Shackleton *et al*., 2022). Evidence shows that community-managed NTFP areas have 30-50% lower deforestation rates than state-managed forests, according to studies from 36 tropical landscapes (Wunder *et al*., 2020). For instance, Brazil's Extractive Reserves recorded an average deforestation rate of 0.12% per year from 2015 to 2022, compared to 0.89% in unprotected Amazon forests (Peres *et al*., 2021). However, this conservation benefit relies on secure community land tenure, effective governance, and competitive NTFP market prices compared to land conversion opportunities. When NTFP markets collapse, like the

natural rubber market in Malaysia, communities often switch to agriculture, highlighting that economic incentives, rather than cultural ties alone, drive conservation decisions (Wunder *et al*., 2020).

Policy Frameworks, Value Chain Inequities, and Governance

The governance architecture for NTFP-based tribal economies varies substantially across nations, reflecting divergent forest tenure histories, colonial legal legacies, and state-community relations. Table 3 presents key policy frameworks and their documented impacts on tribal NTFP rights. India's Forest Rights Act (2006) represents the most expansive statutory attempt globally to vest Community Forest Resource (CFR) rights over NTFP collection, use, and sale in tribal gram sabhas. Implementation has been deeply uneven: only approximately 50,000 CFR rights have been recognized against an estimated eligible area of over 40 million hectares, owing to bureaucratic resistance and inadequate awareness (Sahu *et al*., 2022). In terms of value chain equity, primary tribal collectors in the tendu leaf market capture only 4-6% of the final consumer price of the processed bidi tobacco product, a concentration of value at intermediary nodes that technology-mediated interventions are beginning to disrupt through mobile price discovery platforms, state procurement at Minimum Support Price, and Van Dhan Vikas Kendras that have generated over USD 200 million in additional tribal income through value addition and direct marketing (Rai and Sarkar, 2021).

Challenges and the Path Forward

Forest degradation reduces NTFP availability by 25-60% in selectively logged secondary forests compared to intact primary stands, compounding the impacts of tenure insecurity that incentivize over-extraction by collectors lacking guaranteed future access rights (Shackleton *et al*., 2022). Adulteration, the absence of standardized grading systems, and the limited reach of Geographical Indication (GI) tags and organic certification pathways effectively confine most tribal NTFP produce to low-value commodity markets. Climate change compounds these pressures: phenological shifts have advanced the Mahua (*M. longifolia)* flowering-to-fruiting window by 15-22 days over three decades in central India, while drought has reduced frankincense (*B. papyrifera*) tapping productivity by 30-40% per tree in Ethiopia between 2010 and 2022, threatening approximately 100,000 livelihoods directly (Wunder *et al*., 2020). Integrating climate-resilient NTFP portfolio diversification, assisted natural regeneration of key species, and participatory phenological monitoring into community forest management plans is now a recognized conservation and livelihood adaptation priority (Shackleton *et al.*, 2022).

Conclusion

Non-Timber Forest Products (NTFPs) are vital for the economies, ecologies, and cultural identities of tribal and forest-dependent communities They contribute significantly to household income, particularly for women, yet remain undervalued and underprotected. Key findings include: NTFPs account for 22-80% of income in the most dependent communities, with women facing structural barriers; secure community tenure and access to markets are crucial for transforming NTFP systems from subsistence to sustained welfare; and climate change is increasingly threatening NTFP availability, necessitating urgent adaptive management strategies. Future efforts should focus on recognizing community forest rights, enhancing value-addition cooperatives, and developing climate-resilient NTFP strategies to convert forest wealth into durable tribal benefits.

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Switching Genes On and Off: Transcription Factors in Plant Biology

Hardik N. Patel and Bhavik R. Gondaliya

Introduction

Climate changes pose significant challenges to crop production worldwide. Recent data have shown that the Global human population has surpassed 8 billion mark. Furthermore, UN suggested that the figure could potentially escalate to approximately 8.5 billion by the year 2030 and may reach 9.7 billion by 2050. Environmental changes pose a significant obstacle for the agriculture in order to fulfil the increasing global demand for food production. Raising temperatures and increased frequency of change in weather patterns show major impact on crop growth, development and yield. Abiotic stress poses a significant threat to global food security, with an estimation of 70% of yield losses in major crops (Cramer *et al*., 2011). According to studies, there could be a 3-10% drop in crop yield for every degree Celsius that the world mean temperature rises. Globally, drought, heat waves, and unpredictable rainfall patterns have already resulted in significant production loss. Wheat yields in a number of provinces, including Punjab, Haryana, and Uttar Pradesh (UP), decreased by 10-35% as a result of an extended heatwave. Additionally, physiological activities including photosynthesis, respiration, and reproductive development can be directly impacted by high temperatures, which can result in yield losses and quality degradation. Abiotic stress affects several facets of plant growth, development, and productivity in addition to the cellular level. Abiotic stress can affect root morphology and architecture, decrease leaf area and chlorophyll content, hinder seed germination, slow plant development rates, and lower crop production and quality. Furthermore, prolonged exposure to abiotic stress can weaken plants, making them more susceptible to various biotic stress such as pest and diseases infestation (Farooq *et al*., 2014). Understanding the molecular mechanisms underlying plant responses to abiotic stress is essential for developing strategies to enhance stress tolerance and improve crop resilience. Plants have evolved sophisticated mechanisms to perceive and respond to abiotic stress at the molecular, cellular, and physiological levels. Plants being sessile organisms, have the need to protect themselves from various biotic and abiotic stresses surrounding them to survive in the adverse conditions, plants have various mechanisms which include tolerance, avoidance and resistance. These mechanisms are governed by various biochemicals which are the products of many genes that are expressed under specific conditions.

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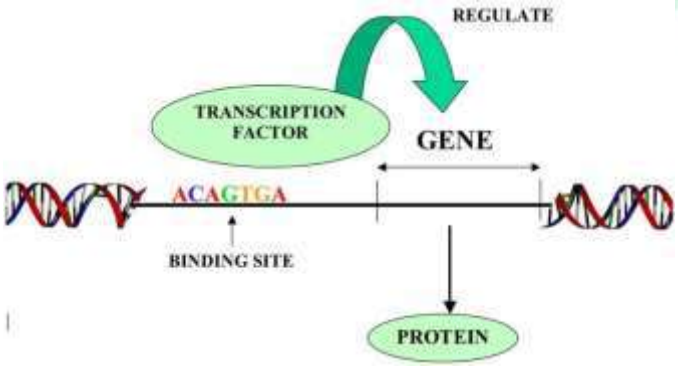
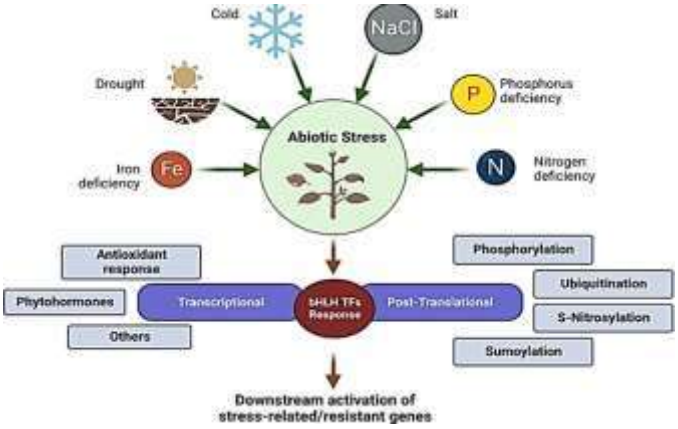
The expression of these stress responsive genes is regulated by specialized proteins called transcription factors (TF). They act as molecular switches, capable of either activating or repressing the transcription of targeted genes. These master regulators (TFs) binds to specific DNA sequence (promotor region) of a gene for transcript-ion initiation and regulation of gene expression. Large complements of TF genes make up the plant's genome. More than 1500 transcription factors, or more than 5% of the entire genome complement, are encoded by the model plant Arabidopsis thaliana. In plants, a number of TF families have been found and thoroughly investigated. Dehydration responsive element binding (DREB), basic leucine zipper (bZIP) domain, MYB, NAC, zinc-finger, heat shock factors (HSF), WRKY, and nuclear factor-Y (NF-Y) have all been identified as important components of stress tolerance processes (Shahzad *et al*., 2021).



Various Transcription Factors Family

AP2/ERF family: The AP2/ERF family is one of the largest and most diverse groups of plant transcription factors. Members of this family share a conserved DNA-binding region that enables them to regulate genes involved in plant growth and stress responses. Based on their structural features, AP2/ERF transcr-iption factors are divided into four major subfamilies: AP2, ERF, DREB, and RAV. Each subgroup recognizes specific DNA sequences and regulates different biological processes. Proteins belonging to the AP2/ERF family are known to play important roles in plant responses to environmental stresses such as drought, cold, heat, and mechanical damage. They also participate in hormone-mediated signaling pathways, particularly those involving ethylene.

B3 family: Another class of transcription factors unique to plants is the B3 family, which is distinguished by a conserved DNA-binding domain. These proteins control genes essential for hormone responses and plant growth. Plant hormones like auxin and abscisic acid are linked to signaling pathways that require B3 transcription factors. They aid in the regulation of activities such as stress adaption, embryonic development, and seed maturation through various pathways. The LAV group and the REM group are two significant subgroups of the B3 family that both aid in the control of plant development.



WRKY family: The WRKY transcription factor family is well recognized for its function in stress

responses and plant defense (Jiang *et al*., 2017). First WRKY TF, Sweet potato factor1 (SPF1) gene, was discovered in 1994 in *Ipomea batatas*. These proteins can attach to particular DNA regions known as W-box elements thanks to a conserved sequence pattern. Genes related to biotic stressors like pathogen infection and abiotic stressors like drought and high temperatures are regulated by WRKY transcription factors. WRKY proteins enable plants to react quickly to environmental challenges by either activating or suppressing defense-related genes. The DNA binding domain (DBD) consists of conserved WKRY heptapeptide amino acid sequence WRKYGQK located within N-terminal b strand. Presence of this conserved sequence is the characteristic feature of the WRKY protein. WRKY TF recognize the W-Box sequence in the promotor region of the specific stress response gene and regulate its expression. The W-Box sequence, which is commonly known as the target recognition sequence for WRKY domains, consists of the nucleotide sequence TTTGACY, where Y can be either T or C.

NAC family: The NAC family represents another large group of plant transcription factors. These proteins function as dimers, meaning that two protein molecules associate together to perform their regulatory role. NAC transcription factors are involved in many important biological processes, including plant development, aging of leaves, and responses to environmental stress. They also participate in regulating genes associated with cell division, tissue differentiation, and stress tolerance. NAC domain consists of approximately 150 amino acids located within the N-terminal region which function is to facilitate DNA binding within the cell nucleus and promote dimer formation; C terminal site of the NAC domain plays a crucial role in transcriptional regulation mechanism. X-ray crystallographic studies made on ANAC019 (Arabidopsis thaliana NAC019) and SNAC1 (stress responsive NAC1 of rice) have shown that the structure of NAC domain consists of a novel transcription factor fold comprising twisted beta-sheet surrounded by a few helical elements (Simpson *et al*., 2003).

SBP (SPL) family: The SBP (SQUAMOSA Promoter Binding Protein) family is a smaller group of transcription factors that play important roles in plant growth and development. These proteins are known to regulate flowering time, plant architecture, and nutrient uptake. Members of this family are particularly important in controlling flower development and copper uptake, which are essential processes for plant reproduction and metabolism.

Role of Transcription Factors in Plant Stress Tolerance

Plants often face environmental challenges such as drought, salinity, extreme temperatures, and attacks by pathogens. In contrast to animals, plants are unable to relocate from unfavorable circumstances. As a result, they depend significantly on molecular regulatory systems, including transcription factors, to adapt and endure. Numerous transcription factors activate stress responsive genes

that assist plants in managing adverse situations. For instance, specific transcription factors oversee the production of protective proteins, osmolytes, and antioxidants that mitigate cellular damage during stressful periods. Others regulate the expression of genes that are crucial for water conservation, ion transportation, and metabolic adjustments. Through these mechanisms, transcription factors are essential in strengthening plant resilience to environmental stresses. Investigating these regulatory pathways has emerged as a key focus of research aimed at developing crops capable of better enduring shifting climate conditions.

Importance of Transcription Factors in Crop Improvement

The exploration of transcription factors has become increasingly vital in contemporary agricultural biotechnology. Since transcription factors govern extensive arrays of genes, altering a single transcription factor can affect numerous biological pathways at once. Scientists are investigating methods to modify transcription factors to enhance crop characteristics such as drought resistance, disease immunity, nutrient utilization, and overall yield. For instance, incorporating stress responsive transcription factors into agricultural plants can boost their capability to endure severe environmental challenges. Progress in molecular biology and genome editing techniques has enabled more in-depth examination of transcription factor networks. These advancements are creating fresh possibilities for the development of climate-resilient crops and promoting global food security.

Conclusion

Important features include the identification of stress-responsive transcription factors (TFs), their regulation of stress-responsive genes, their connection with stress signaling pathways, and their alteration of physiological and biochemical processes. We also discussed how TFs help plants be resilient and stress-tolerant under challenging environmental conditions. Understanding the role of TFs in the abiotic stress response is necessary to decipher the molecular mechanisms behind plant stress adaption. TFs serve a crucial role in controlling the expression of stress-responsive genes, coordinating complex signaling pathways and physiological responses to outside stimuli. By elucidating the functions of TFs, scientists may develop techniques for producing stress-tolerant plants that are more adaptable to adverse environ-mental conditions, thereby addressing problems associated with global food security. The insights gained from studying TF-mediated abiotic stress responses have significant implications for agricul-ture and environmental sustainability. Through the use of TF information, scientists may create crop varieties that are more resilient to stress, decreasing yield losses and boosting agricultural output in the face of environmental degradation and climate change.

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Antimicrobial and Antibiofilm Activity of *Foeniculum vulgare* Miller

Kirti Hari Patil and S. R. Kshirsagar

Introduction

The world is currently experiencing an antibiotic resistance crisis as the microbes are becoming resistant to antibiotics. According to WHO, "Antibiotic resistance leads to higher medical costs, prolonged hospital stays, and increased mortality". Novel antimicrobial compounds are therefore urgently required to treat infectious diseases. In India, the plant extracts have been assessed for a number of medicinal qualities. Plant extracts are being studied for their antimicrobial action in addition to their therapeutic qualities, which include anti-inflammatory, nootropic, antianxiety, anti-aging, anticancer and antiviral activities. The anti-bacterial action of chemicals produced from plants has been shown in numerous investigations (Srivastava *et al*., 2021). Medicinal herbs have a few adverse effects, as they possess antioxidant properties as compared to synthetic medications; they reduce the toxicity of other pharmaceuticals. Moreover, the natural components enhance biological balance and prevent drug accumulation. As a result, a variety of illnesses can be treated by using these plants. Globally, more than 5,000 of the approximately 422,000 flowering plant species are known to have therapeutic properties.

In the food, pharmaceutical, cosmetics, and healthcare sectors, fennel seeds play a crucial role. Although native to the Mediterranean region, fennel grows well in temperate climates. Due to the abundance of wild fennel, the earliest people on Madeira named this plant "Funchal" which combines the word funcho (fennel) with a suffix. Fennel seeds were also grown in Spanish gardens, and eventually the practice made its way to California, where it started to grow as a wild herb (Magon *et al*., 2025). The medicinal plant *Foeniculum vulgare* Miller, also referred to as fennel or saunf, is a member of the Umbelliferae (Apiaceae) family and has been utilized by humans since ancient times. This plant's seeds are used as an aromatic to improve the flavor of Indian tea and prepared foods. Also referred to as a digestive, it is frequently used as a home cure for stomach issues like flatulence and indigestion. Ayurveda, a traditional Indian medical practice, also uses the seeds of *Foeniculum vulgare* Miller. Additionally, *Foeniculum vulgare* Miller has been shown in numerous studies to have anti-inflammatory, anticancer, cytoprotective, hepato-protective, hypoglycemic, estrogenic, and memory-enhancing qualities (Badgujar *et al*., 2014), making it a possible therapy option for a number of illnesses.

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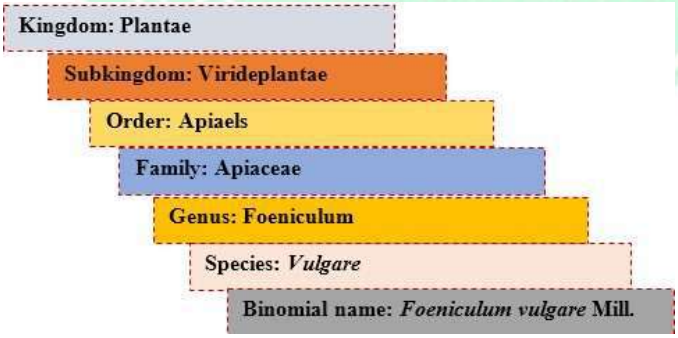
An innovative method for assessing the antibacterial qualities of plant extracts or isolated plant components is antibiofilm activity. An organized bacterial community encased in a self-made polymer matrix composed of polysaccharide, protein, and DNA is called a biofilm. Bacteria develop biofilm under stressful situations, such as extreme pH and temperature, high and low salt concentrations, inadequate feeding, and the presence of antibiotics. Interestingly, biofilms are resistant to every antibiotic that is currently on the market, which leads to persistent infections (Roy *et al.*, 2018). Even the body's defense mechanism finds it more difficult to combat biofilm since it is difficult to phagocytose. About 100,000 deaths in the US alone are attributed to Candida albicans biofilms, according to Nobile and Johnson.

Taxonomic Classification



Botanical Description

Green and white fennel plants with yellow flowers and bulbous leaves. It is ribbed, oval in shape, double achene, and initially bluish before turning brownish grey. The crunchy both the bulb and the seeds of the fennel plant have a subtle, licorice flavor. However, the essential oils in seed blossoms make them more active (Rizvi and Ali, 2016). Along with the similar-tasting anise, it is a very aromatic and peppery plant used in cooking and one of the main components of absinthe. For optimal development and yield, fennel needs a cool, dry climate. A chilly, dry climate will produce high-quality, high-yielding seeds.

Therapeutic Aspects of Fennel Seeds

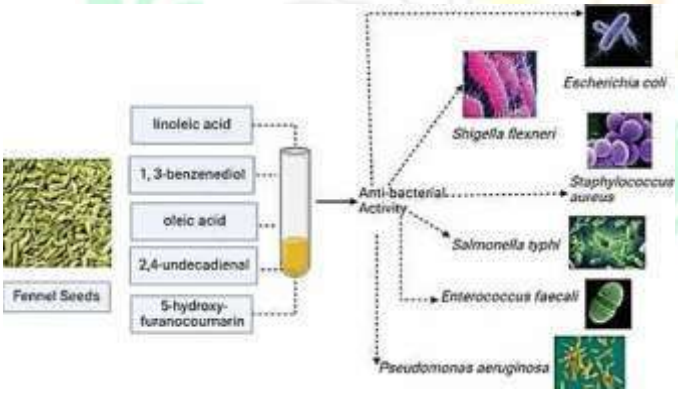
Fennel is a flavorful and aromatic herb that can be used both in cooking and therapeutically (Rabail *et al.*, 2022). For thousands of years, fennel has been used in traditional medicine to treat a wide range of medical conditions. Fennel was thought to have calming qualities in the fifth century, and from the ninth to the fourteenth centuries, it was said to have numerous health advantages. Fennel seed was thought to have the potential to improve vision by the Romans. The English thought the herb helped with digestion and relieved bloating. Since the 18th century, fennel has been used medicinally, and many studies have been conducted on the topic. Different parts of the fennel plant are used in both traditional and modern medicine to treat a variety of health

problems, including digestive disorders. It is also well-known for its therapeutic advantages in the treatment of pneumonia, kidney stones, diabetes, and other long-term illnesses. Additionally, fennel seeds are frequently added to cream-based dishes. The plant can be used to treat kidney and bladder problems because of its diuretic qualities. Additionally, it is used to reduce nausea and vomiting. In addition to treating chronic fever, the herbs can be used to treat obstruction of the gastrointestinal, urinary, respiratory, and hepatic tracts. Fennel seeds are utilized in various dishes and traditional curries. A modest amount of fennel adds a pleasant flavor to curries and is typically used to make flavor soups, Pastries, buns, sauces, meat dishes, and candies.

Antimicrobial and Antibiofilm Activity

Foeniculum vulgare Miller has been shown in numerous studies to have antibacterial properties, giving it a viable option for the creation of new antibiotics. An antimicrobial can be a bacteriostatic agent, which stops bacteria from growing, or a microbicide, which destroys bacteria. These medications are categorized according to the microorganisms they mostly target. Antifungals are used to treat fungi, whereas antibiotics are typically used to treat bacteria. It has recently been discovered that the essential oil (EO) from the leaves of *F. vulgare* Miller subsp. *vulgare* var. *vulgare* possesses strong antibacterial and antibiofilm qualities. EO was used to assess EO's antibacterial properties. It was found to be highly effective against strains of *S. typhimurium, P. aeruginosa, S. aureus* and *E. coli* with 100% mortality at 200 µg mL^{-1}. It was discovered that EO had antibiofilm activity against a strain of non-pathogenic mycobacterium at low concentrations. Additionally, the researchers conducted a chemical analysis of the EO and found significant amounts of the phenylpropanoid estragole (25.06%) and the monoterpene hydrocarbon α pinene (33.75%). These tiny terpenoids and phenylpropanoids, which have shown effectiveness in pure form, were credited by the authors with EO's antibacterial properties. Accordingly, when Marwa *et al*. investigated wild *F. vulgare* Miller cultivated in South Africa, they also found similar results (Khammassi *et al*., 2023). Another study found that EO derived from *F. vulgare* Miller from Italy had the strongest inhibitory effect on strains of *E. coli* that were resistant to ampicillin, ciprofloxacin, and gentamicin (D'Aquila *et al*., 2022). Research on strains that are resistant is more beneficial. Though EO has received the most attention, aqueous extracts have also shown significant antimicrobial and antibiofilm activity in a few studies. In one study, hydrolates formed as byproducts of distillation of *F. vulgare* Miller for EO were found to have substantial antibacterial action against Gram-positive, *S. aureus* and *Ent. faecalis* (Silha *et al*., 2020). The hydrolates were found to be ineffective against the fungus *Candida albicans* CCM 8186, however it did exhibit antibiofilm efficacy against *A. butzleri*, *A. cryaerophilus* and *S. aureus* strains. Following a chemical analysis of fennel hydrolate, 13 compounds were identified, with estragole and fenchone being

the most abundant. Estragole was discovered to be the primary odorant in fennel. Thus, aqueous hydrolates demonstrated antibacterial and antibiofilm activity in addition to EO. This might be because EO and hydrolates contain common phytochemicals. However, the authors claim that hydrolates contained fewer phytochemicals than EO. Alpha phellandrene, a monoterpene present in fennel essential oil, has strong antibacterial activity as well as biopesticide and antitumoral effects. According to Radice *et al*. (2022), suggesting that it may find use. Nevertheless, a different phytocompound called (-)-fenchone, a bicyclic monoterpene found in plant essential oils like *Foeniculum vulgare* Miller, had antifungal but no antibacterial properties.



Conclusion

More research on the antimicrobial and antibiofilm activities of purified compounds extracted from the plant *Foeniculum vulgare* Miller would strengthen its applicability in drug development. *Foeniculum vulgare* Miller is a cuisine spice of the Apiaceae genus that is widely cultivated in the world's tropical and temperate regions. Fennel seeds are primarily developed from dry and semi-dry regions in India. *Foeniculum vulgare* Miller has also been extensively studied for its antimicrobial activity. Fennel contains flavonoids, glycosides and other phytoconstituents present in it which used in medicinal ailments purpose. Phenolic compounds present in fennel can promote to the human health. Trans-anethole, estragole, fenchone and bioactive compounds kaempferol, quercetin, rosmarinic acid have been isolated from this plant and several associate with prospective human body mechanisms.

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Bytes and Books: Public Libraries Redefined

Mahesh Balasaheb Dushing, Gangaram Devram Mengal and Patel Amit Kumar

Introduction

In general, a library is a location where people can access knowledge and concepts. Information access is vital since it speeds up both individual and corporate educational development. The rights of individuals to obtain information at the appropriate time are the main emphasis of access to information. Regardless of a country's culture, ethnicity, language, etc., its significance is also regarded as a determining factor for its economic, social, and political development (Oyeronke, 2012). In India, public libraries were first established during the British era. In three of India's largest cities, public libraries were established in the middle of the nineteenth century. These three largest cities were Calcutta (now Kolkata), Madras (now Chennai), and Bombay (now Mumbai) (Bhattacharjee 2002). Although libraries have been present in India since antiquity, they served as knowledge repositories in temples, the courts of the country's rulers, and several institutions. As India is one of the world's largest countries by population, it is obvious that while increasing the population size, the problems and challenges increase due to various issues relating to literacy and education. Therefore, the public library makes an important contribution to overcoming these problems (Ghosh 2005). Libraries have contributed to the growth of literacy, education, and publishing around the world. Every country has a memoir of the rise of libraries, in which influential leaders, emperors, responsible people and philanthropists have worked tirelessly for the rise of public libraries. ICTs, or information and communication technologies, are a broad category of technological instruments and resources for information creation, distribution, storage, value addition, and management. Within Public libraries have a significant role to play in closing the digital gap. The caliber of Infrastructure, resources, personnel, information technology utilization, etc. in public libraries of With the exception of a few urban amenities, India is extremely impoverished. In comparison, each of these features was superior in academic, special and research libraries. Computer-ization will enable rapid communication, internet access, and more precise and superior user service. It is essential significance of developing a network that can reach even the most remote areas of the nation. During recent years though several public library systems have developed but the irony of the situation

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is that neither any effective public library system providing meaningful library services to the enormous rural masses nor an integrated chain of library network has so far developed in the country. There is an urgent need that Public libraries in India must shift its focus from collection to connection. Although Information & Communication Technologies (ICT) was introduced in rural development in the year 1986, rural Public libraries largely remained as a forgotten asset in the dissemination of information to the rural population. Secondly the IT policy formulated in the year 2000 shown little interest in the development of rural libraries.

The state of Indian Public Libraries and Their Untapped Potential

The emergence of public libraries in cities like Bombay, Madras, and Calcutta in the early to mid-nineteenth century helped to prepare the way for later library development. The modern idea of the public library in India has its roots in the British colonial era. However, libraries have existed in India from ancient times, acting as information repositories in temples, universities, and the courts of kings, even if they show the mark of Western influences (Patel and Kumar, 2001). With the enactment of the Madras Public Library Act in 1948, the first library law in newly independent India to provide public library services, the nation's public library development accelerated in the post-independence era. With the enactment of the Madras Public Library Act in 1948, the first library law in newly independent India for the provision of public library services, the nation's public library development accelerated in the post-independence era. A key player in the enactment of this law and an inspiration for the growth of public libraries across the nation was S.R. Ranganathan, an Indian pioneer in library and information science (LIS). Ranganathan promoted the creation of efficient public library systems to reach India's masses, even though he is best recognized in the West for his significant contributions to categorization theory. In the decades that followed, Ranganathan also served as an inspiration for the creation of library laws in other states. State governments are in charge of public libraries, but as of right now, only 11 states have official library laws. The Indian government sponsors the Raja Rammohun Roy Library Foundation (RRRLF), which serves as a coordinating body for the growth of public libraries, especially in rural areas, while states oversee public libraries (Dasgupta, 2000). To increase the availability of public library services in underserved areas, RRRLF collaborates with state governments and non-governmental organizations (NGOs). Yet the untapped potential is immense. The NML, launched in 2014, aimed to modernize and digitally link nearly 9,000 libraries, upgrade 35 State Central and 35 District Libraries as models, and

create a National Virtual Library of India. Recent initiatives like the Festival of Libraries and the "One Nation, One Library" concept are piloting a centralized repository across 13 high-profile libraries to make collections accessible nationwide. Community-run libraries in places like Bansa, UP and Spiti Valley show what is possible when libraries become safe, local hubs. They provide exam guides for youth, tailoring facilities and sanitary pad vending machines for women, and reading sessions for children who otherwise lack access. During the pandemic, such libraries turned into relief centers, distributing ration kits and health information. The vision articulated by library advocates is clear: public libraries can be community information centers, vocational training spaces, cultural centers, and polling stations that build an informed citizenry. For 1.39 billion Indians, that means moving from abstract constitutional rights to real participation through access to knowledge. The challenge now is to shift perception from "study halls" to dynamic community anchors, backed by trained staff, consistent state funding, and policies that treat libraries as essential public infrastructure rather than an afterthought. The potential is already proven in pockets.

Consolidation and expansion of Public Libraries network

In order to close the digital divide, the government should support the creation of communication access centers and provide public libraries with Internet access. The telecoms ministry has proposed opening cyber-cafés, and it would be a good idea to place them in any public library that is close by. It is the duty of public library authorities to guarantee that libraries and information networks are reasonably priced and as widely accessible as other public utilities. In a few years, the nation's public library network should surpass one lakh, and by 2020, it should meet IFLA criteria. The new and existing libraries should be planned with the minimum infrastructure to access electronic information over national and international networks and to access local information in multiple formats. The social entrepreneurs who are actively working on ICT may undertake pilot projects to connect rural villages to Internet and established Rural Public libraries network. Public libraries can use ICT to assist underprivileged communities in a number of ways

E-learning through Public libraries: In a country like India e learning has more relevance especially for higher education. A large percentage of target population are beyond the reach of formal education channels due to various inherent weaknesses of the system and lack of infrastructure. The initiatives may further benefit the rural folk who are the victim to leave formal education channels either due to lack of facilities or due to lack of commitments.

Use of ICT in Library Extension Programs: Libraries need to advertise their services in the neighborhood. Some people believe that libraries may not be necessary for those who are illiterate. It must be stated that those who lack literacy are not

ignorant. Many of them are very enlightened and open to fresh perspectives. Through their extension activities, which include lectures, discussions, film presentations, folk dramas, exhibitions, puppet performances, and book readings, public libraries could further educate all of them.

E-Governance/E-Commerce: The Gateshead Council Library in London is an illustration of a public library that has embraced the e-government project. Anyone with internet access who resides, works, or studies in Gateshead is able to utilize the library's services around-the-clock, seven days a week. The 66,000 library patrons in Gateshead can access the system by calling any nearby library using their current ticket number, which is a unique personal identification number that grants them complete access to the library's Internet service around-the-clock, seven days a week. The goal of the Pravara village PRAGATI project in Maharashtra's Ahmednagar district is to provide a wireless MAN solution (WMAN) to 100 villages with a combined population of over 2.5 lakh.It would enhance the quality of life and empower rural residents, particularly women. The seven-lane program will assist the villages in setting up local IT centers, distributing information about government programs, marketing agricultural products, health care, education, agro-processing, and economic development.

Education and Training for Staff: In order to provide online services for users of public libraries, training is essential. In order to fully utilize ICT technology in providing public library services, staff members must be encouraged to participate in continuing education programs and skill development. A full-time library professional must oversee the public libraries, and they should have benefits and working circumstances similar to those of their academic, research, and special library colleagues. A capable librarian who can arrange services in a way that is equitable for all segments of the community the library serves is most needed.

Conclusion

Public libraries have a moral obligation to give everyone access to information that can be used for national development, economic growth, education and self-empowerment. Additionally, public libraries are meant to assist community members in obtaining information about necessary materials and information literacy initiatives. Public libraries should work to get current and pertinent print and electronic resources on social, economic, political, and educational developments in order to increase community literacy.

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Flames of Pollution: Tackling Stubble Burning in Northern India

Marwan Reddy Chinnam and Manda Sai Krishna

Introduction

Stubble or residue is the left over/remaining material after the harvest of crop. In other words all the plant parts other than economically important material is known as residue. Around the globe, among all the crops most of the residue accounts from cereals and pulses. Considering in India, rice and wheat stands way front when we compare with other cereals and pulses. Both rice and wheat together contribute about 30% of global food needs by making it major source of food for billions of people around the world. India stands second in rice and wheat production after China, by producing 175.58 Mt of rice and 101.29 Mt of wheat per annum. Moreover, approximately rice covers an area about 44 million ha and wheat covers 29.5 million ha, which resembles the importance of both the crops in Indian agriculture. According to the Indian Agricultural Research Institute (IARI) in New Delhi, cereal crops produce the most residues, with 352 Mt. Paddy and wheat account for 34% and 22% of total production. Burning crop residue in situ is the easiest way to clear an agricultural field and begin land preparation for the succeeding crop. Stubble burning is deliberate act of burning the left over crop residues in the field in order to start land preparation for sowing of following crop. Rice wheat cropping pattern is prominent in India; precisely it is mostly followed in Indo-Gangetic plains of Haryana and Punjab which accounts largest quantity of stubble burning in India (Sain, 2020). Mostly, rice is harvested using combine harvester which leaves considerably more quantity of residue in the farm land itself. Lack of time to collect and make use of the left over material instead, farmer burn those residues so that land preparation can be started immediately to sow wheat crop in the month of November. Following the Green Revolution in India in the 1960s, the country's agricultural system saw a number of changes, including changes in government policies and farmer practices. Since then, there has been an annual increase in food production, especially in rice and wheat, to feed the nation's expanding population. As crop output rises, so does biomass production, which results in a large amount of residue remaining on the ground following crop harvesting. A significant amount of garbage is produced annually by leaves, stubble, straw, stems, and other agricultural leftovers 53% of cereal crop leftovers come from paddy, whereas 33% come from wheat. In 2010, 253 Mt of crop leftovers were produced.

Root Cause for Stubble Burning in India

Lack of time period between two successive crops:

Time/date of sowing is a fundamental and crucial agronomic activity in agriculture. Paddy should be

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sown in the second fortnight of May, transplanted in the second fortnight of June to the maximum of July 5th, and matured in November. Ironically, under the rice-wheat cropping schedule, the first two weeks of November are when the next wheat crop is sown, giving farmers no opportunity to properly manage rice straw. However, there are now late-sown types that can be planted up until the first week of December, leaving a maximum of 20 days between crops (Ravindra *et al*., 2018).

Lack of knowledge in stubble management: Despite the fact that farmers are unaware of residue management in short period, and they consider burning is the easiest method to get rid of crop remains, government of India is making effort to reach out and educate them (Vadrevu *et al*., 2019).

Mechanical harvesters: Since rice is the most significant grain crop and is grown across vast areas, the amount of labor needed to harvest it is lavish. As a result, mechanical harvesters of which combine harvesters are widely employed-came into being. Because it is not intended to cut the plant to the surface and absorb it into the soil, a considerable amount of straw remains in the field.

Lack of responsibility: Despite having knowledge on residue management and its impact on environment, few people desperately burn stubbles in the field due to which new rules/laws has set up by lawmakers to control these irresponsible acts by few farmers.

Scarcity of labour and Escaping from labour cost: The contribution of agricultural workers and all workers in Punjab fell from 62.67% to 35.96% between 1970-1971 and 2012-2013 as a result of the rise in intensive agriculture, a steady decline in the use of labor, and an increase in mechanical power. These days, labor wages have skyrocketed. Farmers just burn their residue, which doesn't even cost a dime, to save these expenditures (Kumar *et al*., 2015).

Stubble Burning Management Strategies

Crop residue as fodder for animals: When it comes to animal feed in India, crop leftovers rank first. In Northern India, the main sources of animal feed are wheat and maize straw. Conversely, rice straw ranks highest in the southern region of the nation despite having a high silica concentration, maybe due to the lack of other feed sources. In southern India, rice husk is ground into a fine powder and fed to animals, especially cattle. When urea and dry straw are combined and fed to animals, their health improves. According to statistics, 415.83 million tons of crop residue are needed for cattle in India, but only 253.26 million tons are available.

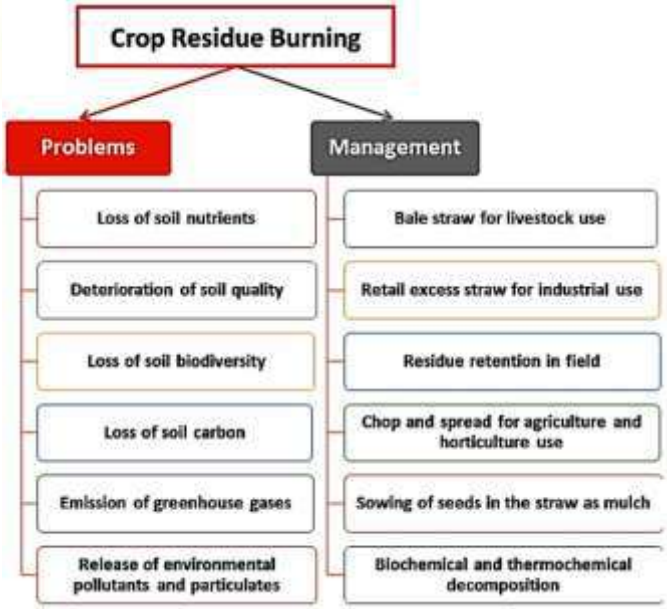
Crop residue as bedding material for cattle: Paddy straw is used as bedding material in cattle shed which is commonly done in southern states of India. However, now a days this is also practiced in northern parts mostly during cold seasons on government recommendation. Bedding in winter seasons helped cattle in keeping warm and regulates the body's heat loss. Moreover, It creates a safe, hygienic, secure, dry, and gripping atmosphere, reducing the likelihood of lameness and injury.

Healthy legs and hooves contribute to increased milk production and reproductive ability in livestock.

Crop residue in Biogas plants: Biogas, which is made from agricultural waste, is an alternative to fossil fuels. One important source of the ligno-cellulose needed to produce biogas is agricultural crop leftovers, especially rice straw. Agricultural wastes can also be used to make biogas and biochar. In order to produce biogas, stubbles are chopped into small pieces and added to digesters together with other materials using grinders. This entirely anaerobic method yields solid and liquid organic fertilizers as byproducts in addition to biogas (Singh *et al*., 2016).

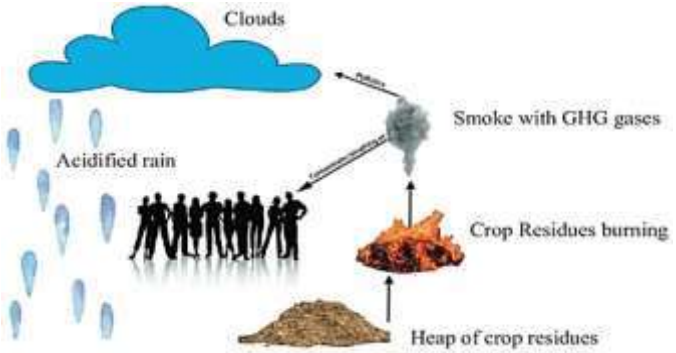
Crop residue in Mushroom Production: Residues of rice, wheat and sugarcane bagasse are excellent sources of substrate in mushroom production. Paddy straw is comparatively cheaper source with high lignocellulosic content which is highly preferred for mushroom making. Hence, it can be profitably utilized in mushroom production to combat the booming cost of mushroom production. Among various mushroom species, *Agaricus bisporus* (Button mushroom), *Calocybe indica* (Milky mushroom), *Volvariella* spp. (Paddy straw mushroom), and Oyster mushroom (*Pleurotus ostreatus*) are most commonly available edible species in India. The growth of these mushrooms largely depends upon the type of compost used for their nutrition.

Crop residue in compost making: Composting is the traditional method of preparation of enriched organic material. Composting is a natural mechanism that involves the breakdown of organic materials such as animal waste, crop residues, vegetable waste, and some municipal waste with the involvement of some microorganisms. It is used as natural organic fertilizer upon completion of the decomposition process. This natural fertilizer improves the soil physical, chemical, and biological properties. The harvest refuses include stubble, straw, stover and haulms of various crops. Crop remains from thrashing sheds and left over material during crop processing are also used in composting. These residues have tremendous potential to be used as organic fertilizer after it turns to manure by process of composting.



Crop residue in paper industries: The paddy straw along with wheat straw in the ratio of 40:60 is used in papermaking. The sludge from the remains after paper making could be used to produce energy by bio-methanization. This technology is already in use in some paper mills, where it provides approximately

60 percent of the energy needed. Paddy straw is also used as a common raw material in the production of paper and pulp board.



Stubble mulching: Stubble/straw mulching is the process of spreading of residues evenly on the land surface such that soil erosion due to wind and water is prevented, soil moisture is conserved and weed growth is suppressed. Few studies showed, Soil moisture in the deeper layers is conserved due to mulch hence, about 40% higher root length is observed when compared with no mulch treatments.

Conclusion

Given its detrimental consequences on the environment and human life, stubble burning has become a hotly discussed topic in recent years. Farmers, researchers, and government officials have discovered a number of causes for residue burning. Ironically, a couple of the farmers' justifications were absurd, such as running away from their jobs to gather straw and starting fires instead, which is entirely the result of carelessness. One of the main causes of stable burning in India is insufficient time between the harvesting of the rice crop and the planting of the subsequent wheat crop. As a result, the government and agricultural universities regularly advise farmers to sow rice in nurseries ten days ahead of the date that was previously followed. Farmers have numerous options in managing straw which includes cattle feed, mushroom production, bio-thermal plants, paper industries, bio-char preparation, mulching, soil incorporation etc.

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Flavouring Livestock Feed: A Palatable Path to Sustainable Animal Agriculture

Michelle C. Lallawmkimi, Ajay Baldaniya and Jessy Bagh

Introduction

One of the greatest challenges faced by farm managers, livestock rearers, animal scientists, as well as nutritionists involved in animal feed industry or research domain is designing the balanced ration practices of high yielding animals along with maintaining the cost-benefit ratio. Also, to be taken in consideration is the fact that meat, dairy, and animal by-product costs are not stable and vary for various reasons, and one among them is the feed cost involved (Thornton, 2010). Feed costs represent the largest input cost in animal husbandry practices (estimated to be 35-50%). There is a common belief that animals consume grass, plants, or other "food" that is typical of their kind, but in actuality, in today's Feeding animals and poultry on farms is a challenging task full with disagreement and debate. Feed additives are a class or collection of feed substances that can elicit the required animal response in a non-nutrient capacity. These reactions could include a change in the animal's development, pH, or metabolic response. The European Commission defines feed additives as products used in animal nutrition to improve the quality of feed and food derived from animals, or to improve the performance and health of the animals by, for example, making the feed materials more digestible. Numerous feed additions may include different nutrients like protein and sodium, which are found in yeast culture or sodium bicarbonate, respectively. Feed additives are neither technically required in animal husbandry operations, nor do they ensure high animal productivity or financial profitability. There has been a rapid increase in the demand to be met from dairy and meat industry owing to increasing population pressure. Food security which is the second in the list of Sustainable Development Goals in form of "zero hunger" and 12th sustainable development goal which is "responsible consumption and production" are both sought after in animal feed industry up to a greater extent. Feed additives are becoming more and more important because of the advantages they can provide, such as improving feed digestibility, controlling infectious illnesses, and promoting animal growth. The market for animal feed additives has a steady growth graph and is

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expected to continue expanding in the future due to the sharp rise in demand for meat, meat products, and dairy products worldwide. Due to the frequent occurrence of epidemics like bird flu, other diseases like foot-and-mouth disease, and environmental concerns that have raised animal health concerns worldwide, meat and dairy farmers have come to a consensus regarding feed quality and the certifications that go along with it. Animals utilize their senses of taste and smell to determine what constitutes a suitable diet. Feedstuffs with an unpleasant taste and smell may result in reduced feed intake and a low return on investment for farmers. The flavor and aroma of a food or feed are essential qualities that aid in its identification and appreciation. The four basic elements of flavor are salt, sour, sweet, and bitter. Flavoring compounds are non-volatile, water-soluble substances with little to no taste of their own that can change or improve the flavor of a product such as esters, alcohols, and terpenes.

Types, forms and concentration

There are two types of flavouring agents: natural ones like black cumin, garlic, and anise, and artificial ones like fruit extracts and chemical products like sodium glutamate and vanillin. The majority of these materials are supplied in the form of dry powder in free flowing, non-electrostatic concentrations that can be added to feed using a metering equipment made specifically for feed formulations or pre-mixed with other trace ingredients. The amounts of flavours added to the diet for typical feed types range from 0.5% to 1.5%. However, these levels can be changed based on the animal's kind, the type of feed ingredient used in the ration, the feed's storage duration, the water quality, and disease outbreaks all of which call for different flavour treatments.

Natural Flavours

- ✓ Herbs: Basil, mint
- ✓ Spices- Cardamom, clove, turmeric
- ✓ Aromatic Seeds- Aniseed, Cumin
- ✓ Fruits- Orange, Lemon
- ✓ Vegetables- Pees, Onions, Garlic

Processed Flavour

- ✓ Caramelized
- ✓ Roasted
- ✓ Fermented
- ✓ Toasted
- ✓ Baked

Classification of Feed Additives

Feed additives used in animals feed are classified into different groups depending on their use and applications viz. nutrient feed additives e.g. amino acids, minerals, vitamins and non-nutrient feed additives e.g. antibiotics, arsenic, copper supplements, hormones, beta agonists, immuno-modulators, coccidiostats, enzymes, probiotics, yeast culture, acidifiers, antioxidants, sequestrants, mycotoxin binders, anti-caking agents, humectants, preservatives, flavoring agents, coloring agents, dietary buffers, methane inhibitors, roughage substitutes, propionate promoters, bloat controlling agents, surfactants, sweetening agents, tranquilizers,

emulsifiers and stabilizers, etc. From the prospective of feed safety, substances added to the feed are generally divided into two major categories on the basis of level of consumption and similarity to feed itself.

Food-like substances: Additives which are added in food or feed are virtually indistinguishable from food, e.g. fats, oils, fatty acids, starches, modified starches, hydrolyzed protein, sugar and sugar alkaloids. These substances may be added in relatively substantial amounts to food (more than 1% of dietary intake). Due to resemblances with the food, these substances get digested and metabolized as food and consequently raises less toxicological and safety related problems.

Nonfood-like substances: Substances which are added directly or indirectly in only small amounts below 1% and in many cases less than 1ppm. These substances have large margin of safety in test animals and anticipated human exposure. The non-food like substances added intentionally for preservation, coloring and flavoring of food products or may be unintentionally contaminate food through several naturally occurring and synthetic substances present in the food chain and environment. These non-foods like substances tend to fall into certain categories which describe their action in the feed or in the animals. European Union recognized 23 functions for feed additives indicating that each feed additive is recognized to explain its functionally. Accordingly, five other categories of feed additives are technological, sensory, nutritional, zootechnical additives.

When using flavouring agents in dairy rations, the following points should be considered:

To achieve a balance between expenses and milk yield, taste additions should be made gradually while taking the feed materials' palatability into account. Some flavouring compounds build up in the tissues of cows, especially in the fat, and flow into the circulation and, ultimately, the milk. Thus, the cows should be kept off the feed flavours for four to five hours prior to milking and fed after milking.

Anionic salts (chlorine, sulphur, and phosphorus) are typically administered to pre-partum cows in order to maintain the Dietary Cation-Anion Difference (DCAD) at an ideal level of 200 millilitres per kilogramme of feed. Because of their capacity to lower blood pH and increase blood calcium availability, the use of these salts has frequently resulted in a decrease in the incidence of milk fever from 26% to just 4% (Havekes *et al*., 2020). Unfortunately, using anionic salts frequently results in bitter feed, which lowers feed consumption. In this instance, adding feed tastes to the diet will prevent the intake issue while preserving the anionic salts' functionality and lowering the prevalence of milk fever.

What are sweeteners used for ?

It is now widely accepted that sweet-tasting additives significantly boost animal feed consumption. Another rationale for the use of sweeteners is the masking of unwanted flavors, such as bitterness, which may reduce or feed consumption. For many

years, feed has been made more palatable by adding sweet-tasting ingredients. Due to a lack of substitutes, these were primarily sugar (sucrose), dextrose, or lactose in the past. If the sole purpose of adding 3-5% sugar to compound feedstuffs is sweetness, the cost is now too high. Most of the marketed products fall between 50 and 150 g/t of feed. The feed law regulations concerning use limitations for registered combinations must be taken into account. But it's important to remember that when consumed in excess, sweeteners aren't often very helpful. Feed rejection could occur if the amount is too high. There are indications that reducing the quantity can increase the total number of calories consumed. The sweetener's particle size is consistent, and its distribution over the sweetener premix is uniform. The particle size of one commercial sweetener brand (SUCRAM) ranges from 8 to 121 um, with a median size of 57 um and a mean of 48 um. Many final feed pellets will contain an effective concentration of sweetener thanks to a high particle per gramme. As a result, the microparticles maximize the impact of sweet taste potentiators and distribute a consistent level of sweetness throughout the feed.

Conclusion

Incorporation of familiar flavour in the diet increases acceptance of novel feed. The addition of flavour to diet, exerts a masking effect on unpleasantness and in turn results in increased intake of low-palatable feed. Flavour is a useful tool to deal with situations affecting feed intake like weaning, heat stress, transition period etc.

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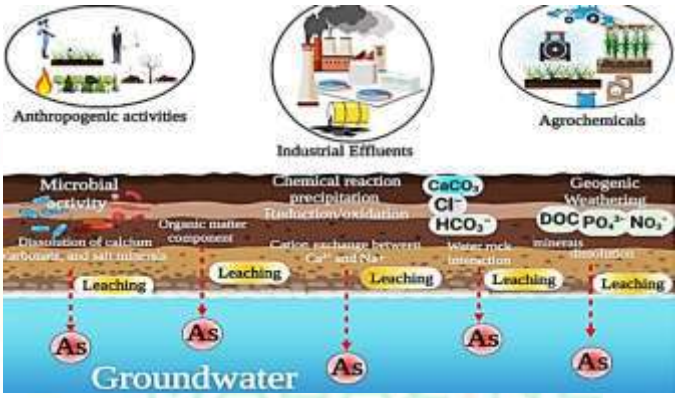
Arsenic Contamination in Groundwater

Nataraja K. D., S. M. Siddiqui and Ajay Baldaniya

Introduction

Groundwater contamination, whether from natural or man-made causes with serious socio-economic repercussions, is now a major environmental concern in many regions of the world. As-rich groundwater is consumed by millions of individuals in various nations, exposing them to elevated As levels (Bhattacharya *et al*., 2002). There is ample evidence of elevated levels of As in groundwater in Chile, Mexico, China, Argentina, the United States, and Hungary. In addition to Bangladesh, Vietnam, and the Indian State of West Bengal. An estimated 150 million people worldwide are thought to be impacted, and this number is expected to rise as new impacted locations are continually found. One of the most dangerous compounds in the world is arsenic, a well-known carcinogen. Overconsumption of hazardous inorganic compounds by humans over an extended period of time (e.g., five to ten years) Arsenicosis, a common term used for As-related health issues like skin disorders, skin cancers, internal cancers (bladder, kidney, and lung), diseases of the blood vessels of the legs and feet, possibly diabetes, elevated blood pressure, and reproductive disorders, can be brought on by consuming water and food (Rai *et al*., 2011). In terrestrial environment, the inorganic forms of As (such as trivalent arsenite (As^{III}) and pentavalent arsenate (As^{V})) are more prevalent and toxic than the organic forms in general. As exerts detrimental effects on general protein metabolism with high toxicity by reacting with sulfhydryl groups existing in cysteine residues.



When people become victims of arsenicosis, their livelihood, family life, and earning capacity suffer greatly. Women are socially marginalized when their physical beauty deteriorates. From a broader viewpoint, contamination of a region may lead to poverty, societal stress, individual disability, and a decline in the market value of potentially polluted agricultural products, which would result in low revenue for the affected farmers. A layperson cannot notice or avoid it if there is no taste, odor,

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color, or exposure. Arsenic's harmful effects on health are highly dependent on exposure time and dosage. Chronic exposure to arsenic can have certain dermatological effects. Melanosis (pigmentation) and keratosis (rough, dry, papular skin lesions) are prominent dermatological characteristics that can be widespread or spotty. Human reproductive, neurological, cardiovascular, respiratory, hepatological, haematological, and diabetic consequences can also result from long-term exposure to arsenic. Inorganic arsenic consumption has been linked to lung, bladder, and skin cancer.

Occurrence of Arsenic in Indian Groundwater

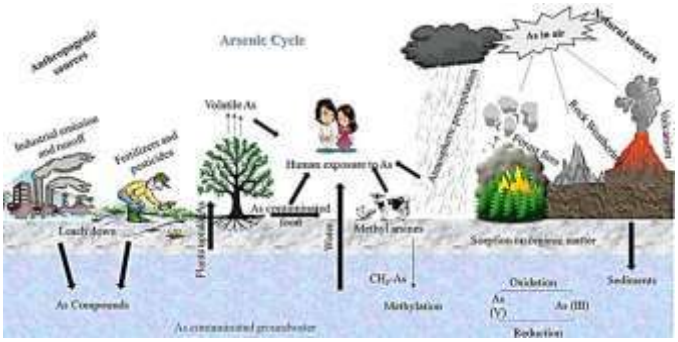
The average concentration of arsenic in the Earth's crust is 1.8 mg/kg, making it a negligible component. Among the most common minerals rich in arsenic are realgar (As_2S_2), orpiment (As_2S_3), arsenopyrite (FeSAs), and enargite (Cu_3AsS_4). The reduced form of arsenic, known as arsenite As(III), is more soluble and mobile in water and is frequently found in anaerobic (low-oxygen) groundwater conditions (Yadav *et al*., 2021). On the other hand, the oxidized form of arsenic is arsenate As(V), or H_2AsO^{4-} and $HAsO_4^{2-}$, depending on pH. Because of its enhanced toxicity and propensity to remain undissociated (e.g., H_3AsO_3) in groundwater throughout a wide pH range, the +3 state is especially concerning. Organic arsenic compounds can be found in groundwater with As(III) and As(V). Methylated forms of arsenic, including dimethylarsinic acid and monomethylarsonic acid, are examples of organic molecules that are often less poisonous than their inorganic counterparts (Raju, 2022). Volcanic eruptions have the potential to release gases and ash that contain arsenic, which can subsequently contaminate both surface and groundwater sources. The release of arsenic into the environment can occur during mining activities, particularly in regions where arsenic is naturally found. Improper disposal of devices and batteries in landfills and dumpsites has the potential to result in the leaching of arsenic into groundwater. Groundwater arsenic contamination has major effects on the alluvial region, especially the Ganga/Brahmaputra/Meghna River basin of the Indian subcontinent (Das *et al*., 2021). About 26% of the whole is covered by the Ganga-Brahmaputra-Meghna River region of India and is home to more than 500 million people. People live in the Bengal basin, which is a part of the larger Ganga-Brahmaputra-Meghna River basin Groundwater arsenic contamination has a major influence on the alluvial region, especially the Indian subcontinent's Ganga/Brahmaputra/Meghna River basin. Over 500 million people live along the Ganga-Brahmaputra Meghna River, which covers about 26% of India's total land area. Parts of the Indian states of West Bengal, Tripura, and Assam make up the Bengal Basin. Arsenic has also been found in Assam and parts of Punjab located on a floodplain of the Ra River, as well as in Uttar Pradesh, Jharkhand, and Bihar inside a floodplain of the Ganga River. Due to the discovery of high levels of arsenic pollution in 32 blocks and 12 districts along the Ganga River, Bihar has attracted scientific attention.

Bihar's Ganges River basin includes Holocene alluvial plains with arsenic mineral deposits in several areas, including Patna, the state capital, Vaishali, Bhagalpur, Munger, and Buxar. Singh and Ghosh's study revealed that water samples from the Maner block in the Patna district had arsenic contamination at a mean value of 52 g L^{-1} and a maximum concentration of 231 g L^{-1}. Arsenic is dispersed vertically in a 4.5-7.5 m thick layer of fine-grained clay (Kumar *et al.*, 2023).

Health Implications of Arsenic Contamination

The arsenic pollution in the ground water of India poses significant health hazards, encompassing a spectrum of adverse effects such as skin lesions, cancer and cardiovascular aliments. About 3000 settlements in the lowlands of West Bengal, Bihar, and Uttar Pradesh, India, especially in the Ganga-Meghna-Brahmaputra (MGB) area, have arsenic concentrations exceeding 50 ppm, putting 6 million people at risk. Long-term exposure to arsenic, mostly from drinking contaminated groundwater, is associated with a wide range of serious and usually irreversible health effects Haldar *et al* (2007) discovered that cancer death, aging, and premature hair graying in Jajjal Village, Bathinda, Punjab.At least 40 of the 75 districts in Uttar Pradesh have air pollution levels beyond allowable limits, putting 23 million people in danger. Chronic arsenic exposure, typically defined as consumption of water containing arsenic above 50 µg L^{-1} for more than six months, leads to a constellation of health effects collectively termed arsenicosis.

The condition progresses through several stages, beginning with characteristic skin manifestations including hyperpigmentation, keratosis, and melanosis. These dermatological changes often serve as the first observable indicators of chronic arsenic toxicity and can appear within 5-10 years of continuous exposure. Beyond cancer, chronic arsenic exposure associates with numerous non-malignant health conditions. Cardiovascular diseases, including hypertension, atherosclerosis, and ischemic heart disease, demonstrate strong associations with arsenic exposure (Naujokas *et al.*, 2013). Neurological effects include peripheral neuropathy and cognitive impairment, particularly concerning in children where developmental neurotoxicity can result in reduced intelligence quotient scores and impaired cognitive function. Diabetes mellitus shows increased prevalence in arsenic exposed populations, with evidence suggesting both direct pancreatic toxicity and insulin resistance mechanisms.



Conclusion

Groundwater contamination by arsenic is a complex worldwide issue that needs ongoing attention from the scientific, public health, and policy communities. Although human activity has a major role in some situations, natural geochemical

processes are the main cause of the issue. The affected areas are spread across several continents, but the effects are most severe in South and Southeast Asia, where tens of millions of people are exposed to tainted drinking water on a regular basis. Chronic exposure to arsenic can lead to a number of malignancies, cardiovascular disease, neurological impairment, and developmental abnormalities, all of which have a significant impact on the morbidity and death rates of the afflicted populations. Accurate monitoring, suitable remediation technology, the creation of alternate water sources, and extensive public health interventions are all necessary for effective management. Future research should prioritize developing cost-effective, sustainable treatment technologies suitable for resource limited settings, improving understanding of climate change impacts on arsenic mobilization, and evaluating long-term health outcomes in exposed populations.

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Unlocking the Potential of Lion's Mane Mushroom: Cultivation and Bioactive Compounds

Niti Kushwaha

Introduction

Hericium erinaceus, commonly known as Lion's Mane, is a culinary and medicinal fungus that has garnered significant global attention for its unique bioactive profile and potential therapeutic applications. As a lignicolous fungus, it possesses the distinct capability to thrive on hardwood substrates, converting complex organic matter into high-value nutraceuticals. Unlocking its full potential requires a rigorous understanding of its cultivation kinetics and the chemical mechanisms underlying its neuro-protective, anti-tumor, and immunomodulatory properties (Jiang *et al*., 2014). *Hericium erinaceus* is a temperate wood-decay fungus belonging to the phylum Basidiomycota. Unlike common gilled mushrooms, it is characterized by a "hydnoid" morphology, producing long, white, icicle-like spines (aculei) from which spores are released. In the wild, it acts as a necrotrophic parasite and saprobe, typically colonizing wounded hardwoods like Oak (*Quercus*) and Beech (*Fagus*). The scientific community's fascination with *H. erinaceus* centers on its ability to cross the blood-brain barrier (BBB) via low-molecular-weight compounds, facilitating the synthesis of Nerve Growth Factor (NGF) and Brain-Derived Neurotrophic Factor (BDNF).

Bioactive Compounds & Molecular Mechanisms

The therapeutic efficacy of Lion's Mane is attributed to a diverse array of bioactive molecules, primarily divided between the fruiting body and the mycelium.

Hericenones (Fruiting Body): Hericenones are aromatic compounds (benzyl alcohol derivatives) found exclusively in the mushroom's fruiting body. While they possess antioxidant and anti-inflammatory properties, their primary role is the stimulation of NGF synthesis in the hippocampus.

- ✓ **Key Analogs:** Hericenones C, D, and E.
- ✓ **Mechanism:** They are thought to stimulate the secretion of NGF by activating the N-terminal kinase (JNK) signaling pathway.

Erinacines (Mycelium): Erinacines are cyathane diterpenoids located within the mycelial biomass. They are significantly more potent than hericenones regarding neuro-genesis (Li *et al*., 2018).

- ✓ **Erinacine A:** The most researched analog; it has been shown to reduce amyloid-β plaque accumulation and increase catecholamine levels in the brain.
- ✓ **Pharmacokinetics:** Due to their low molecular weight and lipophilic nature, erinacines easily cross the BBB, making them a primary target for neurodegenerative research (Alzheimer's and Parkinson's).

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Polysaccharides (β-Glucans): Like many medicinal fungi, *H. erinaceus* contains high concentrations of (1→3), (1→6)-D-β-glucans. These complex carbohydrates modulate the immune system by binding to Dectin-1 receptors on macrophages and Natural Killer (NK) cells, triggering a cascade of cytokine production that enhances host defense (Cornejo-Castillo *et al*., 2026).

Compound Class	Primary Tissue Source	Notable Functions
Erinacines	Mycelium	Primarily linked to neuroprotective effects, including the stimulation of Nerve Growth Factor (NGF) and myelin repair.
Hericenones	Fruiting Body	Structurally distinct terpenoids often associated with broader health benefits, including cognitive support.
β\betaβ-Glucans	Fruiting Body	Generally found in higher concentrations (3–5x) in fruiting bodies compared to grain-grown mycelium; key for immune system modulation.

Advanced Cultivation Techniques

Cultivating Lion's Mane requires a delicate balance of substrate nutrition, gas exchange, and hygroscopic control. The process is generally divided into three phases: substrate preparation, colonization, and fruiting (Mahema *et al*., 2026).

Substrate Formulation: The "Master's Mix"

While *H. erinaceus* can grow on simple straw, commercial yields and bioactive concentrations are optimized using supplemented hardwoods. The industry standard is the Master's Mix:

- ✓ 50% Hardwood Sawdust: Provides lignin and cellulose.
- ✓ 50% Soy Hulls: Provides nitrogen and essential lipids.
- ✓ Hydration: The mixture must be hydrated to approximately 60-65% moisture content.

Sterilization and Inoculation

The high nutrient density of soy hulls makes the substrate prone to contamination.

Sterilization: Substrate bags are typically sterilized in an autoclave at 121°C (15 psi) for 2.5 to 3 hours.

Inoculation: Done in a sterile environment using grain spawn (millet or rye). A 10% inoculation rate is standard to ensure rapid colonization before competing molds can take hold.

Mycelial Colonization (Incubation)

During this phase, the mycelium secretes extracellular enzymes (cellulases, laccases) to break down the substrate.

- ✓ Temperature: 21°C to 24°C
- ✓ Gas Exchange: Mycelium produces CO_2. Filter patches on the bags must allow for gas exchange while preventing the entry of spores or bacteria.

Fruiting Dynamics and Environmental Control

Once the substrate is fully colonized (white and "puffy"), the transition to fruiting is triggered by environmental shifts.

Triggering Primordia: To induce the "pinning" or primordia stage, the grower must introduce:

- ✓ **Fresh Air Exchange (FAE):** Dropping CO_2 levels below 800 ppm. High CO_2 causes the mushroom to grow as a dense, cauliflower-like mass rather than developing spines.
- ✓ **Light:** Low-intensity "cool" light (500-1000 lux) in the blue spectrum (480 nm) acts as a directional signal for fruiting.

✓ **Temperature Drop:** Shifting the environment to 15°C-18°C.

Parameter	Colonization Phase	Fruiting Phase
Temperature	21°C - 24°C	15°C- 19°C
Humidity	60% (Internal)	85-95% (Ambient)
CO_2	5000	800ppm
Light	Dark	12h Cycle (Dim)

Harvesting: The mushroom is ready for harvest when the spines are 5-10 mm long. If the spines begin to turn yellow, the specimen is over-mature and beginning to drop spores, which leads to a bitter flavor and decreased shelf life (Jiang *et al*., 2014).

Potential Applications and Future Directions

The "unlocking" of Lion's Mane's potential extends beyond the culinary world.

Nootropics: Concentrated extracts are being standardized for cognitive enhancement in healthy adults.

Neuroregeneration: Research is ongoing into the use of erinacine-rich mycelium for treating peripheral nerve injuries.

Gut-Brain Axis: New evidence suggests *H. erinaceus* acts as a prebiotic, altering gut microbiota to reduce systemic inflammation.

Conclusion

Hericium erinaceus represents a significant opportunity for both biotechnology and functional food industries. Its cultivation, while technically demanding, allows for the production of a high-value crop rich in neuroprotective compounds.

As our understanding of the biosynthetic pathways of erinacines and hericenones deepens, Lion's Mane may become a cornerstone in the pharmaceutical management of neurological health.

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Miniature Marvels: The Horticulture of Bonsai

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Abstract

Bonsai, the horticultural discipline of cultivating woody plants in shallow containers to produce miniaturized, aesthetically composed replicas of full-scale trees, represents one of the most intricate intersections of applied plant science, ecological mimicry, and living art in recorded horticultural history. Originating in Chinese penjing culture over 1,300 years ago and refined into a codified artistic and scientific tradition in Japan, bonsai has evolved into a globally practiced discipline with an estimated market value exceeding USD 1.5 billion annually (Murata, 2018). Its practice demands a sophisticated command of plant physiology, soil science, canopy architecture, and seasonal management, situating it firmly within the domain of applied ornamental horticulture rather than mere decorative gardening. This article examines bonsai through an integrated horticultural and botanical lens, synthesizing current knowledge on its historical origins, physiological foundations, cultivation techniques, species selection, size classifications, and contemporary global relevance, while foregrounding the plant science that transforms ordinary woody specimens into living masterworks of miniaturization.

Introduction

Among all practices within ornamental horticulture, few demand as comprehensive an engagement with living plant biology as bonsai. The term itself, a Japanese rendering of the Chinese characters (pén zāi), meaning 'tray planting', does not fully convey the scientific complexity embedded within its deceptively simple premise: to induce a long-lived woody perennial to express the structural proportions, aged character, and ecological authenticity of a mature forest tree within a container measuring centimeters rather than meters. Achieving this transformation is not an act of artistic imposition upon a passive subject; it is a sustained, physiologically informed negotiation between the practitioner and the biological imperatives of the plant (Koreshoff, 2019). Root architecture, vascular hydraulics, hormonal signaling, meristematic activity and photosynthetic partitioning must all be understood and purposefully manipulated. This review consolidates current horticultural and plant physiological knowledge on bonsai cultivation,

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offering an evidence-grounded account of how miniaturization is achieved, maintained, and elevated to the status of a living scientific and aesthetic discipline.

Historical Origins and Cultural Transmission

The lineage of bonsai traces back to the Chinese Tang Dynasty (618-907 CE) with penjing, the art of cultivating miniature landscapes of dwarfed trees and rocks in ceramic containers. Evidence like tomb murals suggests this practice began around the 7th century CE, rooted in Daoist cosmology where miniaturized landscapes represented natural forces. Penjing was introduced to Japan by Buddhist monk-scholar during the Kamakura period (1185-1333 CE). The aesthetics of wabi, sabi, and mono no aware refined the practice, focusing on the individuality of trees rather than just landscape replication. By the Edo period (1603-1868 CE), bonsai evolved into a structured discipline with style classifications and dedicated cultivation manuals. The global spread of bonsai surged after the 1964 Tokyo Olympics, leading to the establishment of bonsai clubs and nurseries across Europe, North America, and Southeast Asia.

Botanical Foundations and Species Selection

Suitable Species and Horticultural Criteria: Not all woody plant species are equally amenable to bonsai cultivation. The ideal candidate species possesses several convergent botanical traits: small or reducible leaves (macrophylly constitutes a persistent aesthetic challenge in larger-leaved taxa), short internodes with a propensity for compact ramification, tolerance of root restriction and periodic root pruning without catastrophic decline, a capacity for adventitious bud formation enabling structural redesign, and longevity within container conditions spanning decades to centuries (Ainsworth and Rogers, 2020). Species from genera such as *Ficus, Juniperus, Acer, Pinus, Ulmus*, and *Zelkova* dominate global bonsai practice owing to their favorable intersection of these traits.

Species selection is further governed by climate zone compatibility and intended placement (indoor versus outdoor cultivation). Tropical and subtropical species: *Ficus microcarpa, Carmona retusa, Schefflera arboricola*, tolerate the controlled thermal environments of indoor settings, where light levels of 2,000-5,000 lux are typically achieved through supplemental LED horticultural lighting (Lev-Yadun and Gould, 2023). Temperate species: *Acer palmatum, Pinus thunbergii, Juniperus chinensis*, require seasonal cold dormancy (typically 4-8 weeks at 1-7°C) to complete their annual physiological cycles, precluding long-term indoor cultivation and necessitating outdoor or cold-greenhouse over-wintering protocols (Ainsworth and Rogers, 2020).

Size Classifications and Cultivation Complexity

Bonsai are formally classified by height into a graduated size hierarchy, each tier imposing distinct horticultural demands. The relationship between tree size and cultivation difficulty is inversely proportional below the medium (Chiu) class: smaller containers retain less substrate volume,

Table 1: Commonly Cultivated Bonsai Species: Taxonomic Affiliation, Style Suitability and Key Horticultural Traits

Species	Family	Style Suitability	Notable Horticultural Trait
Ficus microcarpa	Moraceae	Formal upright, Banyan	Adventitious aerial root formation; highly adaptable to indoor conditions
Juniperus chinensis	Cupressaceae	Windswept, Cascade	Deadwood (jin/shari) development; extreme drought tolerance
Acer palmatum	Sapindaceae	Informal upright, Forest	Pronounced seasonal foliar coloration; fine ramification
Pinus thunbergii	Pinaceae	Literati, Slanting	Candle pinching controls internode elongation precisely
Serissa japonica	Rubiaceae	Moyogi, Broom	Prolific small-flower production; responds well to ramification pruning
Carmona retusa	Boraginaceae	Informal upright	Simultaneous flowering and fruiting; suitable for tropical indoor culture

Table 2: Standard Bonsai Size Classifications: Height Ranges, Japanese Terminology and Relative Cultivation Complexity

Technique	Physiological Mechanism	Frequency / Timing	Primary Outcome
Root Pruning	Reduces cytokinin export from root tips; redirects assimilates to shoot architecture	Every 1-5 years (species-dependent)	Container adaptation; canopy-root balance
Branch Wiring	Applies mechanical strain inducing tension wood or compression wood formation in xylem	6 weeks - 18 months	Permanent directional repositioning of branches
Defoliation	Stimulates axillary bud break; promotes smaller replacement leaf set via auxin redistribution	Once per growing season (deciduous spp.)	Leaf size reduction of 30-60%
Candle Pinching	Arrests internode elongation; distributes apical dominance to lateral buds in conifers	Spring bud-swell phase	Dense, compact foliage pad development
Soil Replacement	Restores hydraulic conductivity; replenishes cation exchange capacity in substrate	Concurrent with root pruning	Sustained nutrient and gas exchange

exhibit more rapid desiccation under solar radiation, and offer less buffering capacity against temperature fluctuations and fertilizer salt accumulation (Chaanin, 2022). The most extreme miniaturization tier, Keshitsubo (literally 'poppy seed pot'), accommodating trees below 3 cm in height, demands daily monitoring of substrate moisture, ultra-dilute fertilization regimens (at approximately 25% of standard concentration), and micro-tool wiring techniques that represent the apex of horticultural precision in the discipline. A single, well-developed Keshitsubo specimen may require 15-25 years of attentive cultivation to achieve exhibition-quality ramification at this scale (Murata, 2018).

Physiological Mechanisms of Bonsai Miniaturization

Root Confinement and Shoot Growth Modulation

: The physiological engine of bonsai miniaturization operates primarily through the deliberate manipulation of root-to-shoot signaling networks. Roots are not merely anchoring and absorptive structures, they are active endocrine organs synthesizing cytokinins (particularly zeatin and isopentenyl adenine), abscisic acid, and gibberellins whose export to aerial tissues fundamentally governs shoot elongation, leaf expansion, and apical dominance (Ainsworth and Rogers, 2020). Container restriction progressively reduces root biomass and, consequently, the cytokinin flux reaching shoot meristems. This reduction in cytokinin-to-auxin ratios at apical and axillary buds suppresses internode elongation while preserving meristematic viability, the physiological basis of the compact, dense growth architecture characteristic of well-maintained bonsai.

Empirical measurements of shoot elongation rates in container-restricted versus open-ground specimens of *Ficus microcarpa* demonstrate reductions of 45-68% in annual extension growth under root confinement conditions simulating standard bonsai container volumes of 0.5-2.0 liters, compared to open-ground controls (Chaanin, 2022). This growth suppression is accompanied by proportional reductions in leaf area index (LAI) and individual leaf surface area, the latter decreasing by 30–55% in successive leaf generations following root restriction, a phenomenon exploited deliberately through the defoliation technique in deciduous species.

Substrate Science, Nutrition, and Environmental Management

The bonsai substrate, which is the growing medium in the shallow pot, is crucial for cultivation and differs greatly from conventional potting composts. Standard peat or loam-based media promote excessive growth, which is counter-productive in bonsai culture. Contemporary bonsai substrates prioritize porosity, gas exchange, and hydraulic conductivity, while ensuring adequate cation exchange capacity (CEC) for nutrient retention. Akadama, a Japanese fired clay mineral, is the standard base component, often mixed with pumice for drainage and decomposed granite for stability, typically in a 1:1:1 ratio, adjusted for specific species needs.

Nutritional management is seasonal: high-nitrogen formulations (N:P:K ratios of 10:6:6 or 12:6:6) support spring growth, while balanced or phosphorus-rich formulations (6:10:6) focus on root consolidation and carbohydrate storage in late summer and autumn, preparing trees for winter dormancy and the next growing season.

Contemporary Global Significance and Research Frontiers

The global bonsai community includes an estimated 8-12 million practitioners in over 60 countries, supported by a nursery and horticultural supplies industry valued at USD 1.5-2.2 billion annually (Murata, 2018). Major events like the World Bonsai Convention, the Kokufu-ten Exhibition and European Bonsai Association gatherings serve as competitive and knowledge-sharing platforms, with auction values for top specimens reaching from USD 50,000 to over USD 1 million (Koreshoff, 2019). Scientifically, bonsai cultivation provides a controlled environment for studying the physiological responses of woody perennials to factors such as root restriction and pruning, which are difficult to analyze in traditional forestry (Lev-Yadun and Gould, 2023). Additionally, some bonsai specimens in Japan have been cultivated for over 800 years, offering unique insights into human-directed tree development (Wu and Raven, 2021).

Conclusion

Bonsai represents a sophisticated horticultural discipline that combines aesthetic goals with scientific principles. The art of miniaturizing trees involves precise manipulation of root structure, hormonal levels, and seasonal resource management, making it more than just a decorative art form. Three key conclusions stand out: first, bonsai miniaturization relies on root-induced hormonal suppression of shoot growth, achieved through container limitation and root pruning; second, species selection and substrate choices are critical decisions that impact growth patterns and health; and third, the global practice of bonsai links ornamental horticulture, applied plant physiology, and cultural heritage. Future research focusing on genomic profiling, precision irrigation, and climate-adaptive species will further enhance bonsai cultivation as a scientific pursuit.

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Rooted in Innovation: Hydroponic Vegetable Production

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Introduction

The traditional paradigm of "soil-based" agriculture is facing unprecedented pressure from climate instability and rapid urbanization. Hydroponics the cultivation of plants in a nutrient-enriched aqueous medium offers a controlled-environment solution. By 2026, the global hydroponics market is projected to reach $59.86 billion, driven by a 12.5% CAGR. This growth is rooted in the system's ability to reduce water consumption by up to 90% while increasing growth rates by 25-50% (Al-Mansouri and Schmidt, 2026). Hydroponics is a technique of growing plants in nutrient solutions with or without the use of an inert medium such as gravel, vermiculite, rockwool, peat moss, saw dust, coir dust, coconut fibre, etc. to provide mechanical support. The term Hydroponics was derived from the Greek words hydro' means water and ponos' means labour and literally means water work. The word hydroponics was coined by Professor William Gericke in the early 1930s; describe the growing of plants with their roots suspended in water containing mineral nutrients. Researchers at Purdue University developed the nutriculture system in 1940.

During 1960s and 70s, commercial hydroponics farms were developed in Arizona, Abu Dhabi, Belgium, California, Denmark, German, Holland, Iran, Italy, Japan, Russian Federation and other countries. Most hydroponic systems operate automatically to control the amount of water, nutrients and photoperiod based on the requirements of different plants. Rapid urbanization and industrialization are reducing the amount of arable land, and traditional farming methods are having a variety of detrimental effects on the environment. Techniques for producing enough food must change if the world's expanding population is to be fed sustainably. An alternative for sustainable production and the preservation of rapidly diminishing land and water resources is to modify the growing medium. In the current situation, soil-less cultivation could be successfully started and taken into consideration as a substitute method for producing nutritious crops, vegetables, or food plants. Hydroponics, aquaponics, aerobic agriculture and substrate culture are examples of soil-free agriculture. These hydroponics methods are becoming more and more popular because to their effective resource

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management and food production.

Advanced Architectural Frameworks

Modern hydroponics is no longer a "one-size-fits-all" endeavor. Innovations in system design have optimized production for specific crop morphologies and environmental constraints.

Nutrient Film Technique (NFT) & DeepWater Culture (DWC): While foundational, these systems have undergone significant refinement:

- ✓ **NFT 2.0:** Utilizing refined channels for polyculture, contemporary NFT systems now integrate mechanical and biological filtration to prevent root-zone hypoxia and pathogen buildup.
- ✓ **Oxygenated DWC:** New "Smart Reservoirs" use AI-controlled air stones to maintain dissolved oxygen levels at precise saturation points relative to water temperature.

Vertical and Hybrid Systems: To maximize urban footprint efficiency, Vertical Aeroponic Towers have become the gold standard for leafy greens. These systems mist roots with a nutrient solution, achieving 95% water savings compared to field agriculture (Chen *et al.*, 2025).

System Type	Water Efficiency	Growth Rate	Primary Crop
NFT	High	Fast	Lettuce, Herbs
DWC	Medium	Moderate	Leafy Greens
Aeroponics	Ultra-High	Accelerated	Strawberries, Brassicas
Drip System	High	Standard	Tomatoes, Peppers

The Digital Pulse: AI and IoT Integration

The most significant shift in 2026 is the transition from "manual monitoring" to autonomous agronomy.

- ✓ **Precision Fertigation:** Sensors now track Electrical Conductivity (EC) and pH in real-time, with AI-driven dosing pumps adjusting nutrient ratios every second. This prevents "nutrient antagonism," where an excess of one element (like Potassium) inhibits the uptake of another (like Magnesium).
- ✓ **Predictive Analytics:** Computer vision systems monitor leaf turgor and spectral reflectance to identify pest stress or nutrient deficiencies before they are visible to the human eye.
- ✓ **Blockchain Traceability:** Leading providers now use blockchain to provide a "farm-to-fork" digital ledger, ensuring transparency in chemical-free claims.

Nutrient Chemistry and Sustainability

Innovation extends beneath the surface to the chemical composition of the "working solution."

Scientific Insight: Research in 2025-2026 has focused on Diazotroph integration using nitrogen-

fixing bacteria within hydroponic systems to reduce the reliance on synthetic nitrate fertilizers. Furthermore, the industry is shifting toward Circular Hydroponics, utilizing treated greywater and solar-powered desalination to create closed-loop systems in arid regions like the Middle East and Australia.

Challenges and Future Outlook

Despite the technological leaps, several hurdles remain:

Energy Dependency: High-intensity LED grow lights require significant power, though efficiency is improving.

Initial Capital: The "High-Tech" barrier remains a deterrent for small-scale farmers in developing economies.

Biosecurity: In a recirculating system, a single waterborne pathogen can decimate an entire crop cycle if filtration fails.

Comprehensive Deep Dive

The Physiology of Hydroponic Growth: In a hydroponic environment, the plant is liberated from the energetic cost of "searching" for nutrients. In soil, root architecture is often determined by the localized depletion of Phosphorus or Nitrogen. In a hydroponic system, we maintain a constant concentration gradient at the root-liquid interface.

Lighting Recipes: The New Terroir: In 2026, we no longer speak of "sunlight" but of "Spectral Recipes." Different wavelengths trigger specific secondary metabolites. For instance:

- ✓ **Blue Light (450 nm):** Promotes stomatal opening and chlorophyll production.
- ✓ **Far-Red Light (730 nm):** Used to trigger the "Shade Avoidance Response," accelerating flowering in specific cultivars.
- ✓ **UV-A Supplementation:** Used to increase the anthocyanin and antioxidant content in red-leaf lettuce, effectively "bio-fortifying" the produce.

Economic Viability and Urban Integration

The "food mile" is a critical metric in 2026 sustainability reports. By placing hydroponic facilities in abandoned industrial zones (Adaptive Reuse), we reduce transportation emissions by up to 80%. The concept of "Agritecture" building designs that integrate food production into the HVAC and water systems of the building is no longer theoretical. Heat rejected from data centers is being used to maintain the water temperature required for tropical hydroponic crops.

The Role of Substrates

While "hydro" implies water, many systems use inert media to provide mechanical support. The innovation here lies in Bio-char and Mycelium-based substrates. These are not only carbon-neutral but can be inoculated with beneficial microbes (PGPR - Plant Growth-Promoting Rhizobacteria) that enhance the plant's systemic acquired resistance (SAR).

Conclusion: The Paradigm Shift in Global Food Systems

The evolution of hydroponic vegetable production through 2026 represents more than a mere technological upgrade; it signifies a fundamental shift in our biological relationship with

the environment. By successfully decoupling the production of nutrient-dense food from the geographic and climatic limitations of "the field," we have entered an era of democratized agriculture (Gomez and Patel, 2025).

Synthesis of Scientific Advancements: The convergence of computational fluid dynamics, quantum-dot LED lighting, and metagenomic root-zone analysis has transformed the hydroponic reservoir into a high-precision bioreactor. As highlighted throughout this review, the ability to manipulate the rhizosphere with mathematical precision allows for the optimization of plant secondary metabolites effectively turning vegetables into functional "nutraceuticals." The integration of AI-driven fertigation ensures that every milliliter of water is accounted for, pushing the boundaries of Resource Use Efficiency (RUE) to its theoretical limits (Kumar, 2026).

Socio-Economic and Environmental Implications : Beyond the laboratory, the socio-economic impact of these innovations is profound. Hydroponics acts as a stabilizer against the volatility of the global climate. In regions where topsoil erosion and desertification have rendered traditional farming impossible, soilless culture provides a resilient lifeline. Furthermore, by integrating these systems into the urban fabric utilizing Agritecture and circular waste-to-nutrient pipelines we are effectively shortening the supply chain to a distance measured in meters rather than miles. This not only ensures peak freshness and nutrient density but also drastically reduces the carbon footprint associated with cold-chain logistics (Chen *et al.*, 2025).

A Vision for the Future: However, the journey is not complete. The next frontier in hydroponic innovation lies in Open-Source Agronomy and the reduction of capital expenditure (CAPEX) to make these systems accessible to the Global South. As we refine the "digital twin" of various crop species, we move toward a future where food production is automated, decentralized, and immune to the whims of an increasingly unpredictable climate. In final analysis, Hydroponic Vegetable Production is the cornerstone of a sustainable future. It represents the ultimate synthesis of human ingenuity and biological potential a system rooted in innovation that ensures the humanity of 2026 and beyond can thrive within planetary boundaries. The "Green Revolution" of the 20th century was defined by chemistry and mechanization; the "Transparent Revolution" of the 21st is defined by data, light, and the elegant flow of water (Chen *et al.*, 2025).

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Smart Farming: IoT Application in Agriculture

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Introduction

Agriculture is backbone of many economic, especially in developing countries like India. However traditional farming methods often face challenges such as climate change water scarcity, and low productivity. The emergence of the Internet of Things (IoT) has transformed conventional agriculture into smart farming, enabling data driven and efficient agriculture practices. IoT integrates sensors, communication technologies, and data analytics to improve farm management and productivity IoT in agriculture involves deploying low-cost sensors, wireless networks, and cloud platforms to collect data on soil moisture, temperature, humidity, crop health, and livestock conditions, and then using this data to automate decisions and improve productivity. Studies show that IoT-based smart farming can increase crop yields by up to 30% while reducing water and fertilizer use by 20-30% in many settings.

Concept of smart farming and IoT

Smart farming refers to the use of advanced technologies such as IoT, Artificial Intelligence (AI), and cloud computing in agriculture to enhance efficiency and sustainability. IoT involves interconnected devices that collect and transmit real-time data from the field. These devices include soil sensors, weather stations, drones, and automated irrigation systems. At the heart of smart farming lies the Internet of Things (IoT), which refers to physical devices (sensors, controllers, drones, etc.) connected to the internet so they can collect, transmit, and act on data automatically. In agriculture, IoT enables.

- ✓ Real-time monitoring of soil moisture, temperature, humidity, light, and crop health.
- ✓ Automated control of irrigation, fertigation, and greenhouse conditions.
- ✓ Remote management via smartphones or web dashboards, reducing the need for constant on-site labour.

Smart farming and IoT form a feedback cycle

Sense: Sensors and drones gather data on soil, weather, crops, and livestock.

Transmit: Connectivity modules send this data to cloud platforms via mobile network or wi-fi.

Analyze: Software and sometimes AI process data to detect stress, disease, or inefficiency

Act: The system triggers alerts, recommendations, or automated actions (e.g., turning on irrigation or pesticide sprayers)

Application of IoT in agriculture

Precision Farming: IoT transforms precision farming by enabling real-time data collection and targeted resource use in agriculture. This aligns with your interests in smart farming technologies for plant pathology and integrated management. IoT sensors

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monitor soil moisture, pH, nutrients, temperature, and crop health to optimize irrigation, fertilization, and pest control. Drones and automated systems apply inputs precisely, reducing waste and chemical use while boosting yields. Livestock tracking via wearables improves animal health monitoring.

Smart Irrigation Systems: Smart irrigation systems optimize water use in agriculture by automating delivery based on real-time data, building on IoT precision farming applications. They directly support your focus on smart technologies for efficient crop management in regions like Delhi. These systems integrate soil moisture sensors, weather stations, and flow meters with controllers that adjust watering schedules dynamically. Data from sensors feeds into apps or cloud platforms, triggering valves for drip or sprinkler irrigation only when needed, preventing overwatering. Microcontrollers process inputs like humidity, temperature, and evapotranspiration to calculate precise needs.

Crop Monitoring and Disease Detection: IoT devices and drones help in continuous monitoring of crop health. Early detection of pests and diseases minimizes crop loss and improves productivity and IoT networks deploy sensors for soil moisture, temperature, humidity, and leaf wetness, while cameras or drones capture images analyzed by deep learning models like CNNs for disease classification. Cloud platforms process data to send alerts via apps, forecasting outbreaks based on environmental trends. Systems integrate robotics for automated spraying on affected areas.

Livestock Management: IoT wearables for livestock track body temperature, heart rate, activity, and location, enabling early detection of disease outbreaks and improving reproductive management. Smart cameras and RFID tags can also monitor feeding patterns and animal count, helping farmers optimize feed use and reduce mortality. These systems are particularly useful in peri-urban and commercial dairy or poultry operations, where labor costs and biosecurity are critical concerns

Climate Monitoring: Weather sensors provide real-time data on temperature, humidity, and rainfall. Farmers can plan sowing, irrigation, and harvesting as a result. Climate monitoring using IoT is transforming agriculture by making it more resilient to climate variability. It empowers farmers with accurate, real-time information, enabling them to adapt to changing environmental conditions and improve productivity. As technology becomes more accessible, climate monitoring will play a key role in achieving sustainable agriculture.

Farm Management Systems: IoT platforms integrate farm data into a centralized system, helping farmers manage operations efficiently and make better decisions. A farm management system (FMS) in an IoT-based smart farm acts as the central "control room" that connects sensors, machines, and data to automate and optimize operations. Instead of manual records, the FMS collects real-time data from IoT devices (soil sensors, weather stations, drones, GPS-equipped tractors) and presents it on a dashboard for decision-making.

Drone-Based Surveillance and Input Application: Drones equipped with multispectral or RGB cameras can rapidly scan large fields to detect nutrient deficiencies, pest attacks, and water stress. Some platforms integrate drone imagery with IoT dash-boards to generate prescription maps for variable -rate fertilization or pesticide application. In several Indian villages, farmers have used drone-based crop-monitoring systems to reduce pesticide use by targeting only affected patches, lowering input costs and environmental impact.

Benefits of IoT in smart farming

- ✓ Increased agricultural productivity and effici-ency
- ✓ Efficient use of water, fertilizers, and pesticides
- ✓ Reduced labor costs and human effort
- ✓ Real-time monitoring and decision-making
- ✓ Enhanced sustainability and environmental protection

IoT in smart farming transforms traditional farming into a data-driven, precision activity that saves resources, boosts productivity, and supports more sustainable and resilient agriculture especially valuable for smallholders in regions like India.

Challenges of IoT in agriculture

The primary challenges of implementing Internet of Things (IoT) in agriculture include high initial investment costs, poor or unreliable internet connectivity in rural areas and technical complexities requiring skilled operators. Farmers often lack awareness or training to manage data-driven syste-ms, while interoperability issues between devices, power constraints, and data security concerns further hinder adoption.

High initial investment and maintenance costs. Lack of technical knowledge among farmers. Poor internet connectivity in rural areas. Data security and privacy concerns.

Future Scope

The future of smart farming is promising with the integration of IoT, AI, and machine learning. These technologies will further enhance automation, predictive analysis, and precision agriculture. Governments and research institutions are promoting digital agriculture to ensure food security and sustainable farming practices.

Personal Opinion: Opportunities and Challenges

From a practical and scientific standpoint, IoT-based smart farming aligns well with the principles of precision agriculture and integrated pest and nutrient management. As an agricultural professional, I see IoT as a “force multiplier” that can help smallholders in regions like Uttar Pradesh move from empirical, experience-based decisions toward data-driven management. Real-time soil and weather data can support timely interventions for disease and pest management, while automated irrigation can reduce water wastage and energy costs.

Conclusion

IoT applications in agriculture are reshaping traditional farming into a more precise, efficient, and sustainable enterprise. From soil and weather monitoring to automated irrigation and drone-based surveillance, IoT-enabled smart farming systems are

already delivering measurable gains in yield, water savings, and input efficiency. Case studies from India and other regions demonstrate that even small -scale farmers can benefit from these technologies when they are designed with affordability, usability, and local conditions in mind. As connectivity and computing power continue to improve, the integration of IoT with artificial intelligence and predictive analytics will further empower farmers to make informed, timely decisions. For the agricultural community, the task now is not whether to adopt IoT, but how to make it inclusive, resilient, and truly "smart" in the service of farmers and the planet.

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Waste to Wealth: Agricultural Residue Management

Ritik Roshan

Introduction

Agriculture has long been regarded as the backbone of the Indian economy, sustaining livelihoods and ensuring food security. However, alongside its productivity, it also generates an enormous volume of crop residues each year. Estimates suggest that India produces around 350-500 million tonnes of agricultural residue annually, of which nearly 90-100 million tonnes are burned in open fields. This widespread practice of stubble burning, particularly in the Indo-Gangetic plains, is often adopted as a quick and low-cost method to clear fields between cropping cycles. While it may offer immediate convenience, its long-term consequences are severe. Apart from contributing to air pollution and public health risks, it leads to the wastage of biomass that holds an estimated economic value of around $35 billion per year. What is often labelled as "waste" is, in reality, a valuable resource that remains largely underutilized due to systemic inefficiencies. The concept of "waste to wealth" aims to address this gap by promoting the productive use of agricultural residues. By converting crop leftovers into useful inputs and products, farmers can reduce costs, generate additional income, and contribute to a more sustainable agricultural system.

Overview of Agricultural Waste in India: Types, Quantity and Distribution

Agricultural waste in India is diverse and varies significantly across regions, depending on cropping patterns and agro-climatic conditions. It includes crop residues, agro-processing by-products, and livestock-based waste, all of which contribute to the total biomass generated.

Types of Agricultural Waste

Agricultural residues can broadly be classified into the following categories:

Crop residues: These include paddy straw, wheat stubble, maize stalks, and sugarcane trash. Cereals alone contribute approximately 350-360 million tonnes of residue annually, with paddy and wheat dominating in northern states.

Agro-processing by-products: Materials such as rice husk, bagasse, molasses, bran, and oilcake are generated in large quantities during processing.

Livestock-based waste: India produces millions of tonnes of manure annually, which is increasingly being utilized in composting and biogas production systems.

Quantity of Agricultural Waste

India generates an estimated 350-500 million tonnes of agricultural waste every year. Out of this, around 180 million tonnes remain surplus, meaning they are either underutilized or left unmanaged. A significant portion, approximately 15-20% of total residue (around 90-100 million tonnes) is burned

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annually, especially in northern India.This scale of biomass has the potential to support large-scale production of bioenergy, organic fertilizers, and industrial raw materials, yet much of it continues to go to waste.

Distribution and Regional Patterns

The distribution of agricultural waste is uneven across the country:

Northern plains (Punjab, Haryana, western Uttar Pradesh): Major contributors to paddy and wheat residues, with burning rates often exceeding 70-80% of surplus biomass during peak seasons.

Western and central India: States like Maharashtra generate around 45-50 million tonnes of crop residue annually, largely from sugarcane and oilseeds.

Southern India: Produces residues from paddy, coconut, and horticultural crops.

Eastern and northeastern regions: Generate large amounts of paddy residue, though utilization remains limited due to infrastructural gaps.

Traditional Methods of Agricultural Waste Management

Farmers have never ignored crop residues completely. In fact, traditional systems made use of them in practical ways, depending on local needs. Feeding livestock has always been one of the simplest uses. Many types of straw still serve as important roughage for cattle. In other cases, residues are used as household fuel or even for construction purposes like thatching. Some farmers also return residues to the soil, either by spreading them as mulch or mixing them into the field. This helps maintain moisture and improves soil health over time. Composting is another option, though it requires effort and patience. However, these methods have limits. They work well on a small scale but struggle to handle the massive quantities generated today. That is where burning becomes the "easy way out" quick, cheap, but harmful.

Composition of Agricultural Waste

The real "wealth" in this waste comes from its chemical makeup. Most agricultural residues are "lignocellulosic biomass" with three main parts:

Component	Average Percentage	Key Uses
Cellulose	30-45%	Breaks down into sugars for "2G ethanol".
Hemicellulose	20-30%	Used for chemicals and fermented fuels.
Lignin	10-25%	Gives energy for "bio-pellets"
Ash/Silica	5-15%	High in rice straw; used in "cement and bricks".

Note: Rice straw has especially high silica (about 19% ash), so it's not great for animal feed but perfect for industrial energy.

Policies Driving the "Waste to Wealth" Agenda

India's government has shifted from just punishing burning (with fines) to a "carrot and stick" approach, offering big financial incentives for better management.

- ✓ GOBARdhan (Galvanizing Organic Bio-Agro Resources Dhan)
- ✓ National Policy on Biofuels (Revised)
- ✓ Crop Residue Management (CRM) Scheme

- ✓ SATAT (Sustainable Alternative Towards Affordable Transportation):

Agricultural Waste Valorization: Biochemical, Biorefining and Bio-Conversion

Farm waste turns valuable through smart nature-based methods, no more burning. These fit villages or factories.

Biochemical Ways: Bacteria and enzymes eat straw/dung in tanks. Makes biogas, ethanol, compost. Low-cost village units. Haryana example: 50 homes get cooking gas.

Biorefining: Like a green factory splits waste into parts (cellulose etc.). Yields fuel, plastics, feed from one pile. Punjab firms buy straw for this.

Bio-Conversion: Digestion, pellets, quick compost. Straw to fuel balls, cobs to mushrooms. ₹50,000 digester under aid. Maharashtra briquettes power shops.

Closes farm loop: waste → energy/manure → better crops

How to Create Wealth from Agricultural Waste?

Farm waste can bring real money if handled right. No longer just burn or dump turn it into products farmers and groups can sell. Small steps lead to steady income.

Biogas/CBG Plants: Straw + dung make cooking gas and manure. Sell gas to firms under SATAT. Leftover slurry for fields. Villages cut fuel bills, earn extra.

Compost/Manure: Mix waste with dung in pits. Sell to other farmers. Cuts chemical costs, sells for ₹5-10 kg^{-1}. FPOs run village units.

Bio-Pellets/Briquettes: Press straw into fuel balls for factories/power plants. Small machine ₹2 lakh. Monthly income ₹50,000+ for groups.

Mushroom Farming: Grow on paddy straw in sheds. Quick 30-day crop, sells ₹200 kg^{-1}. Low start cost, good for youth/women.

Biochar: Burn waste safely for soil booster. Use own fields or sell. Carbon credits add bonus cash.

Collect & Supply: FPOs gather straw, sell to biofuel plants. ₹1,500-2,000 $tonne^{-1}$. Simple baler machine helps.

Eco-Products: Women groups make plates/boards from waste. Sell local markets. CRM aid covers machines.

The "Wealth" Message

Wealth from farm waste depends on "aggregation". One farmer with a small plot cannot run a biogas plant alone, but an FPO representing hundreds of farmers can. In 2026, the key to success is moving from "individual farming" to "collective biomass management", turning the whole village into a "Bio-Refinery Hub".

Conclusion

Agricultural waste holds the key to a brighter farming future in India. What was once burned as trouble now fuels homes, enriches soil, and fills farmers' pockets through biogas, compost, pellets, and more. Small steps like village FPOs and GOBARdhan machines turn "waste" into steady income ₹20,000 to ₹50,000 monthly for groups that team up. Like natural farming revives land with simple inputs, waste-to-wealth closes the circle:

crops grow, leftovers return as energy and fertility, farms thrive longer. With CRM aid, SATAT buy-back, and local know-how, villages become self-reliant hubs. No more smoke-filled skies, just clean air, strong soil, and real prosperity. The stalk that fed us can now power us forward.

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Soil Health Card Scheme: Impact and Challenges

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Abstract

Soil Health Card Scheme is a government initiative launched in 2015 that provides farmers with soil nutrient analysis cards every three years. In agriculture, it serves as a tool for balanced fertilizer use that enhances soil fertility, crop productivity, and reduces chemical overuse. The scheme integrates soil sampling, laboratory testing for 12 parameters like N, P, K, pH, and customized recommendations to ensure sustainable farming practices. Below is a structured explanation of the scheme, its achievements, challenges, with emphasis on field-practical points suitable for Indian farmers. In recent years, increasing farmers concern about issues such as soil degradation, food quality, environmental safety has lead to a substantial increase in the use of soil health management practices. Soil Health Card Scheme can be defined as a set of practices that supply nutrient information to farmers by conserve of soil resources and minimum supply of inorganic fertilizers to the crop fields.

Soil Health Card Scheme Feature

The Soil Health Card Scheme is an important initiative introduced to improve soil fertility and encourage balanced nutrient management in Indian agriculture. Under this scheme, farmers are provided with a Soil Health Card that contains detailed information about the nutrient status of their soil along with suitable recommendations for fertilizer use. The major feature of the scheme is scientific soil testing, where soil samples are collected from farmers' fields and analyzed in laboratories for parameters such as nitrogen, phosphorus, potassium, organic carbon, pH level, electrical conductivity, and micronutrients. Based on these results, customized advice is given to farmers for proper nutrient application according to crop needs. The cards are generally distributed after every two years to monitor soil condition regularly. Another important feature is that the scheme helps reduce excessive use of chemical fertilizers and promotes sustainable farming practices. It also supports farmers in improving crop productivity while lowering unnecessary expenditure on fertilizers. Through awareness campaigns and extension services, the scheme encourages farmers to understand the importance of maintaining healthy soils for long-term agricultural growth.

Key Achievements of Soil Health Card Scheme

The Soil Health Card Scheme has achieved remarkable success since its launch. Millions of farmers across the country have received soil health

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cards, making it one of the largest soil testing and advisory programs in the world. The scheme has created awareness among farmers about the significance of soil testing and balanced fertilizer use. Many farmers who followed the recommendations observed reduced expenditure on fertilizers because they applied nutrients according to actual soil requirement instead of guesswork. In several cases, crop yields and quality improved due to balanced nutrient management. The scheme has also encouraged better use of organic manures and micronutrients where deficiencies were identified. Another major achievement is the establishment and strengthening of soil testing laboratories, mobile testing vans, and technical infrastructure in rural areas. The large database created through soil testing has also helped agricultural scientists and policymakers identify nutrient-deficient regions and frame better agricultural policies. Overall, the scheme has contributed to improving productivity, reducing costs, and promoting sustainable soil management.

Key Challenges in Implementation

Despite its success, the scheme faces several challenges during implementation. One major problem is delay in collection of soil samples, testing and distribution of cards to farmers, especially in remote villages. Many soil testing laboratories have limited staff, insufficient equipment, and low testing capacity, which slows down the process. In some cases, farmers receive the cards but are unable to understand the recommendations because of low literacy levels or lack of proper guidance from extension workers. Another challenge is that some recommendations are generalized and may not perfectly match field-specific conditions, irrigation systems, or crop varieties. Many farmers continue to use traditional fertilizer practices instead of following scientific advice due to habit or lack of trust. In addition, regular updating of soil data every two years requires strong administration, trained manpower, and financial resources. Awareness regarding long-term soil health is still limited in many areas, which affects adoption of the scheme's recommendations.

Essential Tips for Farmers

- ✓ Always collect soil samples from 0-15 cm depth, multiple spots per field.
- ✓ Use recommended micro-nutrients like zinc even if costly initially.
- ✓ Link card advice with local weather for timely application.

Future Prospective of Soil Health Card Scheme

The future of the Soil Health Card Scheme is highly promising if supported with modern technology and effective extension services. Digital soil health cards linked with mobile applications can make recommendations easily accessible to farmers at any time. Use of GIS mapping, satellite technology and artificial intelligence can improve precision in soil testing and nutrient recommendations. Portable soil testing kits and village-level mini laboratories can help reduce delays and provide faster services in rural areas. Farmer training programs and awareness

campaigns should be expanded so that farmers can understand and implement the advice properly. The scheme can also be integrated with organic farming, natural farming, and climate-smart agriculture programs to improve sustainability. In the future, soil health cards may become an essential tool for precision farming and resource conservation. If effectively implemented, the scheme can play a major role in restoring soil fertility, increasing agricultural productivity, reducing input costs, and ensuring food security for the growing population while protecting natural resources for future generations.

Personal Opinion

Soil Health Card Scheme embodies sustainable agriculture, synergizing data-driven farming and soil regeneration. Its low-cost profile empowers smallholders (86% of farmers), but challenges like input supply must be fixed. In my view, without local training and subsidies, it's potential wasted integrate with vermicompost for organic boost!

Conclusion

Soil Health Card Scheme synergizes soil testing, farmer empowerment, and sustainability. Its high-impact fixes degraded lands (120 M ha), curbs overuse, positioning it indispensable for resilient farms. Widespread adoption, backed by labs and tech, promises greener fields essential for India's food security.

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Impact of Climate Change on Crop Yields

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Abstract

Climate change is one of the most pressing global challenges affecting agriculture production. Rising temperature, irregular rainfall pattern, increased frequency of extreme weather events, and elevated atmospheric carbon dioxide (CO_2) levels are significantly influencing crops growth and yields. Agricultural, being highly dependent on climate condition, is particularly vulnerable. Change in climate not only affect crops quality. Posing a threat to food security, especially in developing country like India.

Impact of climate change on crops yields

Climate change affects crops yield in multiple ways:

Temperature Rise: increased temperature as crops nuturity, reducing the time available for grain filling, which leads to lower to yields. Heat stress reduces critical growth stages (like flowering) can severely reduce productivity.

Erratic Rainfall Patterns: Unpredictable rainfall causes droughts or floods both of which negativity effect crops. Water stress reduce plant growth while excessive water leads to root damage and nutrient leaching.

Increased carbon dioxide level: Although higher carbon dioxide can enhance photosynthesis in some crops (like wheat and rice), often reduce nutritional quality and does not compensate for losses cause by heat and water stress.

Extreme weather event: Event such as cyclone, heat waves and cold waves damage crops directly leading to sudden yield loss.

Pest and disease outbreak: Warmer climates promoted the spread of pests and disease increasing crop damage and reducing productivity.

Solutions and Adaptation Strategies

To mitigate the negative impact of climate change on crop yield several strategies can be adopted:

Climate Resilience Crop Varieties: Development and use of drought resistant, heat tolerant and flood resistant crop varieties.

Improve Irrigation Practices: Technic such as drip irrigation and rain water harvesting help conserve water and ensure efficient use.

Crop diversification: Growing a variety of crops reduces risk and increases resilience to climate variability.

Sustainable agriculture practices: Practice like conservation agriculture organic farming and integrated nutrient management improve soil health and productivity.

Use of Technology: Weather forecasting tools,

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precision farming, and digital agriculture can help farmers make informed decision.

Policy support and farmer awareness: Government policies, subsidy and farmer education program are essential to promotes adaptation measures.

Impact of Climate Change on Crop Yields

Reduced Productivity: Global crop production is expected to drop, with significant declines predicted for wheat (up to 40% by 2080) and maize (up to 23% by 2080).

Extreme Weather Effects: Unpredictable precipitation and heatwaves cause increased salinity and pest/disease attacks, severely affecting crop output.

Regional Differences: While some northern latitudes may see slight benefits, lower latitudes and rice/wheat crops in regions like the Gangetic Plains face severe declines, with some sugarcane yields expected to fall by 21%.

Adaptation and Mitigation Strategies

Climate actions generally fall into one of two strategies: mitigation efforts to lower or remove greenhouse gas (GHG) emissions from the atmosphere, and adaptation efforts to help communities and ecosystems withstand the impacts of climate change. While mitigation and adaptation are both critical to addressing the climate crisis, they are often viewed as conflicting priorities vying for scarce climate finance. Of the two, mitigation has historically received more attention and investment. Meanwhile has lagged dramatically, putting communities at increasing risk from storms, floods, fires and other climate threat. But this divide between mitigation and adaptation actions doesn't always reflect the reality on the ground. In fact, methods and technologies that both curb climate change and cope with its impacts already exist and the two overlap more than is commonly thought. With the world dangerously that will bring even more severe impacts on people, ecosystems and economies than what we've seen so far, investing in solutions that can curb emissions and build resilience simultaneously is crucial.

Studies Show Climate Adaptation and Mitigation Can Work Together

WRI more than 300 adaptation investments and found that over half of them are also expected to reduce GHG emissions in the long run; for example, by adopting climate-smart farming practices, bringing trees and green spaces to cities, or introducing more resilient renewable energy sources.

Strategies like growing trees can help curb climate change while at the same time helping to buffer communities against its impacts, such as drought and flooding. Photo by Jake Lyell/ Alamy.

For some projects, the expected economic value of these emissions reductions met or even surpassed the projected resilience benefits. For example, the project was estimated to bring $350 million worth of emissions reductions, compared to $166.7 million in avoided losses and other social and developmental benefits. Similarly, the heritage Colombia project, which focused on sustainable land management, was expected to yield over $1.5 billion in emissions reductions and $1.35 billion in other benefits .However, most project designers did not fully assess the value of projected emissions reductions meaning the returns on these investments were under-estimated. Fully accounting for the mitigation benefits of adaptation projects can help crystallize their relationship and drive finance toward projects that achieve both.

Climate Solutions that Can Achieve both Mitigation and Adaptation

Below are examples of actions that can curb emissions in high-polluting sectors of the global economy while also improving our ability to deal with the worsening climate impacts.

Expand Decentralized Renewable Energy: Energy usage and demand is mounting worldwide, particularly in emerging markets and developing economies where populations and development needs are rapidly growing. At the same time, record heat and unprecedented storms due to climate change are damaging energy infrastructure and causing demand surges, leading to more frequent blackouts. The way electricity grids are designed contributes to this risk. Fossil fuels, which accounted for over50% of global electricity production in 2024, dominate centralized grids that consist of infrastructure connected over long distances. A disruption at one point in such vast systems can affect the entire network. This exposes power systems to climate variability at a time when extreme weather events are becoming more intense and frequent. By contrast, decentralized grids powered by renewables can reduce emissions and better withstand climate impacts. Given that renewable energy sources can be harnessed closer to their point of consumption and are affordable even at a small scale, they are particularly well suited to decentralized grids that have shorter transmission lines and smaller distrib-ution areas. In the event of a disaster, a community with an independent energy supply built to be climate resilient isn't affected by power outages in other areas. Smaller, more manageable power sources can also recover more rapidly from disasters. And solar panels or wind turbines that are not connected to any grid (such as rooftop solar and roof-mounted wind turbines) can to hospitals and other emergency services that are critical in the aftermath of floods, wildfires and other extreme weather events.

Regional Impacts: Different regions experience varying impacts. Tropical regions are more vulnerable due to already high temperatures. For example, studies in India show a projected decline in wheat yields due to rising temperatures, while some cooler regions may temporarily benefit from longer growing seasons.

Adaptation Strategies

Development of Climate-Resilient Crops: Breeding drought-resistant and heat-tolerant crop varieties can help mitigate yield losses.

Improved Irrigation Practices: Efficient water management techniques such as drip irrigation can reduce the impact of water scarcity.

Crop Diversification: Farmers can reduce risks by growing a variety of crops instead of relying on a single crop.

Use of Modern Technology: Technologies such as remote sensing, weather forecasting, and precision agriculture can help farmers adapt to changing conditions.

Conclusion

Climate change poses a serious threat to global crop yields and food security. While some regions may experience temporary benefits, the overall impact is expected to be negative. Immediate action, including sustainable agricultural practices and policy interventions, is necessary to minimize these impacts and ensure future food security.

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Climate-Smart Agriculture: Strategies for Sustainable Crop Production

Abhishek Kumar

Introduction

Climate change poses a significant threat to global agriculture by altering rainfall patterns, increasing temperatures, and intensifying extreme weather events. These changes directly affect crop productivity and food security. In response, Climate-Smart Agriculture (CSA) has emerged as a holistic approach that integrates sustainability, resilience, and mitigation strategies into agricultural systems. CSA aims to achieve three core objectives: increasing agricultural productivity, enhancing resilience to climate change, and reducing greenhouse gas (GHG) emissions. Sustainable crop production under CSA involves adopting innovative practices that optimize resource use while maintaining environmental integrity. This article discusses key CSA strategies that support sustainable crop production.

Precision Agriculture: Precision agriculture involves the use of advanced technologies such as sensors, GPS, and data analytics to manage farm inputs efficiently. It enables farmers to apply water, fertilizers, and pesticides in precise quantities and locations. This strategy improves productivity while minimizing environmental impacts by reducing excessive input use. Studies show that precision fertilization enhances yields and reduces GHG emissions by improving nutrient-use efficiency.

Climate-Resilient Crop Varieties: The development and adoption of climate-resilient crop varieties such as drought-tolerant, heat-resistant, and flood-resistant crops are crucial for adapting to climate variability.

Efficient Water Management: Water scarcity is one of the major challenges in agriculture under climate change. CSA promotes efficient irrigation techniques such as drip irrigation, sprinkler systems, and rainwater harvesting. Smart irrigation systems optimize water use, reduce wastage, and improve crop yields. These approaches increase resilience to drought and contribute to sustainable water resource management. These varieties ensure stable yields even under adverse environmental conditions, thereby improving food security. Crop breeding and genetic improvements are key CSA interventions that enhance resilience and productivity.

Soil Health Management: Healthy soils are fundamental to sustainable crop production. CSA encourages practices such as conservation tillage, crop rotation, organic manure application, and cover cropping. These methods improve soil structure, enhance water retention, and increase soil organic carbon, contributing to both productivity and carbon sequestration. Sustainable soil management also reduces dependency on chemical fertilizers, lowering environmental pollution.

Agroforestry Systems: Agroforestry integrates

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trees with crops and livestock systems. This approach enhances biodiversity, improves soil fertility, and provides additional income sources for farmers. Agroforestry also plays a significant role in carbon sequestration and climate mitigation, making it a vital CSA strategy.

Integrated Nutrient and Pest Management: CSA promotes integrated nutrient management (INM) and integrated pest management (IPM) to reduce reliance on synthetic inputs. INM combines organic and inorganic fertilizers to maintain soil fertility, while IPM uses biological control methods, crop rotation, and minimal chemical use to manage pests sustainably. These practices enhance ecosystem health and reduce environmental risks.

Crop Diversification and Rotation: Crop diversification involves growing multiple crops instead of monocropping, while crop rotation alternates crops across seasons. These practices improve soil fertility, break pest cycles, and reduce risks associated with climate variability. Diversified systems are more resilient and sustainable compared to conventional monoculture systems.

Smart Technologies and Digital Agriculture: The integration of digital technologies such as the Internet of Things (IoT), artificial intelligence, and remote sensing enhances decision-making in agriculture. Smart farming systems provide real-time data on soil moisture, weather conditions, and crop health, enabling efficient resource management and improved productivity. These technologies are essential for modern CSA implementation and sustainable agriculture development.

Benefits of Climate-Smart Agriculture

CSA offers multiple benefits for sustainable crop production:

Increased productivity: CSA practices can increase crop yields by 20-38% under climate stress conditions.

Enhanced resilience: Farmers can better cope with climate variability and extreme events.

Reduced emissions: Improved practices lower GHG emissions and promote carbon sequestration.

Resource efficiency: Optimized use of water, nutrients, and energy reduces costs and environmental impacts.

Conclusion

Climate-Smart Agriculture represents a transformative approach to achieving sustainable crop production in the face of climate change. By integrating innovative technologies with traditional knowledge, CSA enhances productivity, resilience, and environmental sustainability. The adoption of strategies such as precision agriculture, efficient water management, agroforestry, and soil health improvement is essential for ensuring long-term food security. Policymakers, researchers, and farmers must collaborate to scale up CSA practices and create resilient agricultural systems capable of meeting future global food demands.

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IoT-based Smart Agriculture Study.

Benefits of Humic Acid on Plant Growth, Development and Stress Tolerance

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Abstract

Humic acid (HA), a major component of humic substances derived from the decomposition of organic matter, has emerged as a crucial natural bio-stimulant in sustainable agriculture. This review synthesizes findings from recent peer-reviewed studies to evaluate the role of HA in enhancing plant growth, nutrient uptake, soil health, stress tolerance, and crop productivity. Evidence indicates that HA application can improve nitrogen use efficiency by up to 27% and increase crop yield by approximately 12%. These effects are mediated through modulation of plant physiological and biochemical processes, including hormonal signaling, membrane permeability, and antioxidant activity. Additionally, HA improves soil structure, microbial activity, and nutrient availability. Despite its significant benefits, the effectiveness of HA varies depending on its source, application rate, crop species, and environmental conditions. Overall, HA represents an eco-friendly alternative to conventional agrochemicals and holds strong potential for climate-resilient and sustainable crop production.

Introduction

Humic acid (HA) is a major fraction of humic substances formed through the microbial and chemical decomposition of plant and animal residues during the humification process. It represents a major component of soil organic matter and plays a critical role in regulating soil fertility and plant productivity (Zheng *et al.*, 2019). Chemically, HA is characterized by a complex structure rich in functional groups such as carboxyl and phenolic moieties, which confer high cation exchange capacity (CEC) and enable interactions with nutrients and soil minerals (Canellas *et al.*, 2015). In agricultural systems, HA functions as a natural biostimulant, enhancing plant growth through both direct and indirect mechanisms. It promotes root development by exhibiting auxin-like activity and improves nutrient uptake by increasing membrane permeability and chelating micronutrients (Olivares *et al.*, 2017). Additionally, HA improves soil structure, water retention, and microbial activity, thereby contributing to enhanced soil health (Muscolo *et al.*, 2013). Recent studies have highlighted its role in improving nutrient use efficiency and crop yield while enhancing tolerance to abiotic stresses such as drought and salinity (Ma *et al.*, 2024). These multifunctional properties make humic acid a key component in sustainable and climate-resilient agricultural practices.

Enhancement of Plant Growth and Development:

Humic acid promotes plant growth by modulating

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key physiological and biochemical processes. It exhibits auxin-like activity, stimulating root elongation, lateral root formation, and root hair development, which collectively enhance water and nutrient uptake. Additionally, HA influences enzymatic activities and gene expression associated with cell division and elongation (Trevisan *et al.*, 2010). Studies have demonstrated that HA regulates redox metabolism and photosynthetic efficiency, particularly in crops such as maize, resulting in improved biomass accumulation under both controlled and field conditions. These effects are often attributed to improved energy utilization and enhanced chlorophyll synthesis (Zandonadi *et al*., 2025).

Improvement in Nutrient Uptake and Use Efficiency: One of the most significant agronomic benefits of HA is its ability to improve nutrient availability and uptake efficiency. HA increases the cation exchange capacity (CEC) of soils, enhancing the retention and gradual release of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K). Furthermore, HA acts as a natural chelating agent, forming stable complexes with micronutrients such as iron, zinc, and manganese, thereby preventing their precipitation and increasing their bioavailability to plants. These mechanisms collectively facilitate efficient nutrient acquisition, particularly in nutrient-deficient soils. Meta-analytical evidence suggests that HA application can improve nitrogen use efficiency by up to 27% and increase overall crop yield by approximately 12%, highlighting its potential to reduce reliance on synthetic fertilizers (Ma *et al.*, 2024).

Soil Health and Fertility: Humic acid significantly contributes to soil health by improving physical, chemical, and biological properties. It enhances soil aggregation and porosity, leading to improved aeration, water infiltration, and root penetration. Additionally, HA increases soil water-holding capacity, which is particularly beneficial under drought conditions (Rose *et al.*, 2014). From a biochemical perspective, HA stimulates microbial activity and increases soil enzymatic functions involved in nutrient cycling. It also promotes beneficial plant–microbe interactions, including mycorrhizal associations, which further enhance nutrient uptake and plant growth.

Enhancement of Crop Yield and Quality: The application of HA has been associated with significant improvements in both crop yield and quality across a wide range of agricultural and horticultural crops. HA enhances chlorophyll content, photosynthetic activity, carbohydrate accumulation, and protein synthesis, all of which contribute to higher productivity (Singh *et al*., 2021). In addition to yield improvements, HA positively influences crop quality by increasing fruit size, weight, and nutritional composition. Field studies have reported substantial yield increases in crops such as wheat, maize, sugarcane, and potato following HA application (Bhatt and Singh, 2022).

Stress Tolerance and Abiotic Stress Mitigation: Humic acid plays a critical role in enhancing plant

tolerance to abiotic stresses, including drought, salinity, temperature extremes, and heavy metal toxicity. It achieves this by modulating antioxidant defense systems, leading to increased activity of enzymes such as superoxide dismutase, catalase, and peroxidase (Canellas *et al.*, 2015). HA also contributes to osmotic adjustment and maintains cellular homeostasis under stress conditions. In the case of heavy metal stress, HA reduces toxicity through chelation and immobilization mechanisms, thereby limiting metal uptake and translocation within the plant. (Rajkumar *et al*., 2020). These protective effects result in improved plant resilience and more stable yields under adverse environmental conditions.

Mechanisms of Action: The beneficial effects of HA on plant systems are mediated through multiple, interconnected mechanisms. HA influences hormonal signaling pathways, particularly those related to auxins, thereby promoting root development and overall plant growth. It enhances membrane permeability, facilitating efficient nutrient transport and uptake (Rose *et al.*, 2014). Additionally, HA regulates antioxidant enzyme activity and redox homeostasis, which are critical for stress adaptation. Emerging evidence also suggests that HA can modulate gene expression related to nutrient transporters and stress-responsive pathways, indicating its role at the molecular level.

Sustainable Agricultural Applications: Humic acid represents a sustainable alternative to chemical fertilizers due to its ability to enhance nutrient use efficiency and reduce environmental impacts. It can be applied through various methods, including soil incorporation, foliar sprays, and fertigation systems, making it adaptable to diverse cropping systems (Ma *et al.*, 2024). However, the effectiveness of HA is influenced by several factors, including its source (e.g., leonardite, compost), molecular composition, application rate, soil type, and crop species. Variability in these factors can lead to inconsistent results, highlighting the need for standardized formulations and optimized application protocols.

Conclusion

Humic acid is a multifunctional biostimulant that improves plant growth, nutrient uptake, soil health, stress tolerance, and crop yield. Its integration into agricultural practices offers an environmentally sustainable approach to enhancing crop productivity. Future research should focus on optimizing application rates, understanding molecular mechanisms, and evaluating crop-specific responses under different agro-climatic conditions.

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Green Leafy Vegetable: A Nutritional Source

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Abstract

Green leafy vegetables (GLVs) are an important component of a balanced and healthy diet due to their high nutritional value. They are rich sources of essential vitamins, minerals, dietary fiber, and bioactive compounds that support overall human health. GLVs such as spinach, fenugreek, moringa leaves, mint, and cabbage are widely consumed in India and play a significant role in meeting daily nutritional requirements. These vegetables contain important nutrients like iron, calcium, potassium, vitamin A, C, and K, along with various phytochemicals and antioxidants that help protect the body from several chronic diseases. Regular consumption of green leafy vegetables has been associated with improved digestion, better immunity, and reduced risk of health problems such as diabetes, cardiovascular diseases, and certain types of cancer. Therefore, the inclusion of green leafy vegetables in the daily diet is essential for improving nutritional security and promoting a healthy lifestyle.

Introduction

Balanced diet is the foundation of good health and the modern, trending healthy lifestyle. Balanced and a healthy diet alone lowers the chance of developing conditions like diabetes, cancer, heart problems and malnutrition, among others. One of the most prevalent components of a healthy diet that calls for a daily balanced diet is Green Leafy Vegetables (GLV). In diet menu consumed form of cooked and fresh GLV to meet every human being's nutritional needs. Greens are refer to those vegetables grown for their leafy portions and use in both cooking salads and as raw. As a group, they are recognized for their high mineral and vitamin contents; In recent years, they have gained new popularity or recognize from nutrition conscious consumers. Minerals like iron, calcium, potassium, and magnesium and vitamins including K, C, E, and many of the B vitamins found in dark green leafy vegetables. Additionally, they supply a range of phytonutrients that shield cells from harm and age-related issues, such as lutein, zeaxanthin, beta-carotene, and omega-3 fatty acids. Moreover, frequent consumption of GLV boost digestive enzymes in human digestion system. Green leafy vegetable also has a chlorophyll content (Gupta and Wagle, 1988).

Types of Green Leafy Vegetables

Vegetables are edible plant portions that are consumed by humans. In particular, green leafy vegetables (GLV) are frequently included in Indian diets. In India different vegetables are grown and harvested depending upon their place and season. The most popular GLV are spinach, fenugreek, Moringa leaves, mint, Cabbage, Curry leaves etc. Due to high moisture content Green leafy vegetables

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are seasonal and perishable. There are significant losses due to a lack of adequate storage, transportation and processing facilities at the point of production (Pande *et al*., 2000). Because GLVs can be easily incorporated into a regular diet and used to cure micronutrient shortages due to there economical, reasonable, sustainable and culturally acceptable. Some are suitable for growing during winter eg. Palak, spinach, fenugreek and mustard and others like amaranthus, portulaca and poi are suitable for growing during summer. The ten most popular green leafy vegetables are spinach, amaranthus, fenugreek, agathi, mustard, mint, gogu, alternanthera, drumstick leaves and coriander. Besides these, great variety of less familiar green leafy vegetables are also used locally in different parts of the country.

Fig. 1: Different types of green leafy vegetables

Vegetables are generally referred to as "protective foods" in the human diet because of their many health advantages, which may be attributed to their abundance of vitamins, vital fatty acids, minerals, amino acids, and dietary fiber. Contains many important bioactive substances. These include plant secondary metabolites that are beneficial to health and are made up of phenolic chemicals and antioxidants. India, endowed with favorable climatic conditions, provides opportunities for growing a wide variety of green leafy vegetables which form an important category of vegetables.

Nutritional composition of green leafy vegetables

It is commonly known that in order to achieve the World Health Organization's (WHO) recommended daily allotment of nutrition, one must consume at least 400g of fruit and non-starchy vegetables (WHO, 2013), and dietary guidelines for americans recommend five servings of vegetables per day based on an intake of 2000 calories (HHS/USDA, 2015). It is also recommended that one of the five servings of vegetables should be green leafy vegetables. Green leafy vegetables such as spinach (*Spinacia oleracea*), broccoli (*Brassica oleracea*) and duckweed (*Lemna perpusilla*) provide all the essential amino acids that meet the FAO nutrition standards (Edelman and Colt, 2016) as Protein content. In other hand Indian green leafy vegetables such as basella, fenugreek, hibiscus, coriander, cabbage and spinach are good sources of soluble dietary fiber content. Some major Green leafy vegetables nutritional composition shows in Table 1.

Health Benefits of Green Leafy Vegetable

Green Leafy vegetables are ideal for weight management as they are typically low in calories. They are useful in reducing the risk of cancer and heart disease since they are low in fat, high in dietary fiber, and rich in folic acid, vitamin C, potassium and magnesium, as well as containing a host of phytoche-

Table 1: Nutritional quality of some leafy vegetables

	Kale	Spinach	Chinese cabbage	Brussel sprout
Dietary fibers	85 mg	2.2 g	1.2 g	3.8 g
Protein	4.3 g	2.9 g	1.2 g	3.4 g
Vitamin A	9990 IU	9377 IU	318 IU	754 IU
Vitamin C	120 mg	28.1 mg	27 mg	85 mg
Vitamin K	704.8 ug	482.9 ug	43 ug	177 ug
Calcium	150 mg	99 mg	77 mg	42 mg
Folates	141 ug	194 ug	79 ug	61 ug
Iron	1.47 mg	2.7 mg	0.31 mg	1.4 mg
Potassium	491 mg	558 mg	238 mg	389 mg
Magnesium	47 mg	79 mg	13 mg	23 mg
Phosphorus	92 mg	49 mg	29 mg	69 mg
Zinc	0.56 mg	0.53 mg	0.23 mg	0.42 mg

micals, such as lutein, beta-cryptoxanthin, zeaxanthin, and beta carotene. An increase of one serving day^{-1} of green leafy vegetables were associated with a nine per cent lower risk of diabetes. The high level of vitamin K in greens makes them important for the production of osteocalcin, a protein essential for bone health. The risk of hip fracture in middle-aged women decreased by 45 per cent among those who consumed one or more servings of green leafy vegetables per day compared to those who consumed fewer servings. Leafy vegetables are the finest food source for pro-vitamins A and C. They also provide adequate levels of iron, folate, and other vital minerals. Additionally, they are a great source of phytochemicals, which help prevent cancer and heart disease.

Conclusion

Green leafy vegetables are an important component of a healthy and balanced diet. They are rich sources of essential vitamins, minerals, dietary fiber and various bioactive compounds that contribute significantly to human health. Regular consumption of these vegetables helps in improving immunity and preventing several chronic diseases such as diabetes, cardiovascular disorders and certain types of cancer. In addition, green leafy vegetables also play an important role in maintaining proper digestion and overall body functioning. Therefore, increasing the intake of green leafy vegetables in the daily diet can help improve nutritional security and promote a healthier lifestyle.

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Advances in Integrated Weed Management for Direct Seeded Rice

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Introduction

Direct seeded rice (DSR) is gaining importance as an alternative to traditional transplanted rice due to increasing labour scarcity, rising production costs and limited water availability. In this method, seeds are sown directly in the field, which eliminates nursery raising and transplanting operations. This results in significant savings in labour and irrigation water, estimated to be around 12-35%. However, one of the major challenges in DSR is severe weed infestation. Since the crop is not supported by standing water in the early stages, weeds emerge simultaneously with rice and compete aggressively for nutrients, moisture, light and space. If weeds are not controlled effectively, they can reduce yield drastically, with losses reported up to 90 %.

Why Weed Problem is Severe in DSR?

The weed problem in DSR is more severe compared to transplanted rice because of the absence of puddling and continuous water stagnation. Aerobic soil conditions favour the germination of a wide range of weed species, including grasses, sedges and broadleaf weeds. Dominant weeds such as *Echinochloa spp.* and *Cyperus spp.* grow rapidly and compete strongly with the crop. Additionally, the presence of a large soil weed seed bank and continuous emergence of weeds throughout the growing season make control more difficult. The most critical period of crop-weed competition in DSR is between 15 and 45 days after sowing, during which timely weed management is essential to prevent yield losses.

What is Integrated Weed Management (IWM)?

Integrated Weed Management (IWM) is a comprehensive and sustainable approach that combines multiple weed control methods to keep weed populations below economic threshold levels. It integrates preventive, cultural, mechanical and chemical methods in a complementary manner rather than relying on a single technique. The main objective of IWM is to improve weed control efficiency, reduce dependence on herbicides, minimize environmental risks and delay the development of herbicide resistance while maintaining crop productivity.

Components of IWM in Direct Seeded Rice

Preventive Measures: Preventive measures are essential to reduce the introduction and spread of weeds in the field. These include the use of certified and weed-free seeds, proper cleaning of farm machinery to avoid the transfer of weed seeds and maintenance of irrigation channels to prevent the

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entry of weed propagules. In addition, removing weeds from bunds and field borders before they set seeds helps in reducing the buildup of the soil seed bank. Such practices play a crucial role in lowering the initial weed population and enhancing the effectiveness of other control methods.

Cultural Methods: Cultural practices are aimed at improving the competitiveness of the crop over weeds. Techniques such as the stale seedbed method allow weeds to germinate before sowing and Senior Scientist AICRP on Forage Crops Unit, PJTAU eliminate them, thereby reducing early weed pressure. Maintaining optimum plant population through appropriate seed rate and spacing ensures better canopy coverage, which suppresses weed growth. The use of fast-growing and competitive rice varieties, adoption of crop rotation and application of mulch further restrict weed emergence by limiting light and space availability. Efficient nutrient management, particularly placing fertilizers close to crop roots, also helps the crop outcompete weeds.

Mechanical Methods: Mechanical weed control involves the physical removal of weeds through manual or mechanical means. Hand weeding is commonly practiced at 20 and 40 days after sowing to keep the field weed-free during the critical period. Mechanical weeders such as cono-weeders and rotary weeders can also be used to uproot weeds and improve soil aeration. Although these methods are effective and environmentally safe, they require significant labour and may not always be feasible under large-scale farming conditions.

Chemical Methods: Chemical control using herbicides is an important component of weed management in DSR, especially where labour availability is limited. Pre-emergence herbicides like pendimethalin are applied soon after sowing to prevent weed germination, while post-emergence herbicides such as bispyribac-sodium and imazeth-apyr are used to control weeds at later growth stages. The success of herbicide application depends on selecting the appropriate chemical based on weed flora, applying it at the correct time and using the recommended dose. Improper use may lead to crop injury and the development of herbicide-resistant weed populations.

Integrated Approach: An integrated approach that combines different weed management methods is the most effective strategy in DSR. For instance, the use of a stale seedbed followed by pre-emergence herbicide application and one or two hand weedings can provide season-long weed control. Similarly, combining mechanical weeding with post-emergence herbicides ensures better efficiency. This approach reduces reliance on any single method, lowers production costs and enhances crop yield while preventing the buildup of herbicide resistance

Advantages of Integrated Weed Management (IWM)

- ✓ Provides effective control of all types of weeds (grasses, sedges, broadleaf)
- ✓ Reduces dependence on herbicides, lowering input costs
- ✓ Helps delay herbicide resistance development in

weeds

- ✓ Improves crop growth and yield by reducing competition
- ✓ Cost-effective in long term due to reduced repeated applications
- ✓ Promotes eco-friendly and sustainable farming
- ✓ Improves soil health and fertility through better practices
- ✓ Ensures efficient use of nutrients, water and sunlight
- ✓ Maintains ecological balance and biodiversity

Conclusion

In conclusion, Integrated Weed Management is essential for the successful cultivation of direct seeded rice. Due to the high susceptibility of DSR to weed infestation, relying on a single control method is not sufficient. A well-planned combination of preventive, cultural, mechanical, and chemical practices ensures effective weed suppression, higher productivity and long-term sustainability. Adoption of IWM not only improves crop yield but also contributes to efficient resource use and environmental conservation, making it a vital component of modern rice production systems

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Carbon Footprint and Sustainability Assessment of Tomato Farming

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Introduction

Tomato (*Solanum lycopersicum*) is one of the most important vegetable crops cultivated globally due to its high nutritional value, economic importance and versatility in fresh and processed forms. It is rich in vitamins, minerals and bioactive compounds such as lycopene, which contribute to human health. However, modern tomato cultivation has become increasingly input-intensive, involving high use of chemical fertilizers, irrigation water, pesticides, plastic materials and energy. These practices contribute to environmental degradation and greenhouse gas (GHG) emissions. Therefore, understanding the carbon footprint and evaluating the sustainability of tomato farming systems is essential for achieving climate-resilient and sustainable agriculture.

Concept of Carbon Footprint in Tomato Farming : Carbon footprint refers to the total amount of greenhouse gases emitted during the production process, expressed as carbon dioxide equivalents (CO_2-eq). In tomato farming, it includes emissions from all stages starting from nursery raising to harvesting and sometimes up to post-harvest handling. These emissions are categorized into direct and indirect sources. Direct emissions mainly arise from soil processes, particularly nitrous oxide (N_2O) emissions due to nitrogen fertilizer application. Indirect emissions originate from the manufacturing, transportation and use of agricultural inputs such as fertilizers, pesticides, irrigation systems, machinery and fuel. The overall carbon footprint is usually expressed as kg CO_2-eq per tonne of tomato yield, which helps in comparing different production systems.

Sources of Greenhouse Gas Emissions in Tomato Cultivation: Tomato farming involves multiple operat-ions, each contributing to greenhouse gas emissions. Among these, fertilizer use is the most significant contributor. Excess application of nitrogen fertilizers leads to higher N_2O emissions, which have a global warming potential much higher than carbon dioxide. Irrigation is another major source of emissions, especially when water is pumped using diesel engines or electricity generated from fossil fuels. Energy use in land preparation, transplanting, intercultural operations and harvesting also adds to emissions. The use of plastic mulch, stakes, nursery trays and packaging materials contributes to embodied carbon.

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In protected cultivation systems such as polyhouses, emissions can increase significantly if heating, cooling or artificial lighting systems are used. Transportation of inputs and produce further increases the carbon footprint.

Life Cycle Assessment Approach: Carbon footprint in tomato farming is commonly evaluated using Life Cycle Assessment (LCA), which considers emissions across different stages of production. The "cradle-to-farm gate" approach includes emissions from input production, field operations and harvesting. In some cases, "cradle-to-consumer" assessment is also used, which includes transportation, storage and processing. LCA helps in identifying major emission hotspots within the production system and provides a scientific basis for improving efficiency. Studies have shown that open-field tomato cultivation generally has lower emissions compared to protected cultivation, although yield per unit area may be lower. Therefore, emission intensity per unit yield becomes an important parameter.

Environmental Sustainability Indicators: Environmental sustainability in tomato farming is assessed using several key indicators. Carbon footprint is the primary indicator, reflecting the total greenhouse gas emissions. Water-use efficiency is another important parameter, as tomato is a water-intensive crop. Efficient irrigation systems can significantly reduce water consumption and energy use. Nutrient-use efficiency indicates how effectively applied fertilizers are utilized by the crop. Low efficiency results in nutrient losses and environmental pollution. Soil health indicators such as organic carbon content, microbial activity and nutrient availability are also crucial for long-term sustainability. Excessive pesticide use can harm beneficial organisms and lead to ecological imbalance. Therefore, minimizing chemical inputs and promoting biodiversity are essential aspects of environmental sustainability.

Economic Sustainability in Tomato Farming: Economic sustainability focuses on profitability and efficient resource use. Tomato cultivation often involves high input costs, including seeds, fertilizers, pesticides, labour and irrigation. While high-input systems may increase yield, they can also reduce net returns if input costs are too high. Sustainable farming practices aim to optimize input use and improve cost efficiency. Adoption of improved varieties, precision farming techniques and integrated nutrient management can enhance yield while reducing production costs. Higher marketable yield, better quality fruits and reduced post-harvest losses contribute to improved economic sustainability.

Social Sustainability and Farmer Well-being: Social sustainability includes aspects such as labour efficiency, farmer safety, employment generation and consumer health. Tomato farming provides employment opportunities in rural areas, particularly in nursery raising, transplanting, harvesting and post-harvest operations. However, excessive use of pesticides poses health risks to farmers due to exposure during spraying. Residues in fruits can also

affect consumer health. Sustainable practices such as integrated pest management (IPM), use of biopesticides and proper safety measures can improve social sustainability. Ensuring fair market prices and access to resources also plays a significant role in improving farmer livelihoods.

Strategies to Reduce Carbon Footprint in Tomato Farming: Reducing the carbon footprint of tomato farming requires the adoption of integrated and climate-smart practices. Integrated nutrient management, combining organic manures, biofertilizers and reduced chemical fertilizers, helps in lowering emissions and improving soil health. Biofertilizers such as Azotobacter, phosphate-solubilizing bacteria (PSB) and potassium-solubilizing bacteria (KSB) enhance nutrient availability and reduce dependence on synthetic fertilizers. Organic amendments such as compost and farmyard manure improve soil organic carbon and microbial activity. Efficient irrigation systems like drip irrigation and fertigation reduce water and energy consumption. Precision nutrient management based on soil testing ensures optimal input application. Use of biodegradable mulches instead of plastic reduces environmental pollution. Adoption of renewable energy sources, such as solar pumps, can further reduce emissions. In protected cultivation, passive ventilation and energy-efficient technologies can minimize carbon emissions.

Role of Post-Harvest Management: Post-harvest losses in tomato are significant due to its perishable nature. Improper handling, storage and transportation can lead to considerable losses, increasing the effective carbon footprint per unit of consumable produce. Improving post-harvest management through proper grading, packaging, storage and transportation can reduce losses and improve sustainability. Value addition through processing into products such as puree, ketchup and dried tomato can enhance shelf life and economic returns.

Integrated Sustainability Approach: A sustainable tomato production system requires the integration of environmental, economic and social aspects. Efficient resource use, reduced emissions, improved soil health and better profitability must be achieved simultaneously. The integration of biofertilizers, organic inputs, precision farming, efficient irrigation and renewable energy forms a synergistic model for sustainable tomato production. This approach not only reduces environmental impact but also ensures long-term productivity and farmer income.

Conclusion: Carbon footprint and sustainability assess-ment provide a comprehensive understanding of the environmental impact and resource-use efficiency of tomato farming. Modern tomato cultivation must shift from input-intensive practices to resource-efficient and climate-smart approaches. By adopting integrated nutrient management, efficient irrigation, biofertilizers, organic amendments and improved post-harvest management, it is possible to reduce greenhouse gas emissions while maintaining high yield and quality. Sustainable tomato farming is essential for ensuring food security, environmental protection and economic viability in the face of climate change.

Integrated Farming System for Small Farmers: A Sustainable Approach

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Introduction

Integrated Farming Systems (IFS) represent a holistic agricultural approach that combines traditional farming practices with modern techniques to enhance productivity and sustainability. This multi-faceted farming model integrates crops, livestock, aquaculture, and agroforestry within a single operational unit. For small farmers, IFS offers numerous advantages, including improved resource utilization, increased income diversity, and enhanced resilience against environmental and market uncertainties. This article explores the various components of integrated farming systems, their benefits for small farmers, and their potential to contribute to sustainable agricultural practices.

Components of Integrated Farming Systems

An integrated farming system comprises several interconnected sectors that complement each other, optimizing resource use and reducing waste. Key components of IFS include:

Crop Production: In IFS, crop cultivation serves as the foundational element. Farmers can grow a variety of crops, including cereals, vegetables, and fruits, depending on local conditions and market demands. Crop rotation and intercropping practices are often employed to optimize soil health and increase yields.

Livestock Farming: Integrating livestock into the farming system enhances nutrient recycling. Animal waste can be used as organic fertilizer for crops, reducing dependence on chemical inputs. Livestock also provides additional income through meat, milk, and eggs, contributing to food security for smallholder families.

Aquaculture: Incorporating fish farming within agricultural systems can enhance food production and profitability. Nutrient runoff from crops and livestock can contribute to fish growth in ponds, creating a symbiotic relationship that maximizes the use of land and water resources.

Agroforestry: The integration of trees into farming systems promotes biodiversity and provides shade, wind protection, and additional products such as fruits, nuts, and timber. Agroforestry systems can improve soil fertility, enhance water retention, and support ecosystem health.

Waste Management and Recycling: The IFS model emphasizes recycling organic waste produced by crops and livestock, thereby minimizing waste and enhancing sustainability. Composting, vermi-culture, and biogas production are common practices that convert waste into valuable resources.

Benefits of Integrated Farming Systems for Small Farmers

Integrated Farming Systems offer a range of benefits tailored to the needs of small farmers. One of the most significant advantages is increased resou-

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rce efficiency. By combining various agricultural practices, smallholders can make the most of limited resources, such as land, water, and nutrients. For example, using animal manure as an organic fertilizer reduces the need for synthetic fertilizers, lowering production costs. Moreover, IFS promotes income diversification. By simultaneously engaging in crop production, livestock rearing, and aquaculture, small farmers can access multiple income streams, enhancing their financial stability. This diversified approach helps mitigate risks associated with market fluctuations or crop failures. Integrated Farming Systems also improve resilience against environmental stressors. By optimizing biodiversity and utilizing various agricultural activities, small farmers can better withstand adverse weather conditions, pests, and diseases. For instance, the integration of agroforestry practices can improve soil quality and help retain moisture, thus supporting crops during drought periods. Furthermore, IFS supports sustainable agricultural practices. By minimizing chemical inputs and maximizing resource recycling, integrated farming systems promote environmental stewardship. The reduction of synthetic fertilizers and pesticides can lead to improved soil health and biodiversity, contributing to ecosystem resilience.

Role of Technology in Integrated Farming Systems

The integration of technology represents a crucial advancement in the implementation and efficiency of IFS. Precision agriculture, data analytics and mobile technology can significantly enhance small farmers' ability to monitor and manage their integrated systems. Precision agriculture tools allow farmers to track crop health, soil conditions, and livestock performance in real time. By using sensors or drones, farmers can make informed decisions regarding irrigation, nutrient application, and pest management, optimizing resource use. Data analytics plays a vital role in supporting planning and decision-making. By analyzing market data, weather patterns, and production trends, farmers can adjust their practices to increase productivity and profitability. Additionally, mobile applications can provide access to vital information regarding best practices, market prices, and farming techniques. The development of affordable technologies and innovations tailored for smallholders is crucial for the successful adoption of integrated farming systems. Initiatives aimed at training farmers on technology utilization can also enhance their capabilities and knowledge, empowering them to maximize their integrated farming practices.

Challenges Facing Integrated Farming Systems

Despite the many benefits of Integrated Farming Systems, several challenges hinder their widespread adoption by small farmers. One major challenge is the lack of access to resources and capital. Small farmers often face financial constraints that limit their ability to invest in the necessary infrastructure, technology, and inputs required for implementing an integrated system. Additionally, farmers may require training and education to effect-

ively combine various agricultural practices. Knowledge gaps regarding best practices for integrating different components can lead to inefficiencies or mismanagement of the system. Access to extension services and training programs is crucial for equipping farmers with the necessary skills and knowledge. Market access remains a significant hurdle for small farmers. In many cases, effective marketing channels for diversified products are lacking, limiting the profitability of integrated farming operations. Strengthening market linkages and creating cooperatives can empower smallholders to negotiate better prices and access larger markets for their products. Furthermore, land tenure security can be a challenge in some regions. Insecure land rights may discourage investments in long-term integrated farming practices. Policies that promote secure land tenure are essential for encouraging farmers to adopt integrated systems that require significant upfront investments.

Impact on Small Farmers and Sustainability

Integrated Farming Systems can have a profound impact on small farmers, enhancing their productivity, resilience, and sustainability. By adopting IFS, small farmers can improve food security for their families and communities by producing a diverse range of food items, including grains, vegetables, fruits, and animal products. This diversity not only addresses nutritional needs but also reduces dependency on single crops, lowering the risks associated with market volatility and climatic uncertainties.

Moreover, the ecological benefits of IFS promote long-term sustainability. By incorporating various agricultural practices that enhance biodiversity and soil health, integrated farming systems contribute to sustainable land management. Consequently, these practices can help combat soil erosion, conserve water, improve climate resilience, and strengthen local ecosystems. From an economic perspective, IFS can lead to increased income and reduced poverty for smallholder farmers, allowing them to invest in education, healthcare, and improved living standards. As farmers enhance their livelihoods, they can also contribute to rural development, creating job opportunities and promoting economic growth in their communities.

Conclusion

Integrated Farming Systems provide a sustainable and holistic approach to farming that can greatly benefit small farmers. By combining crops, livestock, aquaculture, and agroforestry, farmers can optimize resource use, enhance productivity, and diversify their income sources. Despite the challenges of implementing IFS, including limited access to resources, knowledge gaps, and market access, the positive impacts on food security, environmental sustainability, and rural development make IFS a viable solution for smallholder agriculture. As we move toward a future focused on sustainability and resilience in agriculture, integrating farming systems will play a pivotal role in addressing the challenges faced by small farmers. Policymakers, extension services, and agricultural

organizations must work collaboratively to provide education, resources, and market access to empower smallholders to adopt integrated farming practices. By doing so, we can create a more resilient agricultural sector that supports both farmers and their communities.

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Nursery Management of Medicinal and Aromatic Plants

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Abstract

Medicinal and aromatic plants (MAPs) constitute a vital component of traditional and modern healthcare systems and contribute significantly to the pharmaceutical, cosmetic, perfumery, food & flavor industries. The quality and productivity of these crops largely depend on the availability of healthy, uniform, and disease-free planting material. Nursery management plays a crucial role in the successful establishment of medicinal and aromatic plant cultivation. This article highlights the principles, techniques, and best Agro-technologies for nursery management of MAPs to ensure sustainable quality planting material production as well as quality raw material.

Introduction

Medicinal and aromatic plants have been used since ancient times for their therapeutic, aromatic, and economic value. With increasing global demand for herbal medicines and natural products, systematic cultivation of MAPs has gained importance. Nursery management is the foundation of commercial cultivation, as it ensures the production of high-quality planting material under controlled conditions. Proper nursery practices not only enhance germination and survival rates but also maintain genetic purity and improve overall crop performance. A nursery is a place or fields where we are growing young, healthy plants for raised propagated and cared like watering, insect-pest and disease protection etc. until they are ready for transplanting in main field or place. Nurseries required ordinary setups like raised beds to sophisticated facilities with controlled environments. They play a crucial role in medicinal and aromatic crops by providing a steady supply of healthy, quality seedlings and other planting materials.

What is nursery?

Nursery is a place or field where we are growing plant and propagated to a desired size. Mostly the plants concerned are for gardening, medicinal and aromatic plants production, forestry or conservation, rather than agriculture.

Importance of Nursery Management

Nursery management involves raising seedlings or vegetatively propagated plants in a protected environment until they are ready for transplanting. In medicinal and aromatic plants, nursery management is particularly important due to the sensitivity of seedlings and the high value of the final produce. Efficient nursery practices help in:

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- ✓ Producing uniform and vigorous planting material.
- ✓ Ensuring better field establishment and reduced mortality.
- ✓ Saving seed and planting material.
- ✓ Preventing pest and disease incidence at early stages.
- ✓ Maintaining quality and standardization of medicinal produce.

Selection of Nursery Site: The selection of an appropriate site is the first step in nursery establishment. An ideal nursery site should have well-drained, fertile soil rich in organic matter and should be free from water logging. Adequate sunlight, reliable irrigation facilities, and protection from strong winds and grazing animals are essential. Slightly elevated land with good drainage is preferred to avoid fungal diseases.

Soil and Growing Media: Soil used in nursery beds should be light, friable, and free from weeds and pathogens. A suitable growing medium generally consists of garden soil, sand, and well-decomposed farmyard manure or compost in equal proportions. For container nurseries, soilless media such as cocopeat, vermiculite, and perlite are widely used to ensure better aeration and moisture retention. Soil sterilization through solarization or use of bio-control agents is recommended to control soil-borne diseases, especially damping-off.

Methods of Propagation

Seed Propagation: Many medicinal and aromatic plants such as *Ashwagandha*, *Isabgol*, *Senna*, *Tulsi*, *Satawer*, *Kalmegh*, *Salvia* and *Chemomile* are propagated through seeds. High-quality, viable, and certified seeds should be used. Seed treatment with bio-fungicides or microbial inoculants helps improve germination and reduce disease incidence.

Fig. (a) Ashwagandha, (b) Chemomile, seed propagation in raised bed

Vegetative Propagation: Vegetative propagation ensures true-to-type plants and uniform growth. Common methods include stem cuttings, root cuttings, rhizomes, slips, bulbs, and suckers. Plants like *Mint*, *Lemongrass*, *Vetiver*, *Patchouli*, and *Turmeric* are commonly propagated vegetatively. Use of rooting hormones and mist chambers enhances rooting success.

Fig. (a) Geranium (b) Patchouli, vegetative propagation in poly bags

Nursery Management Practices

Irrigation: Light and frequent irrigation is essential to maintain optimum moisture levels. Over-irrigation should be avoided, as it may lead to root rot and fungal infections.

Shading and Protection: Young seedlings require partial shade to protect them from excessive heat and sunlight. Shade nets (30-50%) are commonly used in MAP nurseries.

Weed and Nutrient Management: Regular removal of weeds is necessary to prevent competition for nutrients and moisture. Application of organic manures, vermicompost, and bio-fertilizers promotes healthy seedling growth while maintaining medicinal quality.

Pest and Disease Management: Nursery plants are highly susceptible to pests and diseases such as damping-off, leaf spots, aphids, and mites. Preventive measures include proper sanitation, optimum spacing, and use of disease-free planting material. Integrated Pest Management (IPM) practices, including neem-based products and biological control agents, are preferred over chemical pesticides to preserve medicinal value.

Hardening and Transplanting: Before transplanting, seedlings should be hardened by gradually reducing irrigation and exposing them to field conditions. Hardening improves stress tolerance and survival rate after transplanting. Transplanting should be done during cooler hours to minimize shock.

Conclusion

Nursery management is a critical and indispensable component in the cultivation of medicinal and aromatic plants. Adoption of scientific nursery techniques ensures the availability of healthy, vigorous, and high-quality planting material, which directly influences crop yield and quality. With increasing emphasis on sustainable and organic production of herbal raw materials, efficient nursery management practices will play a key role in strengthening the medicinal and aromatic plant sector.

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Rose Apple: The Fragrant Tropical Jewel

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Introduction

Rose apple, scientifically known as *Syzygium jambos* (L.) Alston, is a perennial evergreen fruit tree valued for its attractive appearance, pleasant fragrance, and refreshing fruits. Although often described as a shrub when young, it usually develops into a small to medium-sized tree. The species is believed to have originated in the Southeast Asia, particularly the East Indies and Malaya, from where it gradually spread to many tropical and subtropical parts of the world. In India, rose apple is known by several regional names. It is commonly called Gulab Jamun in Hindi, Paneer hannu in Kannada, Champai in Tamil and Boga Jamun in Assamese. Its cultivation and natural occurrence in diverse localities reflect its wide adaptation and cultural importance.

Distribution and cultivation: Over time, rose apple spread far beyond its native region and is now found in tropical areas such as the Caribbean, Fiji, Australia, Myanmar, and Mexico. By 1821, it had already been introduced into botanical gardens across the West Indies, including Puerto Rico. Within India, rose apple is mainly cultivated in the states of Kerala, Karnataka, Tamil Nadu, and in the northeastern region. It is generally propagated by seed, though vegetative methods such as air-layering are also practiced.

Botanical features: Rose apple is an evergreen tree that generally reaches a height of 7.5-12 metres. It develops a broad canopy with slender spreading branches, forming a dense crown. The leaves are opposite, narrow to elliptical in shape, leathery, glossy, and dark green at maturity, while young leaves often appear reddish. The flowers are attractive and fragrant, borne in terminal clusters. Each flower bears numerous conspicuous stamens, giving the tree considerable ornamental appeal. The fruit is usually greenish-yellow to pale yellow, sometimes with a pinkish tinge. Its skin is smooth and thin, enclosing crisp, juicy, mildly sweet flesh with a characteristic rose-like aroma. A mature fruit typically contains one to four brown, hard, polyembryonic seeds. One simple maturity sign is that the seed becomes loose and produces a rattling sound when the fruit is gently shaken.

Climate and soil requirements: Rose apple thrives well under tropical and semi-tropical conditions. In India, it can grow up to an altitude of about 1,350 metres (4,400 feet) above sea level. The crop performs best in regions receiving 1,200-1,600 mm annual rainfall, though it can survive under rainfall as low as 700 mm and as high as 4,000 mm. The ideal

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temperature range is 18-38°C, but established trees can tolerate temperatures between 5-40°C. Mature trees show moderate tolerance to frost, whereas young plants require protection. The species adapts to a wide range of soils, including sandy soils with low organic matter. However, deep, red loamy, well-drained soils are considered most suitable. It can also tolerate high groundwater levels and temporary waterlogging.

Propagation: Most rose apple plants are raised from seed. Seedlings may produce one to three sprouts, but they often vary in growth and fruit characteristics. For true-to-type planting material, vegetative propagation is preferred. Hardwood cuttings generally show poor rooting, even with growth promoters. Semi-hardwood cuttings perform somewhat better. Air-layering has given promising results, especially when performed during spring or monsoon. Treatment with 1,000 ppm NAA has shown good rooting success, and studies in West Bengal have reported 80-100% success during July. Seedling trees usually begin fruiting after 5-6 years, while vegetatively propagated plants may bear earlier, often within 3-4 years.

Planting and orchard management: Rose apple is commonly planted as a backyard fruit tree or ornamental species. For commercial cultivation, a spacing of 5-6 × 5-6 metres are generally recommended. The ideal planting season in India is June-July. Young plants require regular irrigation during establishment. Mature trees are comparatively hardy and may survive under rainfed conditions but supplemental irrigation during flowering and fruit development improves yield and fruit quality. Intercropping with legumes or vegetables can be practiced during the early years of orchard establishment. Maintaining weed-free basins and proper cultural management helps ensure healthy growth.

Training and pruning: Regular heavy pruning is usually unnecessary. However, young plants benefit from proper training to develop a strong framework. The main stem should be kept clear up to about 90 cm above ground level by removing basal sprouts and unwanted shoots. Diseased, damaged, and broken branches should be removed promptly. Because branches are somewhat delicate, trees are often trained to maintain a lower and bushier canopy.

Fertilizer requirement: Rose apple generally responds modestly to fertilizers but benefits from organic manuring. During the pre-bearing period, application of about 20 kg farmyard manure (FYM) per plant is recommended. Bearing trees may receive 50 kg FYM per tree annually. For 4-5-year-old plantations, a suggested fertilizer schedule is:

- ✓ **FYM:** 50 kg plant^{-1} year^{-1}
- ✓ **Nitrogen:** 500 g plant^{-1} year^{-1}
- ✓ **Phosphorus:** 200 g plant^{-1} year^{-1}
- ✓ **Potassium:** 200 g plant^{-1} year^{-1}

Fertilizer application is generally done during October and again in February-March to encourage flowering and fruit set.

Flowering and fruiting: The flowering and fruiting period varies across regions. In southern India, flow-

ering generally occurs during January, and fruits ripen in March-April. In some other regions, ripening extends up to June-July. Rose apples are non-climacteric fruits, meaning they should be harvested fully ripe. Fruit development follows a single sigmoid growth pattern and fruits usually reach maturity around 80 days after fruit set. During maturation, total soluble solids and sugars increase, while acidity decreases. Ascorbic acid content rises during early fruit development and declines slightly as the fruit approaches full ripeness.

Yield and harvesting: An average healthy tree may produce 25-50 kg of fruits annually. The fruits are harvested when they change colour from green to light yellow. Rose apple fruits are delicate, easily bruised, and highly perishable because of their thin skin and high moisture content. Therefore, harvesting is generally done manually and with care. Damaged fruits should be removed before packing and transport.

Nutritional value: Rose apple is valued not only for its pleasant flavour but also for its nutritional richness. Per 100 g of edible portion, the fruit contains approximately:

- ✓ Water: 84-93 g
- ✓ Energy: 25 kcal
- ✓ Protein: 0.6 g
- ✓ Fat: 0.3 g
- ✓ Calcium: 29 mg
- ✓ Phosphorus: 123 mg
- ✓ Magnesium: 5 mg
- ✓ Iron: 0.07 mg
- ✓ Vitamin C: 22.3 mg
- ✓ Vitamin A: 339 IU

The fruit also contains small amounts of vitamin B-complex minerals and trace elements.

Medicinal importance: Traditionally, rose apple has been valued for several medicinal properties. The fruits are rich in antioxidants and are believed to possess antibacterial, anti-inflammatory, and protective health benefits. They are commonly used in traditional remedies for digestion, sore throat relief, skin irritation, minor wounds, and cooling effects. In folk medicine, rose apple is also regarded as beneficial for the brain and liver and some communities believe its seeds possess mild anaesthetic properties.

Pests and diseases: Rose apple is relatively hardy but may be affected by aphids, fruit flies and scale insects. Fruit flies can cause significant damage during ripening. Common fungal diseases include:

- ✓ Leaf spot caused by *Cercospora*, *Gloeosporium*, and *Phyllosticta* species
- ✓ Anthracnose caused by *Glomerella cingulata*
- ✓ Root rot caused by *Fusarium* species
- ✓ Myrtle rust caused by *Puccinia psidii*

Proper orchard sanitation, pruning of affected branches, and timely plant protection measures are helpful in management.

Important variety: A notable improved selection is Arka Neelachal Akshay, developed by the ICAR-Indian Institute of Horticultural Research through seedling selection. This variety is known for:

- ✓ Average fruit weight of about 30 g

- ✓ 10-12 kg fruit yield tree^{-1}
- ✓ 77.5% pulp content
- ✓ 14-15°Brix total soluble solids

Post-harvest management: Because rose apple fruits deteriorate rapidly after harvest, post-harvest handling is important. Studies from Thailand have shown that treatment with 1-MCP (1 µL L^{-1}) can extend shelf life and maintain fruit quality.Coating fruits with 2% chitosan has also been reported to reduce moisture loss, preserve firmness, and improve storage life.

Culinary uses: Rose apple is usually eaten fresh and is especially popular among children. Its delicate floral aroma makes it refreshing when consumed directly from the tree. The fruit is also used in a variety of culinary preparations such as:

- ✓ Fresh salads
- ✓ Jams and jellies
- ✓ Syrups and beverages
- ✓ Preserves and candies
- ✓ Desserts cooked with sugar and spices

Because the pulp contains appreciable pectin, it is also suitable as a natural thickening ingredient.

Cultural significance: In Buddhism, the rose apple tree is regarded as sacred and is sometimes associated with enlightenment. In ancient Sanskrit literature, India was referred to as Jambudvipa, meaning "land of the rose apple." This gives the species a notable place in South Asian cultural history.

In summary, rose apple is a versatile tropical fruit tree valued for its attractive appearance, fragrant fruits, nutritional richness, medicinal importance, and adaptability. With greater research on orchard management and commercial cultivation, it has strong potential to become a more important underutilized fruit crop in India.

Citrus Greening: The Unseen Epidemic Threatening Global Citrus Orchards

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Citrus greening, also known as Huanglongbing (HLB), is one of the most destructive diseases affecting citrus worldwide. The disease is caused by phloem-inhabiting bacteria, primarily *Candidatus Liberibacter asiaticus*, and is transmitted mainly by the Asian citrus psyllid (*Diaphorina citri*) (Bove, 2006). HLB has emerged as a major threat to global citrus production because it affects tree health, fruit quality and orchard productivity, often leading to eventual tree death. Due to its rapid spread and lack of an effective cure, citrus greening is often described as an unseen epidemic threatening the sustainability of citrus orchards. The disease was first reported in China in the early 20th century and has since spread across Asia, Africa and the Americas. Today, major citrus-producing countries such as India, Brazil, China and the United States are facing severe challenges due to HLB (Gottwald, 2010). Infected orchards often show significant reductions in fruit yield, poor fruit quality and increased management costs. In regions like Florida, HLB has caused dramatic declines in citrus production, impacting growers and citrus industries alike. HLB is called an "unseen epidemic" because symptoms may remain hidden for months or years after infection. During this period, infected trees serve as sources of inoculum while appearing relatively healthy. This makes early detection difficult and allows the disease to spread silently through orchards. Once infected, the bacteria colonize the phloem tissues and disrupt nutrient transport, gradually weakening the tree (Bove, 2006).

Symptoms of citrus greening are diverse and often resemble nutrient deficiencies, making diagnosis challenging. Common foliar symptoms include blotchy mottle, yellow shoots, vein corking, and asymmetrical chlorosis. Fruits from infected trees are often small, lopsided, poorly colored and remain partially green at maturity. Such fruits usually contain aborted seeds and produce bitter and low-quality juice. Premature fruit drop, canopy thinning, root decline and eventual tree death are also common in advanced stages (Gottwald *et al.*, 2007). The disease spreads mainly through the Asian citrus psyllid, which acquires the bacterium while feeding on infected plants and transmits it to healthy trees during subsequent feeding. Movement of infected nursery stock also contributes significantly to long-distance spread. Warm temperatures and dense citrus

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plantings often favor psyllid multiplication and disease development. Therefore, both vector biology and human-mediated movement of planting materials play major roles in HLB epidemiology. The economic impact of citrus greening is enormous. Reduced yields, declining fruit quality and increased expenses for vector control and orchard management have caused major financial losses. In severe cases, growers abandon orchards due to unprofitability. Beyond economics, HLB threatens the sustainability of citrus-based agroecosystems and the livelihoods dependent on them. Since no permanent cure exists, management of HLB relies on integrated disease management approaches. Vector control remains one of the most important strategies. Management of Asian citrus psyllid through insecticides, biological control agents such as parasitoids, and area-wide pest suppression programs helps reduce disease spread (Hall *et al.*, 2013). However, vector management alone is insufficient.

Another important strategy is removal of infected trees to reduce inoculum sources. Early detection and prompt rogueing can help slow disease progression in orchards. Use of certified disease-free planting material is equally critical to prevent introduction of infected propagules into new areas.

Improved cultural practices and nutritional management have also been used to sustain productivity of infected trees. Balanced fertilization, irrigation management and improved orchard care may help delay decline, though these measures do not eliminate the pathogen. Recently, research has focused on developing HLB-tolerant rootstocks, resistant cultivars, antimicrobial treatments and biotechnological solutions such as gene editing. Modern technologies are also improving early disease detection. Molecular diagnostic tools such as PCR enable accurate identification of the pathogen even before visible symptoms appear. Remote sensing, biosensors and artificial intelligence-based approaches are increasingly being explored for rapid field-level diagnosis.

The long-term management of citrus greening will likely depend on integrated approaches combining vector control, resistant varieties, clean nursery stock and advanced detection technologies. International collaboration, strong quarantine measures and grower awareness are also essential in limiting further spread.

In conclusion, citrus greening represents one of the greatest threats to global citrus production. Its hidden nature, devastating impact and lack of a cure make it a serious agricultural challenge. However, continued research, integrated disease management, and coordinated efforts offer hope for sustaining citrus orchards in the face of this unseen epidemic.

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Crop Diversification as a Climate Change Mitigation and Adaptation Strategy: Evidence from Global Agroecosystems

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Abstract

Agriculture is increasingly vulnerable to climate variability, driven by rising temperatures, erratic rainfall, and frequent extreme weather events. These challenges demand resilient and sustainable production strategies that go beyond conventional monocropping systems. Crop diversification has emerged as a scientifically robust and field-tested approach that simultaneously enhances climate resilience and reduces environmental impact. This article synthesizes global evidence on the role of diversification across agroecosystems, highlighting its contributions to soil health, biodiversity conservation, yield stability, and farmer livelihoods. Evidence from Asia, Africa, Europe, and the Americas demonstrates that diversified systems outperform monocultures in both ecological sustainability and economic resilience, positioning crop diversification as a cornerstone of climate-smart agriculture (FAO, 2019; IPCC, 2022).

Introduction

Agriculture is highly sensitive to climate, depending on factors such as temperature and rainfall. Climate change-characterized by rising temperatures, erratic precipitation, and extreme events like droughts and floods-has increased production risks and threatened food security. Conventional monocropping systems are becoming more vulnerable to pests, diseases and environmental stress, often leading to soil degradation and biodiversity loss. In this context, crop diversification is gaining importance as a sustainable approach that enhances ecological balance, improves resource use efficiency, and strengthens resilience to climate variability (Lin, 2011; Altieri *et al.*, 2015; Tilman *et Al.*, 2020; Lal, 2021).

Understanding Crop Diversification: Crop diversification involves growing a variety of crops within a farming system through practices like intercropping, crop rotation, mixed cropping, and agroforestry. It enhances biodiversity and improves ecosystem functioning by efficiently utilizing resources such as sunlight, water, and nutrients through crop complementarity. Addition-ally, diversification reduces farmers' risks by minimizing dependence on a single crop, thereby improving resilience to climate variability and market fluctuations (Altieri, 2020; Tilman *et al.*, 2020; Birthal *et al.*, 2015).

Crop Diversification as an Adaptation Strategy:

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Crop diversification improves climate adaptation by reducing the risk of total crop failure, as different crops respond differently to stresses like drought, heat, and floods. It also enhances soil health by increasing organic matter, which improves water retention, reduces erosion, and maintains fertility-especially important under erratic rainfall conditions (Lin, 2011; Lal, 2021). Diversified systems further help in managing pests and diseases by breaking pest cycles and supporting natural predators, thereby lowering reliance on chemical inputs (Altieri *et al*., 2015; Pretty, 2021). Economically, it provides farmers with multiple income sources, increasing resilience against climate shocks and market fluctuations (Birthal *et al*., 2015).

Crop Diversification as a Mitigation Strategy:

The contribution of crop diversification to climate change mitigation, while often receiving less attention than adaptation, is considerable and well-documented. Diversified systems particularly those that incorporate leguminous species and perennial trees through agroforestry arrangements enhance carbon sequestration both in plant biomass and below-ground in soil organic matter. Legumes fix atmospheric nitrogen biologically, reducing the need for synthetic nitrogen fertilizers, the manufacture and application of which are associated with substantial nitrous oxide emissions. Perennial components in agroforestry systems serve as long-term carbon sinks, sequestering carbon over multi-decade timescales that far exceed those achievable through annual crop rotations alone (Lal, 2016; Pretty *et al*, 2018). Beyond carbon storage, crop diversification supports mitigation objectives through its role in sustaining biodiversity and ecological functioning. Diversified systems create structural and functional habitat diversity that supports pollinators, soil organisms, and other beneficial fauna whose contributions to ecosystem services are fundamental to agricultural productivity. As reliance on external chemical inputs fertilizers, herbicides, insecticides declines under well-managed diversified systems, the carbon and energy costs embedded in those inputs are also reduced. This reduction in input dependency, combined with enhanced soil biological activity and organic matter accumulation, represents a meaningful contribution to the broader goal of reducing agriculture's net greenhouse gas emissions (Altieri, 2020; Smith *et al*, 2020).

Challenges and Constraints

Notwithstanding the documented benefits of crop diversification, its uptake remains uneven and constrained by structural, informational, and institutional barriers that act at multiple levels of agricultural systems. At the farm level, smallholder farmers who comprise the majority of the world's food producers often face acute resource constraints that limit their ability to experiment with or transition toward diversified systems. Limited access to quality seeds of diverse varieties, insufficient knowledge about appropriate species combinations and management techniques, and initial uncertainties about income flows during the transition period all contribute to risk aversion. Furthermore, the physical

and cognitive demands of managing multiple crops simultaneously are greater than those of monoculture management, and where farm labor is scarce or expensive, this can be a significant deterrent to diversification (Birthal *et al.*, 2015; Lin, 2011).

Policy Implications and Future Directions

Creating the enabling conditions for widespread adoption of crop diversification demands a rethinking of agricultural policy at national and international levels. Governments and development agencies must move beyond input-subsidy models that entrench commodity monocultures and redirect support toward payments for ecosystem services, risk-sharing mechanisms for transitioning farmers, and targeted investments in diversification-compatible infrastructure such as post-harvest facilities and multi-commodity market linkages. Extension and advisory services need comprehensive reorientation, equipping field-level agricultural workers with knowledge of diversification principles, locally adapted species combinations, and integrated pest management techniques suited to complex farming systems. Simultaneously, national agricultural research systems must prioritize the development of improved varieties suited to intercropping and mixed-system environments, which have historically been underserved by plant breeding programs focused on monoculture performance (Lal, 2016; Tilman *et al.*, 2020).

Conclusion

Crop diversification stands out as a practical and science-backed solution to address climate change challenges in agriculture. It strengthens farming systems by improving soil health, reducing production risks, supporting natural pest control, and providing stable incomes. At the same time, it contributes to climate mitigation through carbon storage, lower emissions, and enhanced biodiversity, making it a balanced approach for sustainable agriculture (Lin, 2011; Lal, 2016; Altieri, 2020). However, scaling up diversification requires more than farm-level changes. Supportive policies, better market access, and focused research are essential to encourage its adoption. As climate risks continue to rise, shifting from monocropping to diversified systems is becoming increasingly important for ensuring long-term food security and environmental sustainability (Pretty, 2021; Smith *et al.*, 2020; IPCC, 2022).

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Soil Organic Matter: Heart of Sustainable Agriculture

Kajal D. Bhoyar and Rakesh R. Bagmare

Introduction

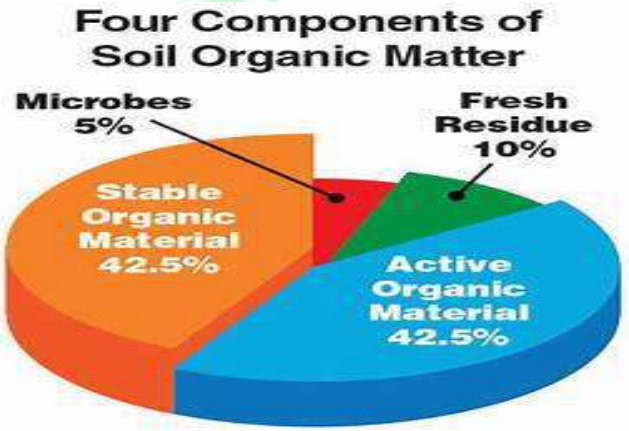
Soil organic matter is the fraction of the soil that consists of plant or animal tissue in various stages of breakdown (decomposition). Most of our productive agricultural soils have between 3 and 6% organic matter. Soil organic matter contributes to soil productivity in many different ways. In this fact sheet, we describe the various components of organic matter and the different roles organic matter plays in soil productivity. We also discuss field management practices that will help preserve or increase soil organic matter levels over time.

What is Soil Organic Matter?

Soil organic matter is any material produced originally by living organism (plant or animal) that is returned to the soil and subjected to decomposition process. At any given time, it consists of range of materials from intact original tissue of plants or animals to the substantially decomposed mixture of materials known as humus. Organic matter is made up of different components that can be grouped into three major types:

- ✓ Plant residues and living microbial biomass.
- ✓ Active soil organic matter also referred to as detritus.
- ✓ Stable soil organic matter, often referred to as humus.

The living microbial biomass includes the microorganisms responsible for decomposition (breakdown) of both plant residues and active soil organic matter or detritus. Humus is the stable fraction of the soil organic matter that is formed from decomposed plant and animal tissue. It is the final product of decomposition.



The first two types of organic matter contribute to soil fertility because the breakdown of these fractions results in the release of plant nutrients such as nitrogen, phosphorus, potassium, etc. The humus fraction has less influence on soil fertility because it is the final product of decomposition (hence the term “stable organic matter”). However, it is still important for soil fertility management

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because it contributes to soil structure, soil tilth and cation exchange capacity. This is also the fraction that darkens the soil's color.

Benefits of Stable Soil Organic Matter

There are numerous benefits to having a relatively high stable organic matter level in an agricultural soil. These benefits can be grouped into three categories:

Physical Benefits

- ✓ Enhances aggregate stability, improving water infiltration and soil aeration, reducing runoff.
- ✓ Improves water holding capacity.
- ✓ Reduces the stickiness of clay soils making them easier to till.
- ✓ Reduces surface crusting, facilitating seedbed preparation.

Chemical Benefits

- ✓ Increases the soil's CEC or its ability to hold onto and supply over time essential nutrients such as calcium, magnesium and potassium.
- ✓ Improves the ability of a soil to resist pH change; this is also known as buffering Capacity.
- ✓ Accelerates decomposition of soil minerals over time, making the nutrients in the minerals available for plant uptake.

Biological Benefits

- ✓ Provides food for the living organisms in the soil.
- ✓ Enhances soil microbial biodiversity and activity which can help in the suppression of diseases and pests.
- ✓ Enhances pore space through the actions of soil microorganisms. This helps to increase infiltration and reduce runoff.

Organic Materials

Over time, the application and incorporation of organic materials can result in an increase in stable soil organic matter levels. Sources of organic materials include:

- ✓ Crop residues.
- ✓ Animal manure.
- ✓ Compost
- ✓ Cover crops (green manure)
- ✓ Perennial grasses and legumes.

The quickest increases are obtained with sources that are high in carbon such as compost or semi-solid manure.

Organic Matter Management

Farm practices that help to maintain or increase soil organic matter levels:

- ✓ Use of conservation tillage practices (for example zero tillage or no-till). Tillage exposes the organic matter to air and will result in the lowering of stable organic matter due to increased mineralization rates and erosion losses.
- ✓ Rotation of annual row crops with perennial grass or legume sods will reduce erosion and build up organic matter as a result of the decomposition of the root mass.
- ✓ Establishment of legume cover crops will enhance organic matter accumulation by providing the nitrogen (N) needed for decomposition of freshly added organic materials, especially those with a high C to N ratio (corn stover, cereal straw, heavily bedded manure, etc.).

- ✓ Avoiding soil compaction which increases waterlogging, and maintaining proper pH to enhance microbial activity and decomposition of freshly added materials. Actual buildup of stable organic matter will, in addition to the amount and source of organic material added, and tillage and rotation practices, also depend on:
  - Soil temperature.
  - Precipitation and soil moisture holding capacity.
  - Soil type and drainage class.
  - Existing microbial community.
  - Soil fertility status and soil pH.

Summary

SOM management is part of a preventive approach to crop production that seeks to maximize the beneficial chemical, physical and biological characteristics of soils. Individual practices for better SOM management have multiple effects on soils and crops and contribute to SOM dynamics by accomplishing one or more of the following:

- ✓ Increasing the amount of organic carbon added
- ✓ Increasing the diversity of organic materials added
- ✓ Decreasing the rate of organic matter loss.

Creative SOM management will combined a number of practices that work together on individual farms. For example better crop rotations, reduced tillage, intensive use of cover crops, and efficient use of animal manures offers a powerful combination of practices to improve soil and agro-ecosystem health.

Techniques for Improving Fertilizer Use Efficiency

Kajal D. Bhoyar and Rakesh R. Bagmare

Some researchers have predicted that the human population of world is going to cross 9 billion and the supply of food are supposed to enhance by 70-100% by 2050. For more than half of the global population Rice is the staple food for half of the world's population. Hence in order to fulfill the demands of the growing population rice production must be enhanced. But we are also facing many challenges like Global climate change, occurrence of pests and diseases frequently, intensified natural disasters and decreased land area under cultivation. Nitrogen and phosphorous are highly demand for growth and development of plant, the soil nitrogen-phosphorous availability commonly restrict the crop productivity. Adding more and more fertilizers to increase crop yields have showed plateau, so excess dose of fertilizers may not result in improving the yield but it will responsible for several environmental issues. Nitrogen, phosphorous is most commonly deficient in all the soils and world's cropping system. So in order to fulfill the demand of the emerging population external application of nutrients in form of fertilizers are required. Though the nitrogen gas shares about 78% of the atmospheric gases composition crops are unable to use it unless and until they are transformed into the plant usable forms. In simple way we can define Fertilizer Use Efficiency (NUE) as the biomass productivity per unit fertilizer absorbed from the soil. Majorly Nitrogen loss occurs through Volatilization, denitrification, leaching and erosion.

Factor affecting through crop response

Since fertilizer use efficiency is determined by the bio-mass yield and nutrient concentration in tissue will affect fertilizer use efficiency. These factor can be broadly classified into four group.

Crop characteristics

- ✓ Choice of crop (where more than one crop can be grown) and its yield potential
- ✓ Choice of crop variety, its grown potential, yield potential, efficiency of nutrient utilization.
- ✓ Resistance of the variety to disease and pests, drought and other stress factor
- ✓ Resistance of the crop variety to soil problems such as water logging, salinity, alkalinity etc.

Soil Characteristics

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- ✓ Texture and structure - more leaching occurs in light, sandy soil.
- ✓ Topography - surface run-off losses are greatest from upper topographic region
- ✓ Drainage - poor drainage can lead to large de-nitrification losses

Fertilizer Characteristics

- ✓ Rate of application match to crop needs
- ✓ Method of application to reduce nutrient losses
- ✓ Time of application matched to crop nutrient uptake pattern
- ✓ Sources of fertilization
- ✓ Fertilizer amendment

Climate

- ✓ Rainfall and its distribution (large rain leads to runoff and leaching losses
- ✓ Sunny days and sun-shine hours, day length, heat units
- ✓ Occurrence and duration of frost, low night temp
- ✓ Occurrence of thunderstorm, hail, tornadoes

Strategies for Improving Fertilizer Use Efficiency (FUE)

Integrated Nutrient Management: The combin-ation of indigenous components like organic manures, crop residues, Biological nitrogen fixation and Chemical fertilization is termed as Integrated Nutrient Management. In simple terms we can say it as usage of nutrients from several sources (Organic, inorganic and biological sources). The advantage of the integrated use is that it provide physico-chemical environment for better root growth and development and increase supply of the nutrients. In the Integrated Nutrient Management interaction of nutrients with several other macro and micro nutrients could considerably improve the production and fertilizer utilization efficiency. Therefore judicious and optimum of nitrogen from all the available sources leads to higher productivity.

Improved Fertilizer Application Methods: Although there are several methods of application of nitrogenous fertilizers, Among them use of large granules, deep placement and foliar spray of fertilizers can improve the utilization of given fertilizer, whereas spreading of nitrogenous fertilizers which is a very basic process which leads to huge nitrogen losses. In Australia from the large scale field demonstrations it has been demonstrated that the nitrogen utilization efficiency in case of Broadcasting of Urea super granules in rice was 37%, whereas in case of deep placement it was 49%, Hence usage of modified fertilizers sulphur and polymer coated urea super granules with deep placement in case of rice has more nitrogen recovery thereby increasing use efficiency. Foliar spray of fertilizers through spray can also improve the fertilizer use efficiency as it reduces volatilization, denitrification and immobilization prior being absorbed by the plant. The technique of placing the mud balls of urea in the reduced zone of puddled rice field has also reported greater nitrogen recovery thereby increase in the nitrogen use efficiency.

Usage of Slow Release Fertilizers: Nitrogen fertilizers containing nitrate are more prone to leaching whereas nitrogenous fertilizers containing

amide and ammonium are more prone to volatilization; slow release nitrogen fertilizers reduce the nitrogen losses and increase the nitrogen recovery and thereby increasing the nitrogen use efficiency. Slow release nitrogen fertilizers can reduce the nitrogen losses due to the delayed nitrogen release pattern which synchronizes the crop demand and soil nitrogen supply. In India the widely used slow releasing fertilizers coated fertilizers, but due to high manufacturing cost and their non-availability paves the way for their limited usage.

Usage of Inhibitors: Conversion of ammonia to NO^{2-} and then NO^{3-} to nitrate is termed as nitrification; nitrification is a natural phenomenon, where conversion of ammonium to nitrite by nitrosomonas and nitrobacter converts NO^{3-} to NO^{2-}. Ammonium might be absorbed by the colloids of the soil and preserved for long periods which can enhance the nitrogen use efficiency by minimizing the leaching and denitrification. Amendment of inhibitors can check the process of conversion of NH^{4+} to NO^{3-} and can ensure higher amount of ammonium in the soil, where FUE and crop yield increases. DCD (Dicyandiamide) is commercially available inhibitor suitable for rice cultivation.

Crop Rotation: Change the sequence of crops in the same period of year after year on same piece of land is known as crop rotation. Addition of legumes with cereal is a traditional practice and considered as an old age practice for better utilization of resources. The legume crops fixes the atmospheric nitrogen in the soil and increase the nitrogen amount in the soil, where following crop during next time would automatically require less external application of fertilizers.

Practicing Conservational Agriculture: Adoption of Conservational agricultural practices may improve the nutrient supplying power of soil due to the better soil health which leads to higher nutrient availability to the plants. Intensive tillage practices accelerate the diminishes the soil organic carbon because of higher oxidation rate which enormously increased the susceptibility of soil to erosion. Adoption of modern concepts of Zero tillage and bed planting with residue incorporation has been popularized, if these technologies are adopted for long term purposes then it leads to the enhancement in soil health. Long term implementation of such technologies improves the physical, chemical and biological characteristics of the soil including higher soil carbon content.

Crop Residue Management: The portion of crop that is remaining in the field after cutting is termed as crop residue. Crop left over material has the capacity of supplying the nutrients for longer duration. It has been reported that residues of various cereal crops can supply 40-100 kg ha^{-1} nitrogen in a season, which also increases soil organic carbon and leads to the improvement of soil health. Legume crop residues are the most efficient sources of nitrogen as they have low C/N ratio and higher nitrogen content on comparison to cereal crop residues.

Green Manuring: In green manuring crops the legumes are superior to non-legumes because they

also have the capacity of fixing the atmospheric nitrogen in the soil. Green manuring legume crops must possess some characteristics like fast growing, short duration, produce more biomass, fix nitrogen of atmosphere and most importantly with least cultural practices. Annual nitrogen storage by legumes ranges from 20-300 kg hectare^{-1}.

Precision Farming: This is a farm inputs management system depends upon information, technology, which identifies, analyze, and demonstrate the variability in time and space in agriculture operations which are managed for maximum production and gain save the resources and protect the environment. By the precision farming we quantify the variation in field with respect to nitrogen and apply exact fertilizers in appropriate quantity at the appropriate time. This can be done by the usage of GPS and GIS remote sensing technologies.

Enhancing Fertilizer Use Efficiency through Chromatin Modulation: Nitrogen fertilization supports the genome reframing of H3K27me3 methylation with NGR -5 (Nitrogen mediated tiller growth response 5 gene) based on PRC-2. Methylation represses in rice those genes that prevent tillering and consequently increase in number of tillers. Proteasomal destruction is influenced by NGR5 is a target of gibberellin-GID1. Modulation of competitive linkage among NGR5, DELLA proteins, and GID1increase economic yield in rice species and reduces nitrogen fertilization. This type of increase in production and decrease in inputs maintain sustainability.

Conclusion

Integrated Nutrient Management, Improved fertilizer application methods, usage of slow release fertilizers, usage of inhibitors, crop rotation, conservational agriculture, crop residue management and precision farming improve the fertilizer recovery there by improving the fertilizer Use Efficiency, which leads to the agricultural sustainability.

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Diseases of Banana and their Management

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Fusarium wilt (Panama wilt): *Fusarium oxysporum f. sp. cubense*

Symptoms: The initial signs of Fusarium wilt usually appear as a noticeable yellowing along the edges of the lowest, oldest leaves. These leaves fold at the base of the petiole and collapse as the illness worsens, falling down against the pseudostem to create the distinctive "skirt" of dead foliage. When the rhizome or pseudostem is ripped open, the fungus's internal invasion of the vascular system results in the water-conducting tissues turning a dark reddish-brown or purple color that is easily seen as streaks or rings. In more advanced stages, the pseudostem's base may split lengthwise, and the plant eventually stops bearing fruit and perishes from total nutrient and water obstruction.

Management: Planting resistant cultivars like Cavendish (for Race 1) or GCTCV-218 (for TR4) is essential to managing Fusarium wilt effectively and ensuring crop survival over the long run. Carbendazim or Propiconazole drenching can help reduce fungal activity around the roots, even though fungicides are typically ineffective in soil. Using only certified tissue-culture plantlets is essential to preventing the disease's first introduction. Strict biosecurity measures, such as cleaning farm equipment and controlling drainage to prevent spore migration, should be used in conjunction with these techniques.

Black sigatoka leaf spot: *Mycosphaerella fijiensis*

Symptoms: On the underside of young leaves, Black Sigatoka first appears as tiny reddish-brown streaks that quickly grow into dark brown or black lines that run parallel to the veins. Often encircled by a yellow halo, these streaks develop into oval, necrotic patches with black edges and sunken grey centers. Large portions of the leaf dry out and die too soon as the illness gets stronger and several places combine. The plant's capacity to photosynthesize is diminished by this quick loss of leaves, which results in smaller bunches and underdeveloped fruit.

Management: To keep the fungus from becoming resistant, systemic fungicides like Propiconazole or Tebuconazole should be alternated with contact protectants like Mancozeb or copper-based sprays. To increase leaf penetration and stickiness, they are frequently combined with agricultural oil. The most sustainable method is to plant resistant hybrids like FHIA-01 (Goldfinger), FHIA-02, or FHIA-03, which naturally resist the infection better than conventional Cavendish. Because of its great yield potential and tolerance in diseased soils, NARITA hybrids are also used in some areas.

Banana bunchy top disease: *Banana bunchy top*

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virus

Symptoms: Dark green "dot-dash" or Morse code streaks along the leaf veins, midrib, and petiole are the first obvious signs of the Banana Bunchy Top Virus. As the infection worsens, freshly emerging leaves grow more narrow, stiff, and brittle with wavy, yellow margins, and dark green, hook-like streaks known as "J-hooks" appear where the leaf blade meets the stem. These stunted leaves have a distinctive "bunched" appearance because they are unable to fully expand and become packed at the top of the pseudostem. In the end, the plant's growth is drastically slowed, and it typically either fails to produce a bunch or produces one that is undersized and deformed.

Management: Since there are presently no effective fungicides for this viral infection, managing Banana Bunchy Top Disease mostly involves controlling the aphid vectors with pesticides like dimethoate or imidacloprid. It is crucial to plant only certified virus-free tissue-culture plantlets because all commercial cultivars are extremely sensitive and there are no fully resistant variations. In order to stop the infection from spreading further, management relies on "rogueing" or injecting herbicides to immediately destroy infested mats. The only effective techniques to prevent a plantation from being completely destroyed are strict biosecurity and frequent monitoring.

Xanthomonas wilt: *Xanthomonas campestris pv. musacearum*

Symptoms: The fast, systemic withering of *Xantho-*monas wilt is marked by dull green and yellow leaves that eventually seem burnt and collapse. The thick, sticky, yellow bacterial slime that seeps from any damaged portion of the plant, including the fruit and pseudostem, is a key diagnostic indicator. The fruit within flowering plants may ripen early and exhibit dark brown or rusty internal rotting, while the male bud frequently shrivels and goes black. The entire plant gradually rots and dies as the infection worsens, frequently dispersing the germs to nearby suckers through the soil.

Management: Because conventional fungicides are ineffective against this bacterial pathogen, managing Xanthomonas wilt necessitates a concentration on bactericidal sanitation and tolerant hybrids. Some NARITA hybrids and the wild species Musa balbisiana exhibit significant levels of tolerance, but no common commercial bananas are completely resistant. Farmers must use authorized tissue-culture plantlets and thoroughly clean tools with bleach or fire to stop the spread if there is no treatment. In order to give a more long-lasting answer, current research is also concentrated on creating genetically modified cultivars that express resistance genes.

Moko disease: *Ralstonia solanacearum*

Symptoms: The youngest internal leaves of moko disease, which is caused by the bacteria Ralstonia solanacearum, usually start out quickly browning and drooping before turning brown and collapsing. Internal fruit rot, in which the pulp becomes dark brown or black and becomes a dry, rotting mass while the peel stays green, is a crucial diagnostic

indicator. A distinctive white or cream-colored bacterial slime that gradually becomes yellow or brown is released when the pseudostem or fruit stalks are severed. The male bud in blooming plants frequently becomes black and shrivels, and when the bacteria totally obstruct the vascular system, the entire plant eventually perishes.

Management: Traditional fungicides are ineffectual because Moko disease is a bacterial infection rather than a fungal one; consequently, control relies on the use of tolerant hybrids and stringent sanitation. Although several FHIA hybrids and the Pelipita cooking banana exhibit notable resilience in comparison to sensitive Cavendish types, there are currently no commercial kinds with total resistance. Farmers must use certified disease-free tissue-culture plantlets and thoroughly clean their tools with formaldehyde or bleach after each use in order to stop the spread. The main strategy for controlling infested regions is to completely destroy the infected mats and rotate crops or leave the area fallow to lower the amount of bacteria in the soil.

Anthracnose: *Colletotrichum musae*

Symptoms: On ripening fruit, anthracnose generally manifests as tiny, round, light-brown dots that later grow into sunken, dark brown or black lesions. The centers of these lesions frequently develop salmon-pink fungal spore masses when the environment is damp. Severe cases result in soft rot of the internal pulp and an unpleasant taste, but the infection usually remains on the skin. Additionally, the illness can cause the floral portions to turn black and shrivel, which can lead to additional fruit infection.

Management: Fungicides such as Mancozeb, Carbendazim, or Thiabendazole are used in pre-harvest sprays and post-harvest dips to prevent fungal growth on the fruit peel. Certain Plantains including the Embul variety show superior natural resistance to the infection, while the majority of commercial Cavendish cultivars are quite vulnerable. Chemical treatments should be used in conjunction with certified disease-free planting material and cautious handling to avoid skin damage in order to guarantee efficacy. This comprehensive method prolongs the fruit's shelf life throughout storage and transportation while lowering post-harvest deterioration.

Banana bract mosaic disease: *Banana bract mosaic virus*

Symptoms: The pseudostem, leaf sheaths, midribs, and peduncles of banana bract mosaic virus (BBrMV), also referred to as Kokkan disease, exhibit characteristic spindle-shaped pinkish to reddish-brown streaks. These streaks may become necrotic and dark brown or black as the infection worsens, frequently leading to the outer leaf sheaths breaking at the base and separating from the central axis. The dark red-brown mosaic pattern that occurs on the flower bracts the leaf-like structures covering the male flowers gives the virus its name and is a highly diagnostic sign. Stunted growth and a “traveler's palm” appearance, with leaves arranged in a single plane on both sides of the plant, are common symptoms of infected plants. Smaller bunches with

twisted, widely divergent, underdeveloped fingers that may exhibit necrotic stains or chlorotic streaks are the outcome of the significant influence on fruit development.

Management: Fungicides cannot treat Banana Bract Mosaic Virus because it is a viral disease; instead, management concentrates on using insecticides like Dimethoate or Oxydemeton-methyl to suppress aphid vectors. Growers must rely on verified virus-free tissue-culture plantlets to create healthy plantations because there are currently no commercial resistant types available. To stop the virus from spreading by contaminated tools or suckers, management calls for the prompt removal and destruction of infected mats as well as stringent biosecurity.

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Role of Biotechnology in Agriculture

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Abstract

Agricultural biotechnology has emerged as a transformative approach to addressing the growing challenges of global food security, environmental sustainability, and climate change. This paper examines the application of modern biotechnological tools including genetic engineering, molecular markers, and genome editing techniques such as CRISPR-Cas systems in enhancing crop productivity, nutritional quality, and resistance to biotic and abiotic stresses. By enabling the development of genetically improved crop varieties, biotechnology contributes to reduced reliance on chemical inputs, improved resource-use efficiency, and enhanced resilience to changing climatic conditions. The study further explores the role of biofertilizers and biopesticides in promoting sustainable farming practices, highlighting their potential to minimize environmental degradation while maintaining soil health. Additionally, the paper discusses socio-economic and ethical considerations associated with the adoption of genetically modified organisms (GMOs), including issues related to biosafety, regulatory frameworks, and public acceptance. The findings suggest that while agricultural biotechnology holds significant promise for increasing food production and sustainability, its successful implementation requires balanced policy support, robust risk assessment mechanisms, and inclusive stakeholder engagement.

Introduction

Agriculture remains a foundational sector for global food production, rural livelihoods, and economic stability. However, the sector faces increasing pressure from rapid population growth, declining arable land, climate variability, and environmental degradation. According to the Food and Agriculture Organization, global food demand is expected to rise significantly in the coming decades, necessitating innovative approaches to enhance agricultural productivity and sustainability (FAO, 2024). In this context, agricultural biotechnology has emerged as a critical scientific domain that integrates advances in molecular biology, genetics, and bioengineering to improve crop and livestock systems. Biotechnology in agriculture refers to the application of scientific techniques such as genetic engineering, tissue culture, molecular markers, and genome editing to modify living organisms for agricultural purposes. In contrast to traditional breeding methods, modern biotechnological tools enable the targeted manipulation of genetic material, allowing for the development of crop varieties with desirable traits such as higher yield potential, impro-

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ved nutritional quality, and resistance to pests, diseases, and environmental stresses. Techniques such as CRISPR-Cas9 have further accelerated the pace of innovation by offering precise, cost-effective genome editing capabilities (Zhang *et al.,* 2024). One of the most significant contributions of biotechnology is the development of Genetically Modified Organisms, which have been engineered to express beneficial traits, including herbicide tolerance and insect resistance. These advancements have the potential to reduce reliance on chemical inputs, lower production costs, and minimize environmental impacts. Additionally, recent studies have highlighted the increasing role of biofertilizers and biopesticides in promoting sustainable agricultural systems and soil health restoration (Kumar and Singh, 2025). Despite its potential benefits, the adoption of agricultural biotechnology is accompanied by several challenges and controversies. Regulatory bodies such as the World Health Organization and national agencies play a crucial role in evaluating the safety and efficacy of biotechnological applications in agriculture (WHO, 2024).

Genetically Modified Crops: Opportunities and Ethical Concerns

The increasing global demand for food, coupled with environmental constraints and population growth, has intensified the need for sustainable agricultural innovations. Genetically modified crops, a key outcome of Genetic Engineering, have emerged as a promising tool to enhance crop productivity and quality. These crops are developed by inserting or modifying genes using advanced technologies such as CRISPR-Cas9, allowing precise and targeted genetic improvements. Since their commercial introduction in the 1990s, GM crops have been widely adopted in several countries, contributing to increased yields and reduced reliance on chemical pesticides. Recent global adoption reports indicate that biotech crops continue to expand, especially in developing countries where food security challenges are more severe (ISAAA, 2024). However, their rapid expansion has also raised questions regarding biosafety, environmental impact, and ethical acceptability.

Opportunities of Genetically Modified Crops: GM crops are engineered to improve yield potential by increasing resistance to pests, diseases, and adverse environmental conditions. For example, insect-resistant crops reduce losses caused by pests, thereby improving overall agricultural efficiency. One of the most notable achievements in GM technology is Golden Rice, which is fortified with vitamin A to combat nutritional deficiencies. Such biofortified crops have the potential to address malnutrition in developing regions. Genetically modified crops can contribute to sustainable agriculture by reducing the need for chemical pesticides and herbicides. This leads to lower environmental pollution and improved soil health. Herbicide-tolerant crops also enable conservation tillage practices, reducing soil erosion. Biotechnology enables the development of crops that can with-

stand drought, salinity, and extreme temperatures. These climate-resilient varieties are crucial in adapting agriculture to changing environmental conditions. Recent genome-edited rice and wheat varieties have shown improved tolerance to drought and heat stress under field conditions (Li *et al*., 2025).

Ethical Concerns and Challenges: Critics argue that GM crops may have unintended ecological consequences, such as gene transfer to wild relatives, loss of biodiversity, and the emergence of resistant pests or "superweeds." Although many studies indicate that GM foods are safe, concerns persist regarding potential long-term health effects and allergenicity. Organizations such as the World Health Organization emphasize the need for rigorous safety assessments before commercialization. The commercialization of GM crops is often dominated by multinational biotechnology industries, leading to concerns about farmer dependency, intellectual property rights, and unequal access to technology. Small-scale farmers may face challenges due to the high cost of GM seeds. The manipulation of genetic material raises ethical questions related to "tampering with nature." In some societies, cultural and religious beliefs influence the acceptance of genetically modified organisms, making public perception a critical factor (Sharma *et al.*, 2024).

Regulatory and Policy Framework: Governments and international bodies play a vital role in regulating the development and use of GM crops. Agencies establish guidelines for risk assessment, labeling, and environmental monitoring to ensure safety and transparency. Effective policies must balance innovation with precaution, addressing both scientific evidence and societal concerns. Recent regulatory reforms in several countries have focused on distinguishing genome-edited crops from traditional GM organisms to facilitate innovation while maintaining biosafety standards (OECD, 2025).

CRISPR Technology in Crop Improvement

Agricultural systems worldwide face increasing challenges due to climate change, population growth, and limited natural resources. Traditional breeding methods, while valuable, are often time-consuming and less precise in developing improved crop varieties. The advent of genome editing technologies, particularly CRISPR, has transformed the field of agricultural biotechnology by enabling accurate and targeted genetic modifications. CRISPR technology functions by using a guide RNA to direct a nuclease enzyme, such as Cas9, to a specific DNA sequence, where it introduces precise edits. This allows scientists to enhance desirable traits or eliminate undesirable ones in crops without introducing foreign DNA in some cases. As a result, CRISPR is increasingly being used to develop improved crop varieties that can meet global food demands.

Mechanism of CRISPR Technology: CRISPR-based genome editing relies on a simple yet powerful mechanism involving two main components: guide RNA (gRNA) and the Cas enzyme.

The gRNA identifies the target gene sequence, while the Cas enzyme acts as molecular scissors to cut the DNA at the specified location. The cell's natural repair mechanisms then modify the DNA, leading to gene insertion, deletion, or replacement. This precision distinguishes CRISPR from earlier genetic engineering techniques, making it a highly efficient tool for plant genetic improvement. Recent advancements such as CRISPR-Cas12 and prime editing have further improved editing efficiency and reduced off-target effects (Chen *et al*., 2024).

Applications in Crop Improvement: CRISPR technology enables the modification of genes associated with plant growth and development, resulting in higher crop yields. For example, editing genes related to photosynthesis efficiency and plant architecture can significantly improve productivity. Genome editing allows the development of crops with enhanced resistance to pathogens and insect pests. By targeting susceptibility genes, CRISPR reduces the need for chemical pesticides, promoting environmentally sustainable farming. CRISPR has been used to develop crops that can withstand drought, salinity, and extreme temperatures. These stress-tolerant varieties are crucial in mitigating the adverse effects of climate change on agriculture. CRISPR technology also facilitates biofortification by enhancing the nutritional content of crops. Improvements in vitamins, minerals, and protein quality can help address malnutrition in vulnerable populations (Wang *et al.*, 2025).

Biofertilizers and Their Role in Sustainable Agriculture

Sustainable agriculture aims to meet present food needs without compromising the ability of future generations to meet their own demands. However, the excessive use of synthetic fertilizers has led to adverse environmental impacts including soil degradation, water contamination, and loss of biodiversity. To overcome these challenges, there is a growing emphasis on biological alternatives such as biofertilizers. Biofertilizers are formulations containing living microorganisms that enhance nutrient availability by fixing atmospheric nitrogen, solubilizing phosphorus, and stimulating plant growth. These microorganisms establish symbiotic or associative relationships with plants, contributing to improved soil fertility and crop yield.

Types of Biofertilizers

- ✓ **Nitrogen-Fixing Biofertilizers:** Microorganisms such as Rhizobium form symbiotic associations with leguminous plants and convert atmospheric nitrogen into forms usable by plants. Other free-living nitrogen fixers include Azotobacter and Azospirillum.
- ✓ **Phosphate-Solubilizing Biofertilizers:** Certain bacteria and fungi have the ability to solubilize insoluble forms of phosphorus in the soil, making it available to plants. This enhances root development and overall plant growth.
- ✓ **Potassium-Mobilizing Biofertilizers:** These microorganisms help release potassium from soil minerals, improving plant nutrient uptake and resistance to stress.

- ✓ **Mycorrhizal Biofertilizers:** Mycorrhizal fungi form symbiotic relationships with plant roots, increasing the surface area for water and nutrient absorption, particularly phosphorus.

Mechanisms of Action: Biofertilizers improve plant growth through several biological processes. These include nitrogen fixation, phosphate solubilization, secretion of growth-promoting substances such as hormones and enhancement of root growth. Additionally, they improve soil structure and microbial diversity, which are essential for long-term soil health. Recent studies have demonstrated that microbial consortia-based biofertilizers significantly improve nutrient use efficiency and crop productivity under sustainable farming systems (Patel *et al.*, 2024).

Role in Sustainable Agriculture: Biofertilizers enhance soil fertility by increasing microbial activity and organic matter content. They contribute to better soil structure, aeration, and water retention capacity. The use of biofertilizers reduces dependence on chemical fertilizers, minimizing environmental pollution and lowering production costs for farmers. By decreasing the use of synthetic inputs, biofertilizers help reduce greenhouse gas emissions and prevent water contamination caused by nutrient runoff. Biofertilizers improve nutrient availability and uptake, leading to increased crop yields and better-quality produce. Their integration with organic farming and climate-smart agriculture has gained considerable attention in recent years (FAO, 2025).

Challenges and Limitations of Biotechnology in Agriculture

Biotechnology has significantly advanced agricultural productivity and sustainability; however, its application is accompanied by several scientific, ethical, economic, and regulatory challenges. A critical understanding of these limitations is essential for balanced and responsible implementation. One of the primary concerns is the potential impact of genetically modified crops on ecosystems. Although many studies suggest that genetically modified foods are safe, there are ongoing debates regarding their long-term health impacts. Potential allergenicity, toxicity, and unforeseen genetic interactions are areas of concern that necessitate rigorous safety assessments by organizations like the World Health Organization. The use of technologies such as Genetic Engineering often faces opposition based on cultural, religious, and philosophical beliefs, influencing public acceptance. The development and commercialization of biotechnological innovations require significant financial investment. Biotechnology products, including genetically modified seeds, are often protected by patents owned by large corporations. This can restrict farmers' rights to save and reuse seeds, increasing dependency on commercial seed suppliers and raising concerns about equity and fairness. Despite its precision, biotechnology is not entirely free from errors. Issues such as off-target effects in gene editing, limited understanding of complex gene interactions, and challenges in transferring traits across species can

affect outcomes. The widespread adoption of genetically uniform crops may encourage mono-culture practices, which can reduce genetic diversity and increase vulnerability to pests, diseases, and environmental changes. Effective implementation of biotechnology requires advanced laboratory facilities, skilled personnel, and proper extension services. In many regions, especially in developing countries, the lack of infrastructure and technical knowledge limits its adoption (Rao and Mehta, 2025).

Conclusion

Biotechnology in agriculture represents a powerful and transformative approach to addressing global challenges such as food insecurity, climate change, and declining natural resources. Through tools like genetic engineering and advanced genome editing technologies such as CRISPR-Cas9, it has become possible to develop crop varieties with higher yields, improved nutritional quality, and enhanced resistance to pests and environmental stresses. Despite these significant advantages, concerns related to biosafety, ethical considerations, environmental impact, and unequal access continue to limit its full-scale acceptance and application. Therefore, the successful future of agricultural biotechnology depends on a balanced approach that integrates scientific innovation with strong regulatory frameworks, ethical responsibility, and public awareness. By ensuring sustainable practices and equitable access, biotechnology can play a crucial role in achieving long-term agricultural development and global food security.

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Biotechnology Boosts Plant Breeding

Aarti Kamboj

Introduction

Plant breeding has been an essential process to develop crops that have improved yield, better nutritional quality, and enhanced resistance to biotic and abiotic stresses. In the past, traditional plant breeding methods, such as hybridization and selection, have been used to achieve these objectives. However, with the advances in biotechnology, new tools have been developed that have revolutionized the plant breeding process.

Traditional Plant Breeding Methods

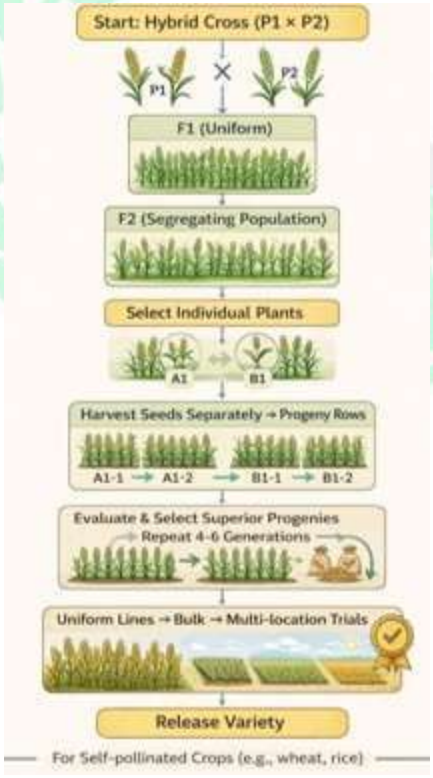

Fig. 1: Conventional plant breeding showing hybridization followed by selection across generations (Source: Food and Agriculture organization, Plant breeding resources)

Traditional plant breeding methods rely on the natural process of hybridization and selection. The process involves crossing two plants with desirable traits and selecting the progeny with the desired traits. However, traditional breeding methods are time-consuming and require multiple rounds of backcrossing to obtain a stable genetic makeup. The process is also limited by the genetic diversity of the parent plants.

Biotechnological Tools for Plant Breeding

Biotechnological tools have made significant contributions to plant breeding in recent years. These tools allow scientists to manipulate the genetic makeup of plants to introduce desired traits and increase genetic diversity. The following biotechnological tools have been widely used in plant breeding:

Genetic Engineering: Genetic engineering involves the manipulation of DNA to introduce new traits into plants. This technology has been widely used to introduce traits such as herbicide tolerance, insect resistance, and improved nutritional quality, e.g., the development of *Bt* cotton, which contains a gene from the bacterium *Bacillus thuringiensis* that produces a protein toxic to certain insects. This technology has been widely adopted by farmers, reducing the need for chemical pesticides and increasing yields. Another example is the developm-

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ent of Golden Rice, a genetically modified rice variety that produces beta-carotene, a precursor to vitamin A. This has the potential to combat vitamin A deficiency, a major health problem in many developing countries. Genetic engineering has also been used to improve crop yield by introducing traits that promote growth and development, e.g., the development of herbicide-tolerant crops, such as soybeans and corn. This results in higher crop yields and lower costs for farmers.

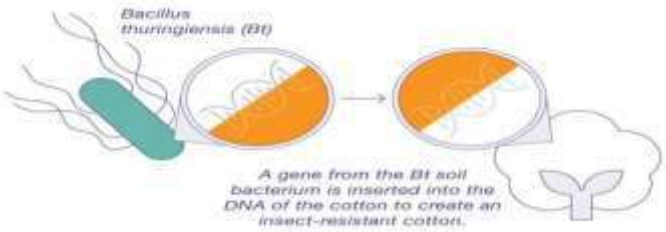

Figure 2: Genetic engineering process showing gene transfer and development of transgenic plants

Marker-Assisted Selection: Marker-assisted selection involves the use of molecular markers to identify plants with desirable traits. This technique is used to identify genes associated with traits such as disease resistance, yield, and nutritional quality. By using molecular markers, breeders can select plants with desirable traits more quickly and efficiently.

Fig. 2: Types of DNA markers (Source: Advances in Plant Breeding Strategies: Cereals, Volume 5)

Genomics and Transcriptomics: Genomics and transcriptomics involve the study of the complete genetic makeup and gene expression patterns of plants. These technologies allow scientists to identify genes associated with specific traits and to study the interaction of genes with each other and the environment. The information obtained from genomics and transcriptomics can be used to develop new breeding strategies and to identify genes that can be manipulated to introduce desirable traits.

CRISPR-Cas9 Technology: CRISPR-Cas9 is a gene editing technology that allows for precise and efficient changes to be made to the plant genome. This technology has been used to introduce new traits into plants, such as disease resistance and improved nutritional quality. In India, scientists have used CRISPR-Cas9 to develop a tomato variety that is resistant to a common fungal disease. The researchers used this technology to target and disable a gene responsible for the production of a protein that the fungus needs to infect the plant. In the world, CRISPR-Cas9 has been used to develop wheat varieties that are more resistant to drought and produce higher yields. Additionally, it has been used to create a variety of rice that is resistant to bacterial blight, a devastating disease that can wipe out entire crops. These examples demonstrate the enormous potential of CRISPR-Cas9 technology in improving plant traits and increasing food security.

Advantages of Biotechnology in Plant Breeding

Increased efficiency: Biotechnology has made it possible to accelerate the breeding process, which can take years or even decades with traditional methods, thereby saving time and resources.

Resistance to pests and diseases: Biotechnology

has made it possible to develop plants that are resistant to pests and diseases, which reduces the need for chemical pesticides and herbicides, making agriculture more sustainable.

Biofortification: Biotechnology can improve the nutritional value of crops, by enhancing the levels of vitamins, minerals, and other important nutrients.

Tolerance to environmental stresses: Biotechnology tools can also be used to develop crops that are more tolerant to environmental stresses such as drought, salinity, and extreme temperatures, which are becoming increasingly important in the face of climate change.

Disadvantages of Biotechnology in Plant Breeding

Potential risks to the environment and human health: Genetic modification may lead to unintended consequences, including the spread of modified genes to other plants or organisms, and the development of new pests and diseases.

Dependency: The use of biotechnology in plant breeding may lead to dependence on large agribusiness corporations that hold the patents for genetically modified crops, which can have economic and political consequences.

Public perception: The public perception of genetically modified crops is often negative, which can lead to reluctance by consumers to purchase products made from these crops.

Cost: Biotechnology stools can be expensive to develop and implement, which can limit their availability to small-scale farmers and breeders.

Conclusion

The use of biotechnological tools in plant breeding has revolutionized the process of developing crops with desirable traits. The tools discussed in this article have allowed for the introduction of new traits, increased genetic diversity, and the development of new breeding strategies. Despite some concerns, the benefits of biotechnology in plant breeding are undeniable, and it will continue to play a vital role in the development of crops that are better suited to meet the needs of a growing population.

Bacteriophage

Sumitha S., Jesima Barveen U. S. and Vinodhini A.

Introduction

Bacteriophages represent the most abundant biological entities on Earth, outnumbering bacteria by at least 10-fold and killing about half of all bacteria daily. Discovered independently by Frederick Twort in 1915 and Félix d'Hérelle in 1917, phages initially served as research tools in the West and antibacterial agents in Eastern Europe before antibiotics overshadowed them. They drive bacterial evolution through horizontal gene transfer, with prophages integrated phage genomes comprising up to 20% of some bacterial genomes, like in *Streptococcus pyogenes* or *E. coli* O157:H7. Phages also encode virulence factors, such as Shiga toxins in pathogenic *E. coli* or CTX phage in *Vibrio cholerae*, linking them directly to disease emergence.

Structure of bacteriophage

Bacteriophages, or phages, exhibit diverse yet characteristic structures optimized for infecting bacteria, typically featuring a head-tail morphology in tailed families like Myoviridae, Siphoviridae, and Podoviridae. These viruses consist of a nucleic acid genome encased in a protein shell, with appendages for host recognition and genome delivery.

Main Components

The head, or capsid, forms an icosahedral or prolate polyhedral protein shell made of about 2000 capsomeres that protect the double-stranded DNA genome, which measures 40-170 kbp in length. A short collar connects the head to the helical tail, which includes an inner hollow tube for DNA injection, surrounded by a contractile sheath with 24 annular rings in complex phages like T4.

Tail and Fibers: The tail terminates in a hexagonal basal plate bearing 6 short tail fibers (STFs) or 6 long tail fibers (LTFs) that act as sensors, recognizing specific bacterial receptors via tip domains like gp37 in T4 phage. During infection, the baseplate undergoes conformational changes, extending fibers, contracting the sheath, and piercing the cell wall to deliver DNA.

Variations: While most phages are tailed and non-enveloped, some filamentous forms like M13 lack tails and have helical capsids; enveloped or isometric shapes exist but are less common. Additional neck structures, like fibritin whiskers in T4, sense infection conditions.

Characteristics of bacteriophages

Bacteriophages, or phages, are obligate intra-cellular parasites that exclusively infect bacteria, exhibiting high host specificity and diverse morphologies. They possess a protein capsid enclosing genetic material, typically double-stranded DNA, and lack metabolic machinery, relying entirely

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on host resources for replication. These viruses demonstrate lytic or lysogenic cycles and dominate Earth's biosphere, outnumbering bacteria 10:1.

Morphological Traits

Most bacteriophages display tailed morphology belonging to the order Caudovirales, with icosahedral heads (50-150 nm diameter) composed of 2000+ capsomeres and helical tails (up to 925 Å long) featuring contractile sheaths, baseplates, and tail fibers for adsorption. Non-tailed forms include filamentous phages like M13 (helical capsid) or isometric heads without tails, but tailed types comprise over 95% of known phages. Phages adsorb via tail fiber receptors, inject genomes through tail tubes, and either lyse hosts (lytic cycle) or integrate as prophages (lysogenic).

Phages life cycle of lytic and lysogenic

Bacteriophages exhibit two primary life cycles: the lytic cycle, which destroys the host bacterium, and the lysogenic cycle, which integrates into the host genome without immediate lysis. These cycles allow phages to either rapidly propagate or persist latent within bacterial populations.

Lytic Cycle: The lytic cycle unfolds in five main stages: adsorption, where tail fibers bind bacterial receptors; penetration, injecting phage DNA via the tail tube; biosynthesis, hijacking host machinery to replicate phage DNA and synthesize proteins; maturation, assembling new virions; and lysis, where phage enzymes like lysozyme degrade the cell wall, releasing 100-200 progeny phages.

Lysogenic Cycle: In the lysogenic cycle, phage DNA circularizes and integrates as a prophage into the bacterial chromosome via site-specific recombination, replicating passively with host division. The host remains viable, potentially gaining virulence factors from prophage genes, as in lambda phage. Under stress like UV exposure or starvation, the prophage excises, shifting to the lytic cycle via induction.

Synthesis of phage component

Bacteriophage component synthesis occurs during the biosynthesis phase of the lytic cycle, where the injected phage genome commandeers the host bacterium's machinery to produce viral nucleic acids and proteins. This phase follows penetration and precedes assembly, marking the eclipse period when no infectious phages exist inside or outside the cell.

Biosynthesis Process: Phage genes direct host ribosomes to translate viral mRNA into early proteins, including nucleases that degrade bacterial DNA and RNA polymerase modifiers that prioritize viral transcription. Phage DNA replicates via host or viral polymerases, while late genes produce structural components like capsid proteins, tail fibers, and sheath proteins. Chemical modifications, such as cytidine hydroxymethylation in T4 phage, protect the viral genome from degradation.

Key Components Synthesized

Nucleic acids: Phage genome copies (dsDNA, 5-500 kbp).

Head/capsid proteins: ~2000 capsomeres forming icosahedral shells.

Tail elements: Hollow tube, contractile sheath, baseplate, and fibers.

Lysis proteins: Lysozyme and holins for cell wall breakdown.

Classification of bacteriophages

Bacteriophages, or phages, are viruses that infect bacteria and are classified primarily by morphology, genome type, and replication strategy. The most common system groups them into tailed and non-tailed forms, with tailed phages dominating as the order Caudovirales. Classifications evolve with new discoveries, often following International Committee on Taxonomy of Viruses (ICTV) guidelines.

Main Orders and Families

Caudovirales comprises over 95% of known phages and includes three major families based on tail structure.

Myoviridae: Contractile tails (e.g., T4 phage), with heads around 60-100 nm and tails 100-200 nm long.

Siphoviridae: Long, non-contractile tails (e.g., lambda phage), targeting bacteria like *Lactobacillus* and *Streptococcus*.

Podoviridae: Short tails (e.g., T7 phage), with heads 60 nm and tails about 20 nm.

Non-Tailed Phages

These belong to unassigned orders or families like Leviviridae, Inoviridae and Microviridae, often with icosahedral, filamentous, or pleomorphic shapes.

Leviviridae: ssRNA genome, ~26 nm icosahedral, infects Enterobacteria.

Inoviridae: Filamentous ssDNA phages (e.g., M13), no lysis, extrude from host.

Cystoviridae: dsRNA with lipid envelope, rare segmented genome.

Genome-Based Classification

Phages divide by nucleic acid: ssDNA (e.g., Microviridae), dsDNA (most Caudovirales), ssRNA (Leviviridae), or dsRNA (Cystoviridae).

Bradley's morphological types (A-F) provide an older scheme: Type A (contractile tail), Type B (long flexible tail), up to Type F (filamentous).

Uses of phages

Bacteriophages serve diverse practical roles beyond research, primarily in combating bacterial infections and enhancing safety in various sectors. Their high specificity and self-replicating nature make them valuable alternatives to antibiotics, especially amid rising resistance.

Phage Therapy: Phages target and lyse specific bacteria, treating infections like sepsis, chronic wounds, and antibiotic-resistant cases such as those from *Pseudomonas aeruginosa*. They show promise in human, animal, and plant health, with applications in veterinary medicine and agriculture to control pathogens without harming hosts.

Food Safety and Preservation: Phages act as natural antimicrobials to reduce foodborne pathogens like Listeria and Salmonella on surfaces, produce, and during processing. Commercial products use them for biopreservation, extending shelf life and decontaminating equipment in farms and factories by disrupting biofilms.

Disinfection and Biotechnology

As self-replicating disinfectants, phages clean hospital surfaces and inhibit bacterial conjugation to curb resistance spread. In biotech, phage display aids vaccine development, drug delivery, and bacterial detection sensors.

Conclusion

Bacteriophages represent a cornerstone of microbial ecology and hold immense promise as targeted tools against bacterial threats. Their specificity, safety for non-bacterial life, and versatility position them as vital allies in addressing antimicrobial resistance and beyond. Phages regulate bacterial populations in nature, drive genetic diversity via horizontal transfer, and underpin molecular biology advances like gene cloning.

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Nutrient Interaction of Fertilizers in Plants

Chandru B., M. Saravana Kumar and K. Pooja

Abstract

Plant nutrient interactions are important in determining plant growth, development, and crop productivity. Essential nutrients present in soil do not act independently; instead, they interact with each other during nutrient uptake, transport, and utilization in plants. These interactions can be positive (synergistic), negative (antagonistic), or neutral, depending on nutrient concentration, soil conditions, crop type, and environmental factors. Synergistic interactions improve nutrient absorption and enhance plant growth, while antagonistic interactions may reduce nutrient availability and cause deficiency symptoms, leading to poor crop performance. Understanding these nutrient relationships is essential for effective fertilizer management and balanced crop nutrition. Proper nutrient management based on these interactions can improve nutrient-use efficiency, increase crop yield, maintain soil fertility, and support sustainable agricultural production. This article discusses the major types of plant nutrient interactions, their effects on plant growth, and their importance in modern agricultural practices.

Introduction

Plant nutrients are essential chemical elements required for plant growth, development, reproduction, and completion of the life cycle. Plants obtain these nutrients from air, water, and soil. Each nutrient performs specific physiological and biochemical functions in plant metabolism. Essential plant nutrients-17 are from air and water: Carbon (C), Hydrogen (H), Oxygen (O), From soil: N, P, K, Ca, Mg, S, Fe, Zn, Mn, Cu, B, Mo, Cl, N. carbon, hydrogen, oxygen, and nitrogen. These four elements constitute from 90 to 99 per cent by weight of all ordinary plant material. Customized nutrient management plans that follow the 4Rs: Right Place, Right Time, Right Rate and Right Source. By utilizing the 4Rs, farmers can ensure fertilizer goes where it's needed into the crops while reducing losses to the environment as runoff. Nutrient use efficiency refers to the ability of a plant to absorb nutrients from the soil and convert them efficiently into biomass or economic yield. Fertilizer sale and distribution in India is primarily enforced by State Government authorities including Agricultural Officers and Fertilizer Inspectors acting under the Fertilizer (Control) Order (FCO), 1985, and the Essential Commodities Act, 1955. These officials monitor quality, conduct raids, and issue, suspend, or cancel dealer licenses to prevent hoarding and black marketing. Commercial fertilizers are manufactured synthetic or natural materials in manufacturing

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industries and designed to provide high concentrations of essential nutrients primary NPK (nitrogen, phosphorus, potassium) or secondary/micronutrients to enhance plant growth and agricultural yields. Used to improve nutrient availability, they come in liquid, solid, or granular forms (like urea or ammonium sulfate) and are essential for modern high-yield farming.

Types of Commercial Fertilizers

Nitrogenous (N): Promote leafy growth, such as urea (46% N) and ammonium sulfate.

Phosphatic (P): Promote root development, such as superphosphates and diammonium phosphate (DAP).

Potassic (K): Improve overall plant health, such as potash.

Complete: Contain all three primary nutrients (e.g., 10-10-10).

Commercial Organic: Derived from organic recycling sources, processed into granules using materials like soybean meal, pig manure, and mushroom residue.

Forms of Application

Solid/Granular: Common forms include pills, powder, and granules, which are spread over the soil.

Liquid: Applied directly or through irrigation (fertigation), allowing for easy mixing with herbicides and lower labor needs.

Commercial fertilizers available in markets

Primary Nutrients (NPK)

Nitrogen (N): Essential for growth, primarily supplied via Urea (46% N), Ammonium Sulphate (20.6% N), and Calcium Ammonium Nitrate (CAN).

Phosphorus (P): Vital for root development and energy. Supplied by Diammonium Phosphate (DAP - 18% N, 46% P_2O_5), Single Superphosphate (SSP - 14-16% P_2O_5), and Ammonium Phosphate.

Potassium (K): Improves disease resistance and water retention. Supplied by Muriate of Potash (MOP/KCl - 60% K_2O) and Potassium Sulphate (SOP - 50% K_2O).

Complex Fertilizers: NPK combinations like 17:17:17, 20:20:0, and 10:26:26 are common.

Secondary & Micronutrients

Sulphur (S): Found in SSP, Ammonium Sulphate, and Potassium Sulphate.

Calcium & Magnesium: Supplied via Calcium Nitrate and Magnesium Sulphate.

Micronutrients: Zinc Sulfate and Boron are commonly applied to address specific soil deficiencies

Specialty Fertilizers

Water Soluble Fertilizers (WSF): Used for drip irrigation, containing high-concentration NPK blends.

Bio-fertilizers: Liquid consortia of bacteria (Rhizobium, Phospho bacteria) to enhance nutrient uptake

- ✓ Urea accounts for over 80% of nitrogenous fertilizer consumption.
- ✓ DAP makes up about 63% of phosphate fertilizer consumption.

Balanced fertilization is the practice of supplying all essential plant nutrients in the right amounts and proper proportions based on crop

SYNERGISTIC NUTRIENTS IN PLANTS

(Nutrients that help each other in uptake, utilization and function)

No.	Nutrient Synergy	How They Work Together	Benefits to Plants	Common Crops / Examples
1	N (Nitrogen) + S (Sulfur)	Sulfur is needed for synthesis of sulfur-containing amino acids and enzymes that use nitrogen.	• Better protein synthesis • Improved growth and yield • Higher crop quality	Cereals, Oilseeds, Vegetables
2	N (Nitrogen) + P (Phosphorus)	Phosphorus promotes root growth and energy transfer; nitrogen promotes vegetative growth.	• Strong roots and early growth • Better establishment • Higher yield	All Field Crops, Vegetables
3	N (Nitrogen) + K (Potassium)	Potassium improves enzyme activation and water regulation for efficient use of nitrogen.	• Improved growth and yield • Better water use efficiency • Increased stress tolerance	Cereals, Sugarcane, Vegetables
4	P (Phosphorus) + Zn (Zinc)	Zinc activates enzymes involved in phosphorus metabolism and auxin (hormone) synthesis.	• Better root development • Improved nutrient uptake • Higher seedling vigor	Cereals, Pulses, Horticultural Crops
5	Ca (Calcium) + B (Boron)	Boron helps in cell division and sugar transport; calcium strengthens cell wall.	• Better flower and fruit set • Strong cell walls • Improved fruit quality	Fruits, Vegetables, Horticultural Crops
6	Fe (Iron) + Mn (Manganese)	Both are involved in photosynthesis and enzyme systems; support chlorophyll formation.	• Improved photosynthesis • Enzyme activation • Better metabolic activity	All Green Crops
7	Mg (Magnesium) + P (Phosphorus)	Magnesium activates enzymes using ATP produced with the help of phosphorus.	• Better photosynthesis • Efficient energy transfer • Improved growth and yield	Cereals, Oilseeds, Vegetables

ANTAGONISTIC NUTRIENTS IN PLANTS

(Nutrients that interfere with each other's uptake or utilization)

No.	Antagonistic Nutrients	How Antagonism Occurs	Effects / Deficiency Caused	Examples / Crops Affected
1	K vs Mg	High potassium competes with magnesium for uptake sites.	Magnesium deficiency – interveinal chlorosis in old leaves.	Cereals, Fruits, Vegetables
2	K vs Ca	Excess potassium reduces calcium absorption and transport.	Calcium deficiency – poor cell wall development, poor fruit quality.	Fruits, Vegetables
3	Ca vs Mg	High calcium competes with magnesium for absorption.	Magnesium deficiency – yellowing of older leaves.	Vegetables, Horticultural Crops
4	P vs Zn	High phosphorus forms insoluble compounds and reduces zinc availability.	Zinc deficiency – stunted growth, rosetting, chlorosis.	Cereals, Pulses
5	Fe vs Mn	Excess iron interferes with manganese uptake and vice versa.	Manganese or iron deficiency – chlorosis, poor growth.	All Crops
6	Fe vs Zn	High iron reduces zinc absorption by competition.	Zinc deficiency – chlorosis, poor internode growth.	Cereals, Horticultural Crops
7	NH_4^+ (Ammonium) vs Ca, Mg, K	Excess ammonium suppresses uptake of cations like Ca, Mg and K.	Deficiency of Ca, Mg or K – poor growth, weak stems, low yield.	All Crops
8	Na vs K (Potassium)	High sodium competes with potassium uptake (common in saline soils).	Potassium deficiency – marginal leaf scorch, weak plants.	All Crops (saline soils)

Legend: Synergy (positive interaction); Antagonism (negative interaction)

Takeaway

Balanced and integrated nutrient management ensures optimal uptake, healthy growth, higher yield and better quality.

Balanced Nutrition
= Healthy Plant
= Higher Yield & Quality

nutrient requirements and the existing soil fertility status.

Nutrient interaction

Nutrient interaction means, impact of one nutrient on other nutrients absorption or bioavailability of other nutrients affects overall health and nutritional status in plant. These interactions can be positive (synergistic), increasing absorption or nega-

tive (antagonistic), where one nutrient inhibits another, such as phytates hindering mineral absorption.

Types of Nutrient Interactions

Synergistic (Positive): The presence of one nutrient increases the uptake or effectiveness of another, increasing yield more than expected. Example: Nitrogen (N) and Potassium (K) work together to boost efficiency.

Antagonistic (Negative): An excess of one nutrient inhibits the uptake of another, suppressing growth. Example: High Potassium (K) inhibits Magnesium (Mg) and Calcium (Ca) uptake.

Liebig-Synergism: The addition of a nutrient only improves yield if another previously deficient, but now added, nutrient is present.

Factors Influencing Interactions

Soil pH: Raising pH through liming can decrease the uptake of micronutrients like Zn, Fe, and Cu.

Nutrient Concentration: Excess of one cation (Mg, K, Ca, NH_4) suppresses others.

Environmental Factors: Soil moisture, temperature and aeration also affect these interactions.

Conclusion

Nutrient interactions play a critical role in plant growth, development, and yield. Synergistic interactions occur when the presence of one nutrient enhances the uptake, availability, or utilization of another nutrient, resulting in improved plant metabolism, nutrient use efficiency, and overall crop performance. For example, the interaction between nitrogen, phosphorus, and potassium often promotes balanced growth and higher productivity. In contrast, antagonistic interactions occur when an excess or imbalance of one nutrient reduces the absorption or effectiveness of another nutrient, which may lead to nutrient deficiencies, poor growth, and reduced yield.

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Regenerating Our Soil, Protecting Climate

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Food grain production of India is estimated to be 330.5 million tonnes in 2022-23 which is 15 million tonnes more than that of the preceding year as per the third advance estimate of 'production of major crops' released by the Ministry of Agriculture & Farmers Welfare. Despite the success in crop production that has ensured food security in the country, food inflation and its volatility is still challenging the food production sector. The growing population, increase in average per capita income, and effects of globalization will definitely raise the demand for a greater variety of good quality food products in India. But, global developments such as declining availability of resources (e.g., land, water, nutrient) and climate changing effects may challenge our future food production targets while ensuring sustainable use of natural resources. Furthermore, issues such as land degradation, soil erosion, and loss of organic matter are deeply intertwined with decline in environmental quality and threaten livelihoods of millions of people around the world (Bouma *et al.* 2017). In this context, the Sustainable Development Goals (SDGs) provide clear guiding principles and targets to encourage sustainable food production under the global theme of eradicating poverty.

SDG 2 (Zero Hunger) is the most straight forward link that connects soils, food production, and healthy living. Therefore, there is a need to focus on cost-effective agriculture technologies that are capable of protecting environment along with conserving natural resources. Regenerative agriculture (RA) is one of the solutions to resolve most of these issues discussed. RA is a form of farming that aims to rehabilitate and restore the quality of soil used for agricultural purposes. In addition to restoring the soil quality, RA can also help to restore the water cycle and is an effective tool for carbon sequestration and a major milestone for climate change as it improve the resilience and vitality of soil that forms the food everyone consumes. There is no separate entity or practice that can define the nature and meaning of RA, but it encompasses a variety of sustainable agricultural practices that are used in various combinations to ensure maximum Our Climate efficiency in the soil restoration process. For example, crop residue recycling (as much as possible) along with regular addition of compost or biochar improves soil fertility. With time, adoption of regenerative agriculture practices reduces requirement of agricultural chemicals without much

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reduction in crop yield compare to 'before transformation period'. The major technology used in regenerative agriculture is the cultivation of crops and vegetation that would effectively capture carbon from the atmosphere whilst contributing effectively as a carbon sequestrating tool. In short, a combination of agricultural practices those have less negative or even net positive effects on the environment and/or society. In addition to restoring the fertility of the soil, it also helps to rehabilitate and restore impulsive lands which are not currently used for farming practices.

Major Techniques in Regenerative Agriculture

Minimum Soil Disturbance-Conservation tillage: Disruption of soil due to ploughing and tillage may lead to erosion that can negatively affect texture and quality of the soil. In conservation tillage, where the soil surface used for farming is covered with about 30% of crop residues, soil building process get renewed with time along with soil fertility restoration. Besides, this tillage widely reduces soil erosion caused by water. Minimum soil disturbance also augment biodiversity of the agro-ecosystem by providing shelter to small animals such as rabbits, quail, and mice. Meena *et al.* (2016) observed soil fertility and texture improvement with time due to the adoption of conservation tillage Keep the Soil Covered: A permanent soil cover is essential to protect soils against the deleterious effects of exposure to rain and sun as well as to provide a regular supply of food micro and macro-organisms in the soil and to alter the soil physical environment to support the growth and development of soil organisms. Crop residue is the key component of soil cover that protects top soil from erosion and plays an important role in building soil organic matter, nutrient recycling and improving soil quality (Chauhan *et al.*, 2012). Crop residue is an important source of carbon and also has significant effect on physical, chemical and biological properties of soil (Kumar and Goh, 2000).

Crop Rotation with Maximum Crop Diversity: Crop rotation ensures specific nutrients are not stripped off from soil and prevent build-up of specific materials or elements in the soil over prolonged periods. Rotating crops using legumes minimizes build-up of population of pest and diseases causing agents through life cycle disruption, promote biological nitrogen fixation, control off-site pollution and enhance biodiversity. Growing diverse crops helps to bring farmers to soil rebuilding process; and good textured, rich, varied, and nutrientdense soils provide them the best yield in return. Also, crop diversity and crop rotation allows not all nutrients but only specific set of nutrients to get absorbed by specific crops and this process ensures soil get enough time to get rejuvenated incorporating nutrients it lost in each crop season

Agroforestry with Perennial Crops: Agro-forestry is a collective name for land use system in which woody perennials (trees, shrubs etc.) are grown in association with herbaceous plants (crops, pastures) or livestock in spatial arrangement. Agro-forestry systems consists of 4 basic components i.e., Agri-

silviculture system (crops + trees), Agri-horticulture system (crops + fruit trees), Silvipastoral system (trees + pasture or animals), and Agri-silvipastrol system (trees + crops + pasture or animals). Agroforestry systems are much more than annual cropping systems in enhancing productivity, soil fertility, nutrient cycling, carbon sequestration potential micro climate, and conserving soil. For example, sugarcane+ poplar combination gave the higher returns than any other crop in first three years (and then poplar intercropping with wheat-kharif fodder for successive years (Chauhan *et al.,* 2009). Dhyani *et al*. (2009) reported that alley cropping with leguminous tree subabul (*Leucaena leucocephala*) was effective for controlling soil erosion on sloppy lands. Agro-forestry is a promising land use system to increase and conserve aboveground and soil C stocks to mitigate climate change. Also, trees crowns act as windbreaks and shelterbelts together with protecting soil from the impact of rain drops and creating a specific micrclimate in particular area.

Biochar: Biochar, a fine-grained black carbon material produced through pyrolysis of plant biomass can improve soil fertility by improving the moisture retention quality of soil and allowing soil to retain nutrients for long time period. Use of biochar in agricultural fields not only contributes to carbon positivity but also reduce the greenhouse effect by sequestering carbon in soils. Lehmann *et al.* (2006) reported that biochar sequesters approximately 50% of the carbon available within the biomass feedstock being pyrolyzed, depending upon the feedstock type. Remaining percentage of carbon is released during pyrolysis and this may be captured for energy production. Biochar can effectively valorize the soil nutrients and enzyme dynamics, by enhancing soil water-holding capacity, cation exchange capacity, surface sorption capacity and base saturation when added to the soil (Liang *et al.,* 2006). As regenerative agriculture emphasis on self-reliance, farmers may be motivated to produce biochar at farm level using their crop residue rather than relying on off-farm inputs. However, quality check of biochar produced at farm level is required because, quality of biochar depends upon a number of factors such as type of feedstock, temperature at which it is either pyrolyzed, gasified, torrefied or burnt, duration of the reaction that make biochar and the pre-treatment techniques.

Integration of Livestock with Cropping System: Ecosystem services can be significantly influenced by the nature and spatial configuration of the crop-ping systems, grasslands, and animal components of the farming system. Integration of livestock with cropping system and grassland at the farm level are often considered to have key economic and social benefits. Crop-livestock integration has three aims 1) reducing the openness of nutrient cycles following the rationale of industrial ecology, 2) organizing land use and farming practices to promote ecosystem services, 3) increasing farm resilience to adverse climatic and economic events. Integration of live-stock with cropping system promotes introduction of cover crops, legumes and short duration grass lands

as a source of livestock feed and these changes offer recoupling of carbon, nitrogen and phosphorus cycles. This kind of alliances are ideal for the dryland regions where crop-livestock systems dominate as this would also help in taking maximum benefit of livestock excreta (dung and urine). In fact, integration of livestock with cropping systems and grasslands is one of the key actions helped spreading concept of RA in many countries. On the whole, it helps in making the system as a carbon sink and neutralizing the higher GHG emission from the livestock.

Conclusion

RA is not a single technology but it is an innovative process about which various stakeholders of agriculture need to be educated because, this process involves regenerating of the top soil and increasing biodiversity and input-use efficiency. It is based on the idea that healthy soils are the cornerstones of RA, which enable a symbiotic association between soil microbes and plants. RA centres around ecosystem services that mitigate climate change, sustain agri-food systems and produce healthy foods using innovative practices of conservation agriculture, integrated farming systems, agroforestry, organic farming, etc. along with Best Agricultural Practices (BMPs). In nutshell, RA improves the health of agr-ecosystem through a holistic systems approach including the wellbeing of animals, farmers and the society. It builds agro-ecosystem resilience by mitigating the changing climate effects.

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Waste to Wealth: Sustainable Uses of Agricultural Residues

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Abstract

Agricultural waste, or agro-waste, arises from crop, livestock, poultry, dairy, aquaculture, and agro-industrial activities. Improper disposal causes pollution, greenhouse gas emissions, and biodiversity loss. However, agro-waste can be converted into valuable products through composting, recycling, animal feed production, nutrient recovery, and bioenergy generation. Sustainable waste management improves soil health, renewable energy production, farmers' income, and environmental sustainability while supporting climate change mitigation and food security.

Introduction

Agro-waste includes residues from crops, livestock, poultry, dairy, and aquaculture in solid, liquid, or slurry forms. These wastes, including crop residues, manure, rice husk, and bagasse, can be converted into compost, biofuels, organic fertilizers and animal feed. India generates about 350-990 million tonnes of agro-waste annually (Koop and van Leeuwen, 2017; Shyamsundar *et al*., 2019). Improper disposal, especially residue burning, causes pollution and greenhouse gas emissions, whereas recycling and waste-to-value approaches promote soil health, renewable energy and sustainable agriculture.

Sources of Agricultural Waste

Crop residue: Crop residues are plant materials remaining after harvest (Shahane and Shivay, 2016). India produces nearly 686 million tonnes of agricultural residues annually with cereals contributing about 58% (Singh and Mina, 2022). Due to labor shortages and mechanized harvesting, excess residues are often burned, causing environmental pollution (Lohan *et al*., 2018). However, when properly managed, crop residues improve soil fertility, conserve moisture, and enhance microbial activity, supporting sustainable agriculture (FAO, 2014; Chandra *et al*., 2024).

Livestock waste: Livestock waste includes manure, urine, wastewater, and bedding materials. Improper disposal causes greenhouse gas emissions, odor

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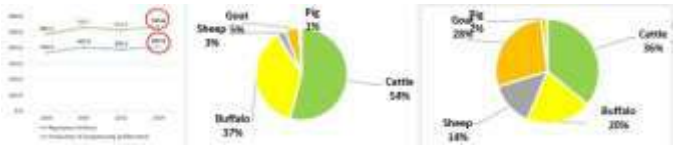
problems, and water pollution. However, livestock waste serves as an important substrate for biogas production and organic manure preparation (Singh *et al.*, 2020).



Population Livestock wastes

Fig. 1: Livestock population and excreta produced (Source: 20th Livestock census, 2019)

Agro-Industrial Waste: Agro-industrial waste includes molasses, bagasse, rice husk, fruit pomace, oilseed cakes, and slaughterhouse residues. Improper disposal causes pollution and greenhouse gas emissions (Kour *et al.*, 2023; Freitas *et al.*, 2021). These wastes can be converted into bioethanol, biogas, enzymes, nutraceuticals, and biopolymers. Apple pomace and sugarcane bagasse are widely used for biofuel production (Capanoglu *et al.*, 2022; Pattanaik *et al.*, 2019).

Aquaculture Waste: Aquaculture waste includes uneaten feed, fish excreta, and dissolved nutrients such as nitrogen and phosphorus (Dauda *et al.*, 2019). Excess nutrient discharge causes eutrophication, oxygen depletion, and deterioration of aquatic ecosystems, highlighting the need for proper waste management in aquaculture systems.

Problems Caused by Agricultural Waste

Soil, Water and Air Pollution: Improper agricultural waste disposal pollutes soil, water, and air, releasing greenhouse gases and harmful contaminants (Sharma *et al.*, 2021).

Eutrophication and Aquatic Damage: Nitrogen- and phosphorus-rich runoff causes eutrophication, oxygen depletion, and fish mortality (Dauda *et al.*, 2019).

Human Health Hazards: Agricultural pollutants contaminate food and water, causing diseases such as blue baby syndrome and heavy metal toxicity (Sharma *et al.*, 2021).

Principles and Methods of Waste Management

Composting: Composting converts agricultural residues into nutrient-rich manure through aerobic microbial decomposition. Factors such as moisture, aeration, pH, and C:N ratio influence the process (Sanchez *et al.*, 2017). Compost improves soil fertility and suppresses pathogens (Bernal *et al.*, 2009).

Organic Fertilizers and Nutrient Recycling: Organic fertilizers derived from crop residues and manure improve soil structure, microbial diversity, and nutrient availability (Wu *et al.*, 2020). Integrated Nutrient Management (INM) sustains crop productivity while reducing environmental pollution (Verma *et al.*, 2020).

Animal Feed Production: Agricultural by-products such as wheat straw, fruit peels, and vegetable residues can be used as animal feed after suitable treatment, reducing waste and improving livestock nutrition (Singh and Arya, 2020).

Pyrolysis and Biochar Production: Pyrolysis converts agricultural waste into biochar and bio-oil under oxygen-free conditions. Biochar improves soil fertility and carbon sequestration, while bio-oil serves as a renewable fuel (Pattanaik *et al.*, 2019).

Bioenergy and Biorefineries: Agricultural residues can be converted into biodiesel, bioethanol, biogas, and biohydrogen, producing lower emissions than fossil fuels. Agro-industrial waste-based biorefineries also generate fertilizers, chemicals, and other value-added products (Sadh *et al*., 2018).

Conclusion

Agricultural waste generation has increased with intensified farming and rising food demand, causing pollution and greenhouse gas emissions. However, these wastes can be converted into valuable products such as compost, biofuels, organic fertilizers and biochar. Sustainable waste management through recycling and bioenergy production can improve soil fertility, reduce pollution, and support climate change mitigation.

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Breaking the Chemical Chain: Pathways to Sustainable Agriculture in Nadia's Smallholder Villages

Debjyoti Majumder, Sayan Sahu, Somedip Chatterjee and Rounak Panda

Introduction

Nadia District in West Bengal is celebrated for its fertile alluvial plains fed by the Bhagirathi-Hooghly river system a landscape that has fed millions for generations. Yet beneath this agricultural abundance lies a quietly unfolding crisis. Decades of chemically intensive farming, driven by Green Revolution and input subsidies, have steadily eroded the soil's biological vitality, depleted local aquifers, and pushed farmers into a costly treadmill of synthetic fertilisers and pesticides. A Natural Resource Management (NRM) assessment conducted across seven villages of Krishnanagar-I Block covering 30 smallholder farming households has put hard data to this concern, revealing a farming system stretched to its ecological and economic limits. This article distils those findings, exploring what is at stake and, crucially, what can be done.

A Landscape Dominated by One Rotation

The most striking finding of the survey is the near-total uniformity of cropping: paddy (*Kharif*, June-October), mustard (*Rabi*, November-February), and jute (*Zaid*, March-May). All 30 farmers grow paddy; 29 of 30 grow mustard; all 30 cultivate jute. This three-season cycle yields a cropping intensity close to 300%, leaving no fallow period for soil recovery. While this maximises short-term income for land-poor smallholders average holdings are just 0.92 ha it exacts a long-term ecological toll through progressive soil organic matter depletion, nitrogen imbalance (no legume in the rotation) and continuous groundwater extraction during the water-scarce *Zaid* season (March-May). Only Purbapara Bhatjangla stands apart, with farmers cultivating flowers, elephant foot yam (*Amorphophallus paeoniifolius*) and mango along-side the dominant cereals, and reporting comparat-ively lower chemical input use. This village offers a proof-of-concept that diversification is feasible and potentially beneficial within the same agro-ecological context.

Table 1: Village Resource Profile-Key Demographic and Land-Use Parameters

Village	Avg. Population	Avg. Households	Avg. Land (ha)
Bhatjangla	327	70	0.93
Charuigram	400	100	0.13
Golakata	633	120	1.13
Harinagar	455	105	1.20
Mathpara	425	85	0.53
Poragacha	560	120	0.53
Purbapara Bhatjangla	545	103	0.96

Water: The Silent Vulnerability

Every one of the 30 surveyed farmers draws irrigation exclusively from bore wells; not a single household uses canals, ponds, or other surface water resources. This is a structural vulnerability. Annual rainfall of 1,200-1,400 mm (concentrated in the *Kharif* season, June-October) provides natural recha-

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rge, but continuous extraction for three crops per year is depleting local aquifers faster than they can recover. The complete absence of community water management no tank restoration, no farm pond construction, no check dams means there is no buffer when bore wells fail or deepen beyond affordable reach. The transition to even one crop of solar-powerd drip irrigation could meaningfully reduce extraction pressure while cutting energy costs.

The Chemical Cost Burden

Rising Input Expenditure: Average seasonal expenditure on synthetic fertilisers (primarily urea, DAP, and MOP) stands at Rs. 4,788 per season, with pesticide costs adding a further Rs. 2,211 a combined seasonal burden of nearly Rs. 7,000 per household. Across three seasons, annual chemical input costs likely reach Rs. 15,000-20,000 per household. Golakata and Charuigram report the highest input costs, at Rs. 10,500 and Rs. 12,000 per season respectively. Every village records an increasing cost trend, reflecting both input price inflation and escalating application rates as soil fertility declines and pest resistance builds. The economic incentive to change is therefore real: a household that successfully substitutes even 30% of synthetic inputs with farm-prepared bio-inputs could save Rs. 2,000-4,000 per season. Critically, none of the 30 surveyed farmers has conducted a soil test all fertiliser decisions are empirical. Targeted soil health cards and block-level testing camps could eliminate this guesswork, reducing over-application and input costs simultaneously.

Table 2: Village-wise Seasonal Chemical Input Cost Analysis (Rs. per season)

Village	Fertilizer Cost (Rs./season)	Pesticide Cost (Rs./season)	Total Input Cost (Rs./season)	Trend
Bhatjangla	3,630	1,364	4,994	↑
Mathpara	3,000	750	3,750	↑
Poragacha	2,350	2,750	5,100	↑
Harinagar	5,000	3,875	8,875	↑
Charuigram	7,000	5,000	12,000	↑
Purbapara Bhatjangla	5,875	3,175	9,050	↑
Golakata	9,000	1,500	10,500	↑
Overall Average	**4,788**	**2,211**	**6,999**	↑

Pathways to Sustainability

Out of the 30 farmers surveyed, only one farmer currently uses bio-inputs. However, most families already have the materials needed to prepare them at home. Around half of the households own livestock, which provides cattle dung and urine that can be used to make Jeevamrit and Beejamrit natural farming inputs that improve soil health and crop growth. Crop residues that are often thrown away or burned can also be used for making vermicompost. This shows that the main problem is not the lack of resources, but the lack of awareness, training, and support. Farmers need practical demonstrations and guidance on how to prepare and use these inputs effectively. One possible solution is to create a community bio-input production centre that can support several villages together. Similar models have already been successfully used in Andhra Pradesh under the Zero Budget Natural Farming programme. Such centres can reduce costs, ensure regular supply of bio-inputs, and help farmers learn from each other through local knowledge sharing and demonstration activities.

Renewable Energy: Unlocking the Solar Dividend

A single solar pump in Bhatjangla is the sole renewable energy installation across all seven surveyed villages. No biogas plants exist despite 50% livestock ownership. The PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan) scheme offers subsidised solar pump installation for farmers a direct mechanism to reduce diesel dependency and lower irrigation costs. Biogas units, supported under the National Biogas and Manure Management Programme (NBMMP), could simultaneously provide clean cooking fuel and nutrient-rich bio-slurry for soil amendment, reducing both LPG expenditure and synthetic fertiliser demand.

Table 3: Key Sustainability Indicators: Current Status and Recommended Interventions

Indicator	Current Status	Recommended Action
Soil Testing	Zero adoption (0/30 farms)	Mandatory soil health cards; district-level testing camps
Bio-input Use	1 of 30 farmers (3%)	Community bio-input production hubs; Jeevamrit/ Beejamrit training
Crop Diversity	~3 crops; near-monoculture	Introduce legumes (e.g., lentil, cowpea) to fix N_2 naturally
Irrigation	100% borewell; no surface water	Rainwater harvesting; pond restoration; solar pump subsidy
Renewable Energy	1 solar pump only	Solar irrigation under PM-KUSUM scheme expansion
Chemical Inputs	Rs. 6,999 season^{-1} average	Progressive substitution with bio-inputs; 30% reduction target

Introducing Legumes: Nature's Nitrogen Factory

The absence of any legume in the dominant crop rotation is agronomically significant. Grain legumes such as lentil (*Lens culinaris*), black gram (*Vigna mungo*), or cowpea (*Vigna unguiculata*) fix atmospheric nitrogen (N_2) at rates of 50-200 kg N ha^{-1} year^{-1}, naturally replenishing soil nitrogen reserves and reducing the need for nitrogenous fertilisers. Introducing a legume into the *Rabi* or *Zaid* season replacing or rotating with mustard or jute on at least a portion of cultivated land would break pest and disease cycles, improve soil structure, and create an additional nutritional food source for households.

Conclusion

The smallholder farmers of Krishnanagar-I Block are not failing they are farming with skill and resilience within a system that was not designed for long-term ecological health. The paddy-mustard-jute monoculture, 100% groundwater dependence, zero soil testing, and near-total chemical input reliance are not individual choices but systemic outcomes shaped by decades of policy, market, and extension failures. What the data reveal is that the costs of inaction are mounting ecologically, in declining soil health and aquifer stress, and economically, in input costs that now consume a significant portion of farm income.

The good news is that entry points for transition are already present: a natural farming practitioner in Bhatjangla who can serve as a resource farmer, livestock in half the surveyed households, crop diversification in Purbapara Bhatjangla that demonstrates what is possible, and a policy environment (PM-KUSUM, NBMMP, Natural Farming Mission) that, if actively channelled, could accelerate change. Soil testing, bio-input training, legume introduction, solar irrigation, and biogas adoption are not utopian ambitions they are practical, proven, and within reach. What is needed now is coordinated action: by

extension agencies, development organisations, and above all, by a farming community that has every reason to reclaim the ecological capital that sustains its future.

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Units & Abbreviations: ha = hectare (SI unit of area; 1 ha = 10,000 m^2); kg = kilogram; mm = millimetre; Rs. = Indian Rupee (₹); NRM = Natural Resource Management; DAP = diammonium phosphate; MOP = muriate of potash; N_2 = atmospheric dinitrogen; N = nitrogen.

Organic Carbon Management for Building Resilient Soil Production Systems

Gaytri Soni

Introduction

Soil organic carbon (SOC) plays a vital role in maintaining soil health, agricultural productivity, and environmental sustainability. It is a major component of soil organic matter and acts as the foundation of a resilient soil production system. In recent decades, intensive farming practices, excessive use of chemical fertilizers, deforestation, soil erosion, and climate change have led to a significant decline in soil organic carbon levels across many agricultural regions. This decline has negatively affected soil fertility, water-holding capacity, microbial activity, and overall crop productivity. Organic carbon management refers to the practices and strategies used to maintain or enhance the organic carbon content in soils. Effective management of soil organic carbon improves soil structure, nutrient availability, moisture retention, and biological activity, thereby increasing the resilience of agricultural systems against drought, floods, and other environmental stresses. Practices such as crop residue incorporation, compost application, green manuring, cover cropping, conservation tillage, agroforestry, and biochar application are widely recognized for their role in enhancing soil carbon storage. Building resilient soil production systems is essential for ensuring long-term food security and sustainable agriculture. Soils rich in organic carbon are better able to support healthy plant growth while reducing the risks associated with climate variability and land degradation. Moreover, increasing soil carbon sequestration also contributes to climate change mitigation by reducing atmospheric carbon dioxide levels. Therefore, organic carbon management has become an important approach in modern agriculture for restoring degraded soils, improving productivity, and promoting ecological balance. Sustainable management of soil organic carbon not only benefits farmers economically but also supports environmental conservation and agricultural resilience for future generations.

Importance of Soil Organic Carbon

Soil organic carbon (SOC) is a key component of soil organic matter and plays a vital role in maintaining soil health, agricultural productivity, and environmental sustainability. It originates from decomposed plant residues, animal remains, microorganisms, and organic amendments added to the soil. SOC is considered an important indicator of soil quality because it influences the physical, chemical, and biological properties of soil. One of the major functions of soil organic carbon is improving soil fertility. It acts as a storehouse of essential nutrients such as nitrogen, phosphorus,

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sulfur, and micronutrients. As organic matter decomposes, these nutrients are gradually released into the soil, making them available for plant uptake. This process supports healthy crop growth and reduces nutrient losses.

SOC also improves soil structure by binding soil particles into stable aggregates. Good soil aggregation increases pore space, aeration, and root penetration while reducing soil compaction. Well-structured soils are easier to cultivate and provide a favorable environment for plant roots and soil organisms. Another important role of soil organic carbon is enhancing the water-holding capacity of soil. Organic matter acts like a sponge, helping soil retain moisture for longer periods. This is especially beneficial in drought-prone regions where water availability is limited. Increased water retention improves crop tolerance to dry conditions and reduces irrigation requirements. Soil organic carbon supports a diverse population of soil micro-organisms, including bacteria, fungi, and earth-worms. These organisms play an essential role in decomposition, nutrient cycling, and maintaining ecological balance within the soil. Higher microbial activity leads to better soil fertility and improved plant health. SOC also helps reduce soil erosion by improving soil stability and aggregate formation. Soils rich in organic carbon are less susceptible to erosion caused by wind and water. This protects the topsoil layer, which is crucial for agricultural productivity. In addition, soil organic carbon contri-butes significantly to climate change mitigation. Soil acts as a major carbon sink, storing large amounts of carbon that would otherwise remain in the atmosphere as carbon dioxide. Increasing SOC through sustainable agricultural practices such as conservation tillage, cover cropping, crop rotation, compost application, and agroforestry helps in carbon sequestration and reduces greenhouse gas emissions. Furthermore, soils with higher organic carbon levels are more resilient to environmental stresses such as drought, flooding, and temperature fluctuations. Such resilience is essential for sustainable agriculture and long-term food security under changing climatic conditions. Therefore, maintaining and enhancing soil organic carbon is essential for improving soil productivity, sustaining agricultural systems, protecting the environment, and ensuring the long-term health of soil resources.

Sources of Organic Carbon

Soil organic carbon is mainly derived from the decomposition of plant and animal materials added to the soil. These sources play an important role in improving soil fertility, structure, and biological activity. The major sources of organic carbon are described below:

Crop Residues: Crop residues such as straw, stalks, leaves, husks, and roots left after harvesting are major contributors of organic carbon. When incorporated into the soil, they decompose and add organic matter.

Farmyard Manure (FYM): Farmyard manure is prepared from cattle dung, urine, bedding materials, and farm wastes. It is rich in organic matter and

nutrients, helping to increase soil carbon content and improve soil health.

Compost: Compost is formed through the decomposition of organic wastes such as crop residues, kitchen waste, leaves, and animal manure. It is a stable source of organic carbon and enhances soil microbial activity.

Green Manure: Green manure crops like sunhemp and dhaincha are grown and incorporated into the soil while still green. These crops rapidly decompose and enrich the soil with organic carbon and nutrients.

Animal Wastes: Animal wastes such as poultry manure, sheep manure, and goat manure contribute organic matter and nutrients to the soil, improving carbon levels and fertility.

Plant Litter and Forest Residues: Leaves, twigs, branches, and other plant litter naturally fall on the soil surface and decompose over time, adding organic carbon to the soil.

Cover Crops: Cover crops grown during fallow periods help protect the soil from erosion and add organic matter through their roots and biomass after decomposition.

Biochar: Biochar is a carbon-rich material produced from biomass under limited oxygen conditions. It is stable in soil for a long period and helps increase soil carbon sequestration.

Agroforestry Systems: Trees and shrubs in agroforestry systems contribute organic carbon through leaf fall, root turnover, and pruning residues, thereby improving soil quality.

Microbial Biomass: Soil microorganisms decompose organic materials and their dead cells become part of soil organic matter, contributing to soil organic carbon.

These sources collectively help maintain soil fertility, enhance microbial activity, improve soil structure, and support sustainable agricultural production.

Role in Climate Resilience

Soil organic carbon (SOC) plays a major role in improving climate resilience in agricultural systems. Soils rich in organic carbon are better able to withstand extreme weather conditions such as droughts, floods, and temperature fluctuations. Organic carbon improves soil structure and increases water-holding capacity, allowing soils to retain moisture for longer periods during drought conditions. At the same time, well-structured soils enhance water infiltration and drainage, reducing the risk of flooding and waterlogging. SOC also supports diverse microbial activity, which helps maintain nutrient cycling and soil fertility under changing environmental conditions. Healthy soils with high organic carbon levels are more resistant to erosion caused by heavy rainfall and strong winds. In addition, soil organic carbon acts as a carbon sink by storing atmospheric carbon dioxide in the soil, thereby helping to mitigate climate change and reduce greenhouse gas concentrations. Practices that increase SOC, such as conservation tillage, cover cropping, compost application, agroforestry, and residue management, contribute to sustainable and climate-resilient agriculture. Therefore, maintaining

and enhancing soil organic carbon is essential for ensuring stable crop production, environmental protection, and long-term agricultural sustainability under changing climatic conditions.

Challenges in Maintaining Soil Organic Carbon

Maintaining soil organic carbon (SOC) is essential for sustainable agriculture, but it remains a major challenge due to several environmental, agricultural, and socio-economic factors. Soil organic carbon is continuously affected by land use practices, climate conditions, and soil management systems. The decline in SOC not only reduces soil fertility but also weakens the resilience of agricultural systems.

Intensive Tillage Practices: Frequent and deep tillage exposes soil organic matter to air, increasing microbial decomposition and oxidation of carbon into carbon dioxide. Continuous ploughing also destroys soil aggregates, resulting in rapid loss of organic carbon from the soil.

Continuous Cropping and Monoculture: Cultivating the same crop repeatedly without proper crop rotation reduces the return of diverse organic residues to the soil. Continuous cropping depletes soil nutrients and gradually lowers soil organic carbon levels.

Removal and Burning of Crop Residues: In many farming systems, crop residues are removed for fodder or fuel, while some are burned in the field. This prevents the addition of organic matter to the soil and leads to loss of valuable carbon and nutrients.

Soil Erosion: Wind and water erosion remove the nutrient-rich topsoil, which contains most of the soil organic carbon. Erosion is especially severe in sloping lands, arid regions, and areas with poor vegetation cover.

Deforestation and Land Degradation: Conversion of forests and grasslands into agricultural or urban land decreases organic matter inputs and accelerates carbon loss. Land degradation through mining, overgrazing, and improper land management also negatively affects SOC.

Excessive Use of Chemical Fertilizers: Heavy dependence on chemical fertilizers with limited use of organic manures reduces soil biological activity and organic matter content. Over time, this affects soil structure and decreases carbon accumulation.

Climate Change: Rising temperatures increase the rate of decomposition of organic matter, leading to faster carbon loss. Irregular rainfall, droughts, and floods also affect vegetation growth and reduce organic residue addition to the soil.

Conclusion

In conclusion, maintaining soil organic carbon is challenging due to multiple interacting factors related to agriculture, environment, and land management. Adoption of sustainable practices such as conservation tillage, crop rotation, residue incorporation, compost application, agroforestry, and integrated nutrient management is essential for improving SOC and ensuring resilient soil production systems. Soil organic carbon is a key component of healthy and resilient soil production systems.

It improves soil fertility, enhances water retention, supports microbial activity, and increases crop productivity. In addition, it plays an important role in climate resilience by reducing soil degradation and helping in carbon sequestration. However, factors such as intensive cultivation, soil erosion, residue burning, and climate change continue to reduce soil organic carbon levels. Therefore, adopting sustainable soil management practices such as conservation tillage, crop rotation, organic manure application, and residue management is essential for maintaining soil health, ensuring long-term agricultural productivity and achieving environmental sustainability.

QTL Mapping for Insect Resistance in Crops

Manisha Patel and Radheshyam Ramkrishna Dhole

Abstract

Insect pests are a major constraint to global agricultural productivity, causing substantial yield losses and threatening food security. Developing insect-resistant crop varieties is a sustainable and environmentally friendly approach to pest management. Quantitative Trait Loci (QTL) mapping has emerged as a powerful tool for identifying genomic regions associated with complex traits such as insect resistance. Unlike simple Mendelian traits, insect resistance is often controlled by multiple genes and influenced by environmental factors. QTL mapping enables the detection, localization, and utilization of these genes in breeding programs. This article discusses the principles of QTL mapping, its methodologies, applications in insect resistance breeding, advantages, challenges, and future prospects. The integration of QTL mapping with modern genomic tools is accelerating the development of pest-resistant crop varieties, contributing to sustainable agriculture and enhanced food security.

Introduction

Agricultural crops are continuously exposed to a wide range of insect pests that significantly reduce yield and quality. Conventional pest control methods rely heavily on chemical pesticides, which are associated with environmental hazards, resistance development in insects, and increased production costs. Host plant resistance offers a sustainable alternative, but the genetic basis of resistance is often complex. Insect resistance in crops is typically a quantitative trait controlled by multiple genes, each contributing a small effect. Identifying these genes using traditional breeding approaches is challenging. The advent of molecular genetics and genomics has enabled the use of QTL mapping to dissect complex traits and identify genomic regions associated with insect resistance. QTL mapping bridges the gap between genotype and phenotype by linking observable traits with specific regions of the genome. This approach has become an essential component of modern plant breeding programs.

Key Highlights

Concept of QTL Mapping: Quantitative Trait Loci (QTLs) are regions of the genome that are associated with variation in quantitative traits. QTL mapping involves identifying these regions by analyzing the relationship between genetic markers and phenotypic traits in a mapping population.

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Unlike qualitative traits controlled by a single gene, quantitative traits such as insect resistance are influenced by multiple genes and environmental factors. QTL mapping helps locate these genes and estimate their effects.

Types of Mapping Populations

QTL mapping requires suitable populations derived from crosses between genetically diverse parents. Common types include:

F_2 Populations: Derived from crossing two inbred lines

Backcross Populations: Crossing F_1 hybrids with one of the parents

Recombinant Inbred Lines (RILs): Developed through repeated selfing

Doubled Haploids (DH): Produced using tissue culture techniques

These populations provide genetic variation necessary for detecting QTLs.

Steps in QTL Mapping

The process of QTL mapping involves several key steps:

Selection of Parents: Choose parents with contrasting traits (resistant vs susceptible)

Development of Mapping Population: Generate segregating populations

Phenotyping: Evaluate insect resistance under controlled and field conditions

Genotyping: Use molecular markers such as SSRs, SNPs, or AFLPs

Linkage Map Construction: Determine the position of markers on chromosomes

QTL Analysis: Identify genomic regions associated with the trait

This systematic approach enables precise identification of QTLs.

Molecular Markers Used in QTL Mapping

Molecular markers are essential for QTL analysis. Common types include:

- ✓ Simple Sequence Repeats (SSRs)
- ✓ Single Nucleotide Polymorphisms (SNPs)
- ✓ Amplified Fragment Length Polymorphisms (AFLPs)

These markers help track the inheritance of genomic regions associated with insect resistance.

Applications in Insect Resistance Breeding

QTL mapping has been successfully used in various crops:

Rice: Identification of QTLs for resistance to brown planthopper and stem borers

Maize: QTLs associated with resistance to stem borers and fall armyworm

Wheat: Mapping of resistance loci against aphids and Hessian fly

Cotton: QTLs for resistance to bollworms and sucking pests

These applications demonstrate the importance of QTL mapping in crop protection.

Integration with Marker-Assisted Selection (MAS)

QTL mapping facilitates marker-assisted selection by identifying markers linked to resistance traits. MAS enables:

- ✓ Early selection of resistant plants

- ✓ Reduction in breeding cycles
- ✓ Increased accuracy in selection

This integration significantly improves breeding efficiency.

Advantages of QTL Mapping

Dissection of Complex Traits: Identifies multiple genes controlling resistance

Precision: Locates genomic regions associated with traits

Efficiency: Accelerates breeding programs

Wide Applicability: Useful across different crops and traits

Challenges and Limitations

Despite its benefits, QTL mapping has certain limitations:

Environmental Influence: Trait expression may vary across environments

Low Resolution: QTL regions may be large and contain multiple genes

Epistasis: Interaction between genes complicates analysis

Time and Resource Intensive: Requires large populations and extensive data

These challenges necessitate the use of advanced approaches.

Recent Advances in QTL Mapping

Modern technologies have improved QTL analysis:

Genome-Wide Association Studies (GWAS): High-resolution mapping using diverse populations

High-Throughput Sequencing: Enables dense marker coverage

QTL Fine Mapping: Narrows down candidate genes

Genomic Selection: Uses genome-wide markers for prediction

These advancements are enhancing the accuracy and utility of QTL mapping.

Role in Sustainable Agriculture

QTL mapping contributes to sustainable agriculture by:

- ✓ Developing pest-resistant varieties
- ✓ Reducing pesticide use
- ✓ Enhancing crop productivity
- ✓ Promoting eco-friendly farming practices

Future Strategies

The future of QTL mapping lies in integrating it with advanced genomic and computational tools. Key strategies include:

- ✓ Combining QTL mapping with genomics and phenomics
- ✓ Using artificial intelligence for data analysis
- ✓ Developing high-resolution mapping populations
- ✓ Expanding research to underutilized crops
- ✓ Strengthening collaboration between research institutions

These approaches will further enhance the effectiveness of QTL mapping in crop improvement.

Conclusion

QTL mapping has revolutionized the study of complex traits such as insect resistance in crops. By identifying genomic regions associated with resistance, it provides valuable insights for plant breeding programs. The integration of QTL mapping

with modern genomic tools and marker-assisted selection is accelerating the development of pest-resistant crop varieties. Despite certain challenges, continuous advancements in technology are improving the precision and efficiency of QTL analysis. QTL mapping remains a cornerstone of modern plant breeding, contributing significantly to sustainable agriculture and global food security.

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Role of MPSS and SAGE in Crop Improvement

Manisha Patel and Radheshyam Ramkrishna Dhole

Abstract

Advancements in molecular biology and genomics have revolutionized plant breeding and crop improvement strategies. Among various high-throughput gene expression profiling techniques, Massively Parallel Signature Sequencing (MPSS) and Serial Analysis of Gene Expression (SAGE) have played a significant role in understanding gene function and regulation in plants. These technologies enable comprehensive analysis of transcriptomes, helping identify genes associated with important agronomic traits such as yield, stress tolerance, and pest resistance. This article explores the principles of MPSS and SAGE, their applications in crop improvement, advantages, limitations, and their contribution to the development of commercially viable food plant varieties. The integration of these technologies into modern breeding programs has accelerated the pace of genetic improvement, paving the way for sustainable agriculture and food security.

Introduction

Crop improvement has always been central to ensuring food security and agricultural sustainability. Traditional breeding approaches have contributed significantly to yield enhancement; however, their progress is often slow and limited by environmental interactions and genetic complexity. With the advent of genomics and molecular biology, plant scientists now have access to advanced tools that enable precise identification and manipulation of genes responsible for desirable traits. Among these tools, gene expression profiling techniques such as MPSS (Massively Parallel Signature Sequencing) and SAGE (Serial Analysis of Gene Expression) have emerged as powerful methods to study the functional aspects of plant genomes. These techniques provide a global view of gene activity by quantifying mRNA transcripts, allowing researchers to identify genes involved in key physiological and developmental processes. Understanding gene expression patterns is crucial for improving traits such as insect resistance, drought tolerance, nutrient efficiency, and yield. MPSS and SAGE have contributed significantly to identifying candidate genes and regulatory pathways, thereby supporting the development of improved crop varieties.

Principles of SAGE Technology

Serial Analysis of Gene Expression (SAGE) is a technique that allows quantitative and comprehensive analysis of gene expression patterns.

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It involves the extraction of short sequence tags (typically 10-14 base pairs) from mRNA transcripts. These tags are then concatenated and sequenced, enabling the identification and quantification of thousands of genes simultaneously. Each tag corresponds to a specific gene, and the frequency of a tag reflects the level of gene expression. This digital approach provides a precise measurement of transcript abundance, making SAGE a powerful tool for transcriptome analysis.

Principles of MPSS Technology

Massively Parallel Signature Sequencing (MPSS) is an advanced sequencing-based method that allows high-throughput analysis of gene expression. In MPSS, millions of short signature sequences (typically 17-20 base pairs) are generated and sequenced simultaneously using microbead-based technology. MPSS offers deeper coverage and higher sensitivity compared to SAGE, enabling the detection of low-abundance transcripts. This makes it particularly useful for studying complex plant genomes and identifying rare gene transcripts involved in important biological processes.

Applications in Crop Improvement

MPSS and SAGE have been widely used in crop improvement programs for various purposes:

Identification of Stress-Responsive Genes: These techniques help identify genes activated under drought, salinity, heat, and cold stress conditions.

Insect Pest Resistance: Gene expression profiling reveals defense-related genes involved in plant-insect interactions.

Yield Enhancement: Genes associated with growth, development, and metabolic efficiency can be identified and targeted.

Nutritional Improvement: Expression analysis helps in enhancing nutrient content such as vitamins and minerals.

Disease Resistance: Identification of genes involved in pathogen defense mechanisms supports breeding for disease-resistant varieties.

Contribution to Commercial Crop Varieties

The use of MPSS and SAGE has facilitated the development of commercially improved crop varieties by:

- ✓ Identifying candidate genes for marker-assisted selection.
- ✓ Supporting genetic engineering approaches for trait improvement.
- ✓ Enhancing understanding of gene networks and regulatory pathways.
- ✓ Accelerating breeding programs through precise gene targeting.

These contributions have led to the development of crops with improved yield, quality, and resilience.

Advantages of MPSS and SAGE

High Throughput: Ability to analyze thousands of genes simultaneously.

Quantitative Accuracy: Provides precise measurement of gene expression levels.

No Prior Sequence Knowledge Required: Useful for studying non-model crops.

Discovery of Novel Genes: Enables identification of

previously unknown transcripts

Wide Applicability: Can be used across different plant species and conditions

Limitations and Challenges

Despite their advantages, MPSS and SAGE have certain limitations:

Technical Complexity: Procedures are labor-intensive and require specialized equipment

Cost: High cost of sequencing limits widespread use

Short Tag Length: May lead to ambiguity in gene identification

Data Analysis Challenges: Requires advanced bioinformatics tools and expertise

With the advent of next-generation sequencing (NGS) technologies such as RNA-Seq, the use of MPSS and SAGE has declined; however, their foundational contributions remain significant.

Comparison with Modern Technologies

Modern transcriptome analysis techniques, particularly RNA-Seq, offer several advantages over MPSS and SAGE, including longer read lengths, higher accuracy, and reduced cost. However, MPSS and SAGE laid the groundwork for these advancements by demonstrating the feasibility of large-scale gene expression profiling.

Their principles continue to influence current genomic technologies and methodologies.

Role in Sustainable Agriculture

MPSS and SAGE contribute to sustainable agriculture by enabling:

- ✓ Development of climate-resilient crop varieties
- ✓ Reduction in chemical inputs through improved resistance traits
- ✓ Efficient use of natural resources
- ✓ Enhanced adaptability to changing environmental conditions

These technologies support the transition toward eco-friendly and sustainable farming systems.

Future Strategies

The future of gene expression profiling in crop improvement lies in integrating traditional techniques like MPSS and SAGE with modern genomic tools. Key strategies include:

- ✓ Combining transcriptomics with genomics, proteomics, and metabolomics
- ✓ Utilizing artificial intelligence for data analysis and gene prediction
- ✓ Expanding research to underutilized and orphan crops
- ✓ Developing cost-effective and user-friendly sequencing technologies
- ✓ Strengthening collaboration between research institutions and industry

Such integrated approaches will further enhance the efficiency and impact of crop improvement programs.

Conclusion

MPSS and SAGE have played a pivotal role in advancing our understanding of plant gene expression and its application in crop improvement. By enabling comprehensive and quantitative analysis of transcriptomes, these technologies have helped identify key genes and pathways involved in import-

ant agronomic traits. Although newer technologies like RNA-Seq have largely replaced them, the contributions of MPSS and SAGE remain foundational in the field of plant genomics. Their application has significantly accelerated the development of commercially improved food crop varieties, contributing to sustainable agriculture and global food security. Continued innovation and integration with modern tools will further enhance their relevance in future crop improvement efforts.

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DNA Sequencing Technologies for Developing Improved Food Varieties

Manisha Patel and Radheshyam Ramkrishna Dhole

Abstract

The rapid advancement of DNA sequencing technologies has revolutionized plant breeding and crop improvement. From early Sanger sequencing to modern next-generation sequencing (NGS) and third-generation platforms, these technologies have enabled comprehensive analysis of plant genomes, facilitating the identification of genes associated with desirable agronomic traits. DNA sequencing plays a crucial role in developing improved food crop varieties with enhanced yield, nutritional quality, and resistance to biotic and abiotic stresses. This article discusses the evolution of DNA sequencing technologies, their applications in crop improvement, advantages, challenges, and future prospects. The integration of sequencing technologies into breeding programs is accelerating the development of climate-resilient and high-performing food crops, contributing to global food security and sustainable agriculture.

Introduction

Ensuring food security for a growing global population is one of the greatest challenges of the 21st century. Crop productivity is frequently threatened by insect pests, diseases, and environmental stresses such as drought, salinity, and temperature extremes. Traditional breeding methods, though effective, are often slow and limited in precision. The advent of DNA sequencing technologies has transformed the field of plant genetics and breeding. By enabling detailed analysis of plant genomes, sequencing technologies allow scientists to identify genes responsible for important traits and use this information to develop improved crop varieties. These technologies have made it possible to move from phenotype-based selection to genotype-based breeding, significantly enhancing the efficiency and accuracy of crop improvement programs.

Evolution of DNA Sequencing Technologies

DNA sequencing technologies have evolved through three major generations:

First-Generation Sequencing (Sanger Method): Developed in the 1970s, this method provided accurate but low-throughput sequencing. It laid the foundation for early genomic studies.

Second-Generation Sequencing (Next-Generation Sequencing, NGS): Technologies such as Illumina sequencing allow massive parallel sequencing of millions of DNA fragments, significantly increasing speed and reducing cost.

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Third-Generation Sequencing: Platforms like PacBio and Oxford Nanopore enable real-time sequencing of long DNA molecules, providing better genome assembly and detection of structural variations.

This evolution has dramatically increased sequencing capacity while reducing time and cost.

Applications in Crop Improvement

DNA sequencing technologies are widely used in various aspects of crop improvement:

Genome Mapping and Assembly: Sequencing helps in constructing high-quality reference genomes for major crops such as rice, wheat, and maize.

Gene Discovery: Identification of genes associated with yield, stress tolerance, and pest resistance.

Marker Development: DNA markers such as SNPs (single nucleotide polymorphisms) are used in marker-assisted selection (MAS).

Quantitative Trait Loci (QTL) Mapping: Sequencing aids in identifying genomic regions linked to complex traits.

Genomic Selection: Predicting breeding values based on genome-wide marker information.

These applications have significantly enhanced breeding efficiency.

Role in Developing Insect Pest-Resistant Varieties

DNA sequencing technologies play a crucial role in identifying genes and pathways involved in plant defense against insect pests. By analyzing gene expression and genetic variation, researchers can:

- ✓ Identify resistance genes and alleles
- ✓ Understand plant-insect interactions at the molecular level
- ✓ Develop pest-resistant varieties through marker-assisted breeding or genetic engineering

This reduces reliance on chemical pesticides and promotes sustainable pest management.

Improvement of Nutritional Quality

Sequencing technologies have enabled biofortification of crops by identifying genes involved in nutrient biosynthesis. Examples include:

- ✓ Enhancement of vitamin content (e.g., pro-vitamin A in rice)
- ✓ Improvement of protein quality in cereals
- ✓ Increased mineral content such as iron and zinc

These improvements contribute to addressing malnutrition and hidden hunger.

Development of Climate-Resilient Crops

Climate change poses a significant threat to agriculture. DNA sequencing helps in identifying genes associated with tolerance to:

- ✓ Drought
- ✓ Heat stress
- ✓ Salinity
- ✓ Flooding

By incorporating these traits into crop varieties, breeders can develop resilient crops capable of thriving under adverse conditions.

Integration with Modern Breeding Techniques

DNA sequencing technologies complement advanced breeding approaches such as:

Marker-Assisted Selection (MAS): Accelerates selection of desirable traits

Genomic Selection: Uses genome-wide data for

prediction

Genome Editing (CRISPR): Enables precise modification of target genes

This integration enhances the speed and accuracy of crop improvement programs.

Advantages of DNA Sequencing Technologies

High Throughput: Ability to sequence entire genomes rapidly

Precision: Accurate identification of genetic variations

Cost-Effectiveness: Reduced sequencing costs over time

Comprehensive Data: Provides detailed insights into genome structure and function

Versatility: Applicable to a wide range of crops and traits

Challenges and Limitations

Despite their benefits, DNA sequencing technologies face several challenges:

Data Complexity: Large datasets require advanced bioinformatics tools

High Initial Investment: Infrastructure and expertise can be costly

Interpretation Difficulties: Linking genetic variation to phenotype is complex

Limited Access: Developing countries may face resource constraints

Addressing these challenges is essential for wider adoption.

Recent Advances in Sequencing Technologies

Recent innovations have further enhanced sequencing capabilities:

Single-Cell Sequencing: Enables analysis of gene expression at the cellular level

Metagenomics: Studies plant-associated microbial communities

Epigenomics: Examines DNA methylation and gene regulation

Pangenomics: Captures genetic diversity across multiple varieties

These advances are expanding the scope of crop improvement.

Future Strategies

The future of DNA sequencing in crop improvement lies in its integration with emerging technologies and interdisciplinary approaches. Key strategies include:

- ✓ Combining genomics with phenomics, proteomics, and metabolomics
- ✓ Utilizing artificial intelligence and machine learning for data analysis
- ✓ Developing low-cost sequencing platforms for wider accessibility
- ✓ Promoting public-private partnerships for technology dissemination
- ✓ Focusing on underutilized crops and local varieties

Such strategies will ensure the effective use of sequencing technologies for global food security.

Conclusion

DNA sequencing technologies have revolutionized the field of plant breeding and crop improvement by enabling precise and efficient identification of genes associated with desirable traits.

From improving yield and nutritional quality to enhancing resistance against pests and environmental stresses, these technologies have transformed modern agriculture. Despite certain challenges, continuous advancements are making sequencing more accessible and effective. The integration of DNA sequencing into breeding programs holds immense potential for developing improved food crop varieties, ensuring sustainable agriculture, and addressing global food security challenges.

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Exploiting Wild Germplasm for Pest Resistance Breeding

Manisha Patel and Radheshyam Ramkrishna Dhole

Abstract

Insect pests pose a persistent threat to global agricultural productivity, leading to significant economic losses and increased reliance on chemical pesticides. Developing pest-resistant crop varieties is a sustainable and eco-friendly solution to this challenge. Wild germplasm, which includes wild relatives and landraces of cultivated crops, represents a valuable reservoir of genetic diversity, particularly for traits related to pest resistance. This article explores the importance of exploiting wild germplasm in pest resistance breeding, the mechanisms of resistance, methods of gene introgression, recent advancements, challenges, and future prospects. Harnessing the genetic potential of wild species through modern breeding and biotechnological tools offers a promising pathway toward sustainable crop improvement and food security.

Introduction

Agriculture is continuously challenged by insect pests that damage crops and reduce yield and quality. The widespread use of chemical pesticides has led to environmental degradation, pest resistance and health concerns. Therefore, developing crop varieties with inherent resistance to pests is a key strategy for sustainable agriculture. Modern cultivated crops often have a narrow genetic base due to intensive selection and domestication, making them more vulnerable to pests and diseases. In contrast, wild relatives and traditional landraces possess rich genetic diversity and have evolved natural defense mechanisms against various biotic stresses, including insect pests. Exploiting wild germplasm for pest resistance breeding involves identifying and transferring beneficial genes from wild species into cultivated varieties. This approach not only enhances pest resistance but also contributes to long-term sustainability and resilience of agricultural systems.

Understanding Wild Germplasm: Wild germplasm refers to the genetic material of wild relatives of cultivated crops and traditional landraces. These plants grow in natural ecosystems and have adapted to diverse environmental conditions, often developing resistance to pests and diseases. Sources of wild germplasm include:

- ✓ Wild relatives of crop species
- ✓ Traditional farmer-maintained landraces
- ✓ Gene banks and germplasm collections
- ✓ Forest and uncultivated ecosystems

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These genetic resources are invaluable for crop improvement programs.

Importance of Wild Germplasm in Pest Resistance

Wild germplasm plays a crucial role in providing:

Novel Resistance Genes: Genes not present in cultivated varieties

Broad-Spectrum Resistance: Protection against multiple pest species

Durable Resistance: Long-lasting resistance due to complex genetic mechanisms

Adaptive Traits: Traits that enhance survival under stress conditions

The use of wild germplasm helps diversify the genetic base of crops and reduces vulnerability to pest outbreaks.

Mechanisms of Pest Resistance in Wild Species

Wild plants exhibit various mechanisms of resistance against insect pests:

Antixenosis (Non-Preference): Traits that deter insect feeding or oviposition

Antibiosis: Adverse effects on insect growth, development, or survival

Tolerance: Ability of plants to withstand pest damage without significant yield loss

These mechanisms are often controlled by multiple genes and involve complex biochemical and physiological processes.

Methods of Utilizing Wild Germplasm

Several approaches are used to incorporate pest resistance from wild germplasm into cultivated crops:

Conventional Breeding: Hybridization and selection to transfer resistance traits

Backcross Breeding: Repeated crossing with the cultivated parent to retain desirable traits

Pre-breeding Programs: Development of intermediate lines with desirable traits

Wide Hybridization: Crossing between distantly related species

Marker-Assisted Selection (MAS): Use of DNA markers to track resistance genes

Genetic Engineering: Direct transfer of resistance genes

These methods help overcome barriers such as incompatibility and linkage drag.

Successful Examples in Crop Improvement

Rice: Wild species have contributed genes for resistance against brown planthopper and stem borers

Wheat: Wild relatives have provided resistance to aphids and other pests

Tomato: Wild species have been used to develop resistance to whiteflies and leaf miners

Cotton: Wild germplasm has contributed traits for resistance against bollworms

These examples highlight the practical significance of wild germplasm in pest resistance breeding.

Advantages of Using Wild Germplasm

Enhanced Genetic Diversity: Broadens the genetic base of crops

Sustainable Pest Management: Reduces reliance on chemical pesticides

Environmental Benefits: Promotes eco-friendly

agriculture

Long-Term Stability: Provides durable resistance

Challenges and Limitations

Despite its potential, exploiting wild germplasm presents several challenges:

Crossing Barriers: Genetic incompatibility between wild and cultivated species

Linkage Drag: Transfer of undesirable traits along with resistance genes

Time-Consuming Process: Conventional breeding requires multiple generations

Limited Characterization: Many wild species are not well-studied

Conservation Issues: Loss of wild species due to habitat destruction

Addressing these challenges is essential for effective utilization.

Role of Modern Biotechnological Tools

Recent advancements have improved the efficiency of utilizing wild germplasm:

Genomics and Sequencing: Identification of resistance genes

CRISPR/Cas Genome Editing: Precise transfer or modification of genes

Transcriptomics and Proteomics: Understanding gene expression and protein function

Pangenome Analysis: Capturing genetic diversity across species

These tools help overcome limitations of traditional breeding.

Conservation of Wild Germplasm

Conservation is critical for ensuring the availability of wild genetic resources:

In situ Conservation: Conservation of natural habitats

Ex situ Conservation: Storage in gene banks and seed banks

Community Conservation: Involvement of farmers and local communities

Efforts to conserve biodiversity are essential for future crop improvement.

Future Strategies

The future of exploiting wild germplasm for pest resistance breeding lies in integrating traditional knowledge with modern science. Key strategies include:

- ✓ Strengthening germplasm collection and characterization
- ✓ Promoting international collaboration for genetic resource sharing
- ✓ Developing advanced breeding techniques to minimize linkage drag
- ✓ Enhancing public awareness about the importance of biodiversity
- ✓ Integrating wild germplasm into climate-resilient breeding programs

These approaches will ensure sustainable utilization of genetic resources.

Conclusion

Wild germplasm represents a rich and largely untapped resource for improving pest resistance in crops. By harnessing the genetic diversity present in wild relatives and landraces, plant breeders can develop resilient and high-performing crop varieties.

Although challenges such as crossing barriers and linkage drag exist, advancements in biotechnology are providing effective solutions. The integration of wild germplasm into modern breeding programs is essential for sustainable agriculture, reduced pesticide dependence, and enhanced food security. Protecting and utilizing these genetic resources will play a crucial role in meeting future agricultural challenges.

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Public vs. Private Extension Systems

Dipesh Kumar and Geeta Mohan

Abstract

Agricultural extension systems play a major role in transferring knowledge, technologies, and innovations from research institutions to farmers. These systems help improve agricultural productivity, rural livelihoods, and food security. Extension services are generally categorized into public and private systems. Public extension systems are government-supported organizations that provide advisory services to farmers with the objective of rural development and social welfare. In contrast, private extension systems are managed by private companies, non-governmental organizations, cooperatives, or agribusiness firms with a focus on efficiency, profitability, and market-oriented agriculture. Both systems have distinct strengths and limitations. Public extension services are accessible to small and marginal farmers but often suffer from inadequate funding, limited manpower, and bureaucratic delays. Private extension systems provide specialized, timely, and demand-driven services but may mainly target commercially profitable farmers and crops. In recent years, collaboration between public and private sectors has gained importance for creating a more effective and sustainable agricultural extension framework.

Introduction

Agriculture remains the backbone of many developing economies and supports the livelihood of millions of rural families. Farmers require timely information regarding improved technologies, crop management practices, pest control, irrigation, marketing and climate adaptation. Agricultural extension systems act as a bridge between research organizations and farming communities by transferring scientific knowledge into practical field applications. Traditionally, agricultural extension services were mainly operated by government departments. These public extension systems aimed to improve agricultural production, reduce rural poverty and ensure food security. However, increasing demand for specialized services, technological advancements and financial limitations have encouraged the growth of private extension systems. Today, both public and private extension systems contribute significantly to agricultural development. Public systems emphasize welfare-oriented services, while private systems focus on efficiency and market-driven approaches. Understanding the differences, strengths, and challenges of both systems is essential for improving agricultural productivity and ensuring sustainable rural development.

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Public Extension System

Meaning: A public extension system refers to agricultural advisory services provided and funded by government agencies, universities, or public institutions. These services are generally offered either free of cost or at subsidized rates to farmers.

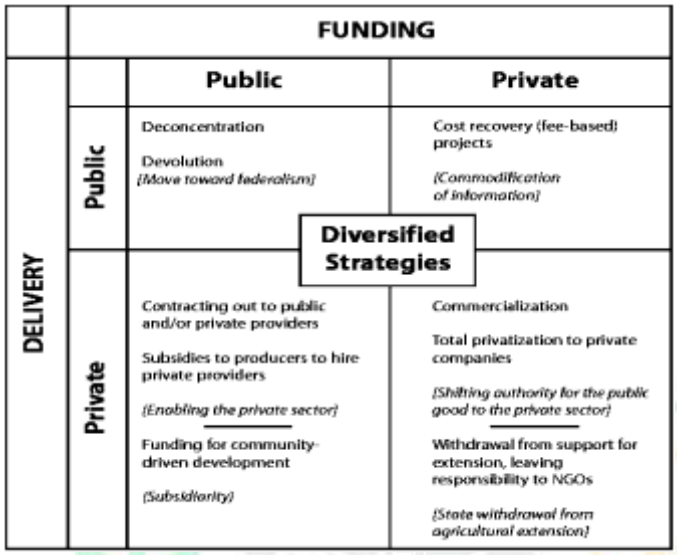

Fig. 1: Structure of Public /Private Extension System

Objectives of Public Extension

- ✓ Dissemination of agricultural technologies.
- ✓ Improvement of rural livelihoods.
- ✓ Promotion of food security.
- ✓ Support to small and marginal farmers.
- ✓ Development of sustainable farming practices.

Features of Public Extension Systems

- ✓ Funded by government resources.
- ✓ Welfare-oriented approach.
- ✓ Large geographical coverage.
- ✓ Focus on rural and social development.
- ✓ Services provided at low or no cost.

Advantages of Public Extension Systems

Wide Accessibility: Public extension services reach remote and economically weaker farmers who may not afford private services.

Social Welfare Orientation: The main objective is farmer welfare rather than profit generation.

Promotion of Inclusive Development: Special emphasis is given to women farmers, tribal communities, and marginal farmers.

Support during Emergencies: Government agencies provide support during droughts, floods, pest outbreaks, and natural disasters.

Limitations of Public Extension Systems

- ✓ Inadequate financial resources.
- ✓ Shortage of trained extension personnel.
- ✓ Slow decision-making process.
- ✓ Limited farmer-to-extension worker ratio.
- ✓ Lack of accountability in some areas.

Private Extension System: Private extension systems are agricultural advisory services provided by private companies, agribusiness firms, cooperatives, NGOs, consultants, or input suppliers. These services are usually commercial and demand-driven.

Objectives of Private Extension

- ✓ Promotion of commercial agriculture.
- ✓ Delivery of specialized advisory services.
- ✓ Improvement of product quality and profitability.
- ✓ Market linkage development.
- ✓ Rapid dissemination of technologies.

Features of Private Extension Systems

- ✓ Profit-oriented services.
- ✓ Demand-driven approach.
- ✓ Specialized technical support.
- ✓ Better use of digital technologies.
- ✓ Faster communication and feedback mechan-

isms.

Advantages of Private Extension Systems

Efficient Service Delivery: Private agencies often provide timely and location-specific recommendations.

Use of Modern Technologies: Digital platforms, mobile applications, and precision farming tools are commonly used.

Better Accountability: Private organizations maintain efficiency due to competition and customer satisfaction.

Market-Oriented Approach: Farmers receive information related to value chains, exports, and agribusiness opportunities.

Limitations of Private Extension Systems

- ✓ Services may be costly for small farmers.
- ✓ Focus mainly on profitable regions and crops.
- ✓ Limited attention to social welfare issues.
- ✓ Risk of biased recommendations for commercial gain.

Comparative Analysis of Public and Private Extension Systems

Basis	Public Extension System	Private Extension System
Ownership	Government institutions	Private firms and NGOs
Objective	Social welfare	Profit and efficiency
Cost to Farmers	Free or subsidized	Paid services
Coverage	Wide rural coverage	Mainly commercial areas
Approach	Generalized services	Specialized services
Accountability	Moderate	High
Technology Adoption	Relatively slower	Faster
Target Farmers	Small and marginal farmers	Commercial farmers

Role of Public-Private Partnership in Extension

Public-private partnership (PPP) combines the strengths of both systems to improve extension efficiency and outreach. Governments can provide policy support and infrastructure, while private organizations contribute innovation, technology, and market expertise.

Fig. 2 Features of Public Private Partnership

Benefits of PPP in Agricultural Extension

- ✓ Improved technology dissemination.
- ✓ Better farmer training programs.
- ✓ Increased investment in agriculture.
- ✓ Efficient resource utilization.
- ✓ Enhanced market access for farmers.

Fig. 3: Advantages of Public Private Partnership

Challenges in Extension Systems

Climate Change: Changing weather patterns create new challenges for extension workers and farmers.

Digital Divide: Many rural farmers still lack access to digital technologies and internet services.

Financial Constraints: Both systems require adeq-

uate funding for effective operation.

Skill Development: Extension personnel need continuous training and capacity building.

Coordination Problems: Lack of coordination among institutions may reduce efficiency.

Future Prospects of Extension Systems

Modern agricultural extension is shifting toward participatory, farmer-centered and technology-driven approaches. Information and Communication Technologies (ICTs), mobile advisory services, artificial intelligence, and digital farming tools are transforming extension delivery systems.

Future extension models are expected to:

- ✓ Encourage climate-smart agriculture.
- ✓ Strengthen farmer producer organizations (FPOs)
- ✓ Promote sustainable farming practices.
- ✓ Increase women's participation in agriculture.
- ✓ Integrate public and private efforts effectively.

Fig. 4: Public Private Partnership in Infrastructure

Conclusion

Public and private extension systems both play important roles in agricultural and rural development. Public extension services ensure social equity and support vulnerable farming communities, while private extension systems provide efficient, specialized, and market-oriented services. However, neither system alone can fully address the diverse needs of modern agriculture. Public systems often face resource limitations, whereas private systems may neglect economically weaker farmers. Therefore, an integrated approach involving collaboration between government agencies, private organizations, NGOs, and farmer groups is essential for sustainable agricultural growth. Strengthening public-private partnerships, improving digital connectivity, and enhancing farmer participation can create a more responsive and effective extension system that benefits all sections of the farming community.

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Traditional Utilization of Orchidaceae in Herbal Medicine: An Ethnobotanical Review

Lalduhsanga, Sujatha A. Nair, Priya Bhusaradi and Zomuansangi

Abstract

Orchids (Family: Orchidaceae) are one of the largest angiosperm families, with a long history of use within the traditional medicine of Asia, Europe and other continents. This article is the documentation and review of the phytochemical evidence, pharmacological validation, and its conservation issues. Five orchids, *viz*., *Gastrodia elata* Bl., *Dendrobium nobile* Lindl., *Dendrobium officinale* Kimura and Migo, *Anoectochilus formosanus* Hayata, and *Eulophia nuda* Lindl., are reviewed for their traditional uses and mechanisms of action. Literature reviews indicated that these species exhibit a variety of biological activity such as antioxidant, neuroprotection, immune modulation, anti-inflammation, and metabolic regulation. However, there is a limited clinical validation (Wang, 2021; Wu *et al.*, 2023). Additionally, conservation issues due to over-harvesting for medicinal purposes requires the development of sustainable cultivation methods and regulatory policies.

Introduction

Apart from their beauty and popularity as garden plants and cut flowers, many orchid species have historically been valued by traditional practitioners of medicine for their therapeutic properties. The ancient tradition of using orchids for medicinal purposes dates back to Vedic times in India. Two orchids ('Rasna'- *Vanda tessellate*; 'Sanjeevani'- *Flickingeria macraei*) were mentioned in the Rig-Veda and Atharva-Veda. Charaka Samhita and Sushruta Samhita listed about a dozen of orchid plants which were used in Ayurvedic medicines. Examples of their uses include treatment for headaches, seizures, digestive issues, coughs, wounds and general weakness. More recently, ethnobotanical studies have highlighted the fact that although ornamental orchid cultivation has become increasingly popular, relatively little information exists regarding medicinal use of orchids and their scientific validation as most information on medicinal uses of orchids remains regionalized. However, the medicinal properties of orchids also poses a threat on the orchid population due to excessive harvesting from their natural habitat leading to decline in their population. This article is an ethnobotany literature that has been gathered from articles published over the past twenty years. The articles consulted includes peer-reviewed literature, regional ethnobotanical studies and species-specific pharmacological studies with primary focus on

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comprehensive reviews on medicinal orchids and high quality articles documenting the highest amount of traditional use for taxa (*Gastrodia, Dendrobium*). When possible, phytochemical evidence and *in vivo/in vitro* pharmacology were referenced to support the possible bioactive constituents for each traditional claim. Sources included recent ethnopharmacological reviews in the *Journal of Ethnopharmacology*, *Frontiers publications*, and comprehensive ethnobotanical open access reviews.

Regional ethnobotanical patterns and primary indications

East and Southeast Asia: In East Asia, orchids are deeply embedded within TCM (Traditional Chinese Medicine) practice. *Gastrodia elata* (Chinese: Tianma) is routinely used for headaches, dizziness, epilepsy and other neurovascular complaints; its active metabolite gastrodin has been the subject of pharmacological research for neuroprotective and anticonvulsant effects. *Dendrobium* species (collectively known in some pharmacopeias as “Shihu”) are used as tonics for “yin” deficiency (TCM) concept representing a lack of cooling, moistening, and calming fluids in the body, resulting in "empty heat" symptoms to relieve dry cough and as general restorative agents. Multiple modern reviews summarize both the traditional indications and laboratory evidence for these species.

South Asia and India: Traditional use of orchid is documented in a wide variety of ethnobotanical studies throughout India. These include preparation of their tuberous or pseudobulbous parts into a poultice to treat wounds, decoctions to treat digestive issues, and starch derived from them to provide nutrition. Most of the terrestrial orchids used is local and has been passed down through generations by oral tradition. The medicinal roles for terrestrial orchids have also led to concern about their wild harvest and potential threats to their conservation status.

Europe and Africa: Historical European herbals (and more recent ethnobotanical fieldwork) document medicinal uses of genus *Orchis* and allied taxa for ailments such as gastrointestinal complaints and topical wounds. African ethnobotany similarly uses orchids in their traditional pharmacopeias, which were used for everything from diuretics to remedies for aches. These traditions are less centralized than East Asian systems but are important for illustrating convergent medicinal uses (e.g., as tonics, demulcents).

Species case studies

***Gastrodia elata*:** Among orchids, *Gastrodia elata* is the most intensively studied in a biomedical sense. Historically, *Gastrodia elata* was used to treat a variety of symptoms that included headache, dizziness and convulsions; in recent times gastrodin and other phenolic compounds with antioxidant, anti-inflammatory and neuroprotective properties have been isolated as active components. Results from preclinical studies using cellular and animal trials supported the use of *Gastrodia elata* in preventing seizures and ischemia and suggest potential mechanisms of action including modulation

of oxidative stress pathways and inflammatory signaling. While there are clinical evidences supporting the efficacy of *Gastrodia elata* for a number of selected neurological indications, the evidence base remains limited.

***Dendrobium* spp.:** The genus *Dendrobium* comprises many plant species that are traditionally utilized in Chinese medicine to nourish the body or to treat respiratory and digestive problems. Studies of phytochemicals in *Dendrobium* species have identified a number of compounds such as alkaloids (dendrobine), polysaccharides and bibenzyl derivatives. In addition, numerous biological assays indicate the presence of several bioactive properties including immunomodulatory, anti-inflammatory and antioxidant activity. As with many other plant genera, there is a considerable variation in chemical constituents and bioactivity among various *Dendrobium* species.

Terrestrial taxa (*Orchis, Anacamptis, Aplectrum* etc.): Traditionally tubers from other genera have been used to create salep (a nutritious mucilaginous preparation), for use in treatment of gastrointestinal disorders, as a source of nutrients, and as an emollient. The phytochemicals present in these plants are not as well studied as those in East Asian orchids; however, their starch and mucilage content supports their use in both food and as a demulcent. Ethnopharmacology is continuing to study the anti-microbial and antioxidant properties of this group of plants.

Evidence Level Classification

High: Multiple phytochemical isolations + strong preclinical data + some clinical studies

Moderate-High: Robust phytochemical and animal model evidence

Moderate: Verified phytochemistry + preliminary pharmacology

Low-Moderate: Primarily ethnobotanical reports with limited lab validation

Low: Ethnographic documentation only

Safety, toxicity and quality control

Safety is not automatically assured by traditional use. Many plant preparations are safe (such as starches, mucilages) and many concentrated plant extracts that contain active alkaloids or other highly active compounds should be subject to toxicology assessment. Although reported adverse events are rare, several factors must be carefully evaluated prior to clinical application including; pharmacokinetics, standardization, and contamination (e.g. heavy metals, misidentification). Species authentication, standardization of the extract, and controlled clinical trials are required by toxicology assessments.

Conservation and ethical considerations

The *Orchidaceae* family is considered one of the most endangered groups of plants in the world due to destruction of habitats by deforestation, agriculture, urbanization, and climate changes. Since many medicinal preparations use tubers or rhizomes as the base ingredient, the harvesting process typically involves removing the entire plant, significantly hindering its ability to reproduce.

Table 1: Ethnomedicinal summary of selected Orchidaceae species

Species	Traditional Uses	Plant Part	Preparation	Principal Compounds	Evidence Level
Gastrodia elata Bl.	Epilepsy, headache, dizziness (TCM)	Rhizome	Decoction, extract	Gastrodin, parishins	High (preclinical + limited clinical)
Dendrobium nobile Lindl.	*Yin* tonic, immune support	Stem	Decoction, dried slices	Dendrobine, polysaccharides	Moderate-High (preclinical)
Dendrobium officinale Kimura & Migo	Metabolic regulation, fatigue	Stem	Herbal infusion	Polysaccharides, flavonoids	Moderate-High (animal studies)
Anoectochilus formosanus Hayata	Hepatoprotection, anti-diabetic	Whole plant	Decoction	Kinsenoside	Moderate (preclinical)
Eulophia nuda Lindl.	Anti-inflammatory, wound healing	Tuber	Paste, decoction	Phenanthrenes, sterols	Moderate (in vitro)
Orchis mascula (L.) L.	Gastrointestinal tonic (salep)	Tuber	Powdered starch drink	Mucilage, glucomannan	Low-Moderate (ethnobotanical)
Aplectrum hyemale	Topical wound healing, boils (North American folk medicine)	Tuber	Poultice	Starch, minor phenolics	Low (ethnographic documentation only)
Vanda tessellata	Joint pain, nervous disorders, bronchitis (Ayurveda)	Roots	Decoction, paste	Alkaloids, triterpenoids	Moderate (experimental pharmacology)

Note: Evidence levels adapted from pharmacological validation hierarchy (Wang, 2021; Wu *et al.*, 2023).

Table 2. Conservation Status and Trade Regulation (IUCN and CITES Perspective)

Species	Geographic Range	Conservation Status	Trade Regulation
Gastrodia elata	East Asia	Regionally Vulnerable	Cultivation programs active
Dendrobium officinale	China	Endangered (regional)	CITES Appendix II
Dendrobium nobile	South & SE Asia	Not globally assessed	CITES Appendix II
Orchis mascula	Europe	Least Concern (regional variation)	Protected in EU states
Eulophia nuda	India & SE Asia	Data Deficient	Requires monitoring
Vanda tessellata	India, Sri Lanka	Included in conservation priority lists	Vulnerable (regional listings)

Note: Conservation information compiled from regional assessments and international trade listings (Hussain *et al.*, 2023).

An important biological factor limiting the recovery of orchids is the obligatory relationship between orchids and mycorrhizal fungi. The seeds of orchids do not contain an endosperm and rely on the presence of symbiotic fungi for germination and growth in their first stages. Therefore, while reducing the number of mature plants in the affected ecosystem through the disturbance, it will also interfere with the fungal organisms needed for reproduction. Regulation of international trade has a major impact on the conservation of orchids. More than half of all species within the *Orchidaceae* family are regulated under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Appendix II, which controls the international commercial movement of those species. Although regulations are in place, there are still problems associated with the illicit harvest of species, as well as unregulated local markets, particularly in areas of high biodiversity. Additionally, some species used in traditional medicine are facing increased pressure to be artificially propagated or grown in tissue culture

to reduce pressure on wild sources. In addition to concerns regarding biodiversity, there are also ethical issues surrounding bioprospecting and the rights of indigenous and local people who have maintained medicinal knowledge of orchids for centuries. Equitable sharing of benefits, prior informed consent and adherence to the requirements of the Nagoya Protocol are necessary if commercial phytopharmaceutical products based upon traditional medicinal practices are to be developed. To ensure sustainable utilization of these species, a combination of the following approaches needs to be integrated into future conservation strategies: (i) community-based cultivation of species; (ii) use of micropropagation and *in vitro* propagation techniques to produce new individuals; (iii) restoration of habitats; (iv) population monitoring and assessment against IUCN Red List criteria and (v) standardization of pharmacognostic methods to reduce the need for large quantities of biomass.

Conclusion

Orchids occupy a distinctive niche at the intersection of cultural heritage and bioactive natural products. The historical use of many orchids as remedies (e.g., nervous system remedies, as tonics, demulcents and as topical agents) has been documented across the globe through ethnobotany, with much of this use being substantiated by phytochemical and some preclinical evidence for the high-use taxa. However, for these traditional uses to be converted into modern, effective, and sustainable therapies, there needs to be an integrated strategy to identify specific plant species, establish standards for phytochemicals, conduct toxicological evaluations and adopt large scale rapid multiplication protocols and conservation conscious supply chains. The most effective way to both preserve the diverse biological features of Orchidaceae and to protect the traditional knowledge of humans about medicine will be to collaborate among ethnobotanists, phytochemists, pharmacologists and conservation biologists.

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Impact of Climate-Resilient Breeding in the Agriculture Sector

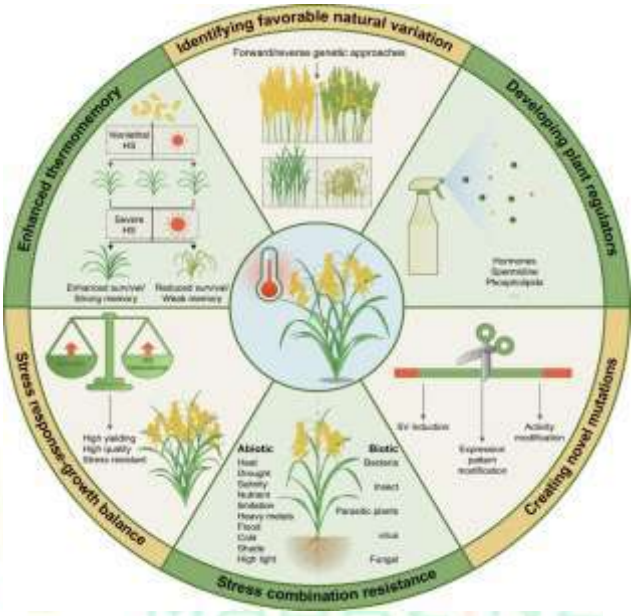
Vengatesh M., Nivetha A. L. and Shridevi S.

Agriculture under Climate Stress

Agriculture is one of the most climate-sensitive sectors in the world. For centuries, farming systems have depended on predictable weather patterns. However, in recent decades, these patterns have become increasingly erratic due to climate change. Rising global temperatures, irregular rainfall, frequent droughts, floods, cyclones, and heatwaves are now common challenges faced by farmers. In countries like India, where a large population depends on agriculture, climate change poses a serious threat to food security and livelihoods. Crop failures due to drought or floods can lead to economic losses, food shortages, and social instability. To address these challenges, scientists and breeders have developed innovative approaches to make crops more adaptable. One of the most important among them is climate-resilient breeding, which aims to develop crop varieties that can withstand adverse environmental conditions while maintaining productivity.

Understanding Climate-Resilient Breeding

Climate-resilient breeding is a scientific approach that focuses on developing crop varieties capable of tolerating environmental stresses caused by climate change. It can be defined as: "The process of developing crop varieties that can maintain stable yield under climate variability and extreme weather conditions."



Types of Stress Addressed

Climate-resilient breeding targets multiple stresses, including:

Abiotic stresses

- ✓ Drought
- ✓ Heat stress
- ✓ Cold stress
- ✓ Salinity
- ✓ Flooding and submergence

Biotic stresses

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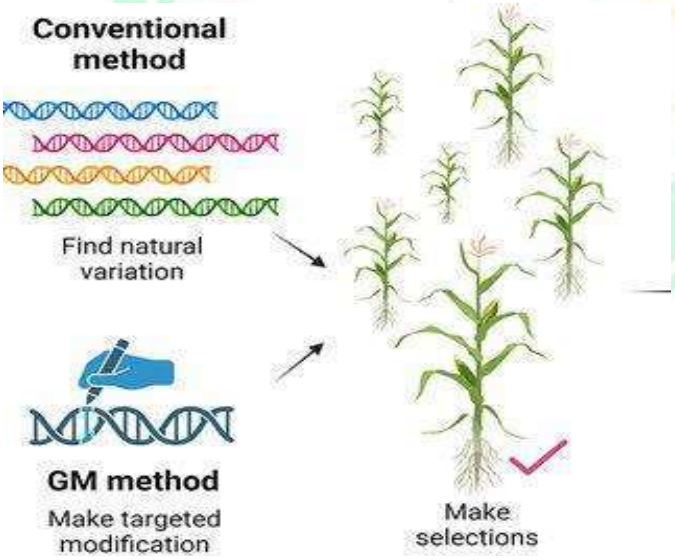
- ✓ Insect pests
- ✓ Diseases
- ✓ Emerging pathogens due to climate change

Key Traits in Climate-Resilient Crops

- ✓ Deep root systems
- ✓ Early maturity
- ✓ Efficient water-use efficiency (WUE)
- ✓ Heat tolerance mechanisms
- ✓ Osmotic adjustment
- ✓ Stay-green character

Evolution of Breeding Approaches

Conventional Breeding: Traditional breeding methods involve selection and hybridization. While effective, they are time-consuming and less precise.



Modern Breeding Techniques

Climate-resilient breeding integrates advanced tools:

- ✓ Marker-assisted selection (MAS)
- ✓ Genomic selection
- ✓ CRISPR and gene editing
- ✓ Speed breeding

These tools significantly reduce the time required to develop improved varieties.

Impact on Crop Productivity

Yield Stability: One of the major impacts is stable yields under fluctuating climates. Even in drought years, resilient crops can produce reasonable yields.

Reduction in Crop Failure: Extreme weather often leads to total crop failure. Climate-resilient crops reduce this risk by surviving harsh conditions.

Improved Harvest Index: Resilient varieties allocate resources efficiently, resulting in better grain production even under stress.

Impact on Food Security: Climate-resilient breeding plays a crucial role in ensuring food security.

Availability: Stable crop production ensures consistent food supply.

Accessibility: Lower production losses help keep food prices stable.

Nutritional Security: Biofortified climate-resilient crops provide essential nutrients such as:

- ✓ Iron
- ✓ Zinc
- ✓ Vitamin A

Global Perspective: Staple crops like rice, wheat, and maize are being improved for stress tolerance, benefiting millions worldwide.

Economic Impact on Farmers

Income Stability: Farmers growing resilient varieties experience fewer losses, leading to stable income.

Reduced Input Costs

- ✓ Less irrigation needed
- ✓ Reduced pesticide use

Risk Management: Climate-resilient crops act as a

form of "biological insurance" against climate risks.

Improved Livelihoods: Smallholder farmers benefit significantly due to reduced vulnerability.

Environmental Sustainability: Climate-resilient breeding supports sustainable agriculture.

Water Conservation: Drought-tolerant crops use water efficiently.

Reduced Chemical Use: Disease-resistant varieties require fewer pesticides.

Soil Health Improvement: Resilient crops maintain productivity without degrading soil quality.

Biodiversity Conservation: Use of diverse genetic resources enhances ecosystem resilience.

Role in Climate Change Adaptation and Mitigation

Adaptation Strategy: Climate-resilient breeding is a key adaptation strategy that helps agriculture cope with climate variability.

Mitigation Potential: Some crops reduce greenhouse gas emissions by:

- ✓ Efficient nitrogen use
- ✓ Reduced methane emissions (in rice)

Technological Advances Driving Climate-Resilient Breeding

Genomics: Identification of stress-tolerant genes.

Phenotyping: Advanced tools measure plant responses under stress.

Artificial Intelligence: AI predicts performance of crop varieties under different climates.

Big Data: Large datasets help breeders make accurate decisions.

Role in Indian Agriculture

India is highly vulnerable to climate change.

Importance

- ✓ Large rainfed areas
- ✓ Dependence on monsoon

Government Initiatives

- ✓ Climate-resilient villages
- ✓ National Innovations in Climate Resilient Agriculture (NICRA)

Contribution of Research Institutions: Agricultural universities and research institutes are developing resilient varieties.

Challenges in Climate-Resilient Breeding

Complex Traits: Climate resilience involves multiple genes.

Time and Cost: Breeding programs require significant investment.

Adoption Issues: Farmers may lack awareness or access to seeds.

Climate Uncertainty: Future climate conditions are unpredictable.

Integration with Climate-Smart Agriculture

Climate-resilient breeding works best when combined with:

- ✓ Crop diversification
- ✓ Conservation agriculture
- ✓ Precision farming
- ✓ Integrated pest management

Future Prospects

The future of climate-resilient breeding includes:

- ✓ Development of multi-stress tolerant crops
- ✓ Integration of AI and genomics
- ✓ Faster breeding through speed breeding

✓ Stronger seed distribution systems

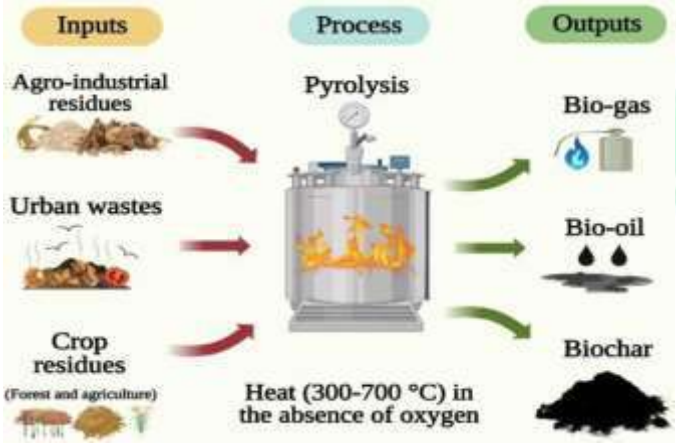
Climate-resilient breeding is essential for the future of agriculture. It provides a sustainable solution to the challenges posed by climate change. By ensuring stable yields, improving farmer incomes, and protecting the environment, it plays a vital role in securing global food systems. As climate change continues to intensify, investment in climate-resilient breeding will be critical to ensure that agriculture remains productive, sustainable, and resilient.

Impact of Biochar Production in Agriculture

Shridevi S., Vengatesh M. and Nivetha A. L.

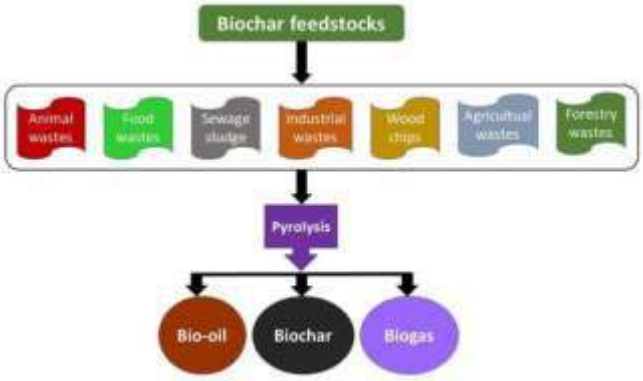
Agriculture today faces multiple challenges including soil degradation, declining fertility, water scarcity, and climate change. Conventional farming practices relying heavily on chemical fertilizers have led to environmental degradation and reduced soil health. Biochar has gained global attention as a sustainable alternative. Biochar is produced by heating organic materials such as crop residues, wood, or manure under limited oxygen conditions (pyrolysis). This process converts biomass into a stable form of carbon that can persist in soils for hundreds to thousands of years.

Biochar Production Process



Feedstock Materials

- ✓ Crop residues (rice husk, wheat straw)
- ✓ Animal manure
- ✓ Forestry waste
- ✓ Municipal organic waste



Pyrolysis Process: Biochar is produced through:

- ✓ Slow pyrolysis (low temperature, high yield)
- ✓ Fast pyrolysis (high temperature, bio-oil dominant)
- ✓ Gasification

Temperature and feedstock type determine biochar properties such as porosity, pH, and nutrient content.

Properties of Biochar

Biochar possesses unique physical and chemical properties:

- ✓ High porosity and surface area
- ✓ Alkaline nature (raises soil pH)
- ✓ High carbon stability
- ✓ Ability to retain water and nutrients

These properties make it an effective soil amendment.

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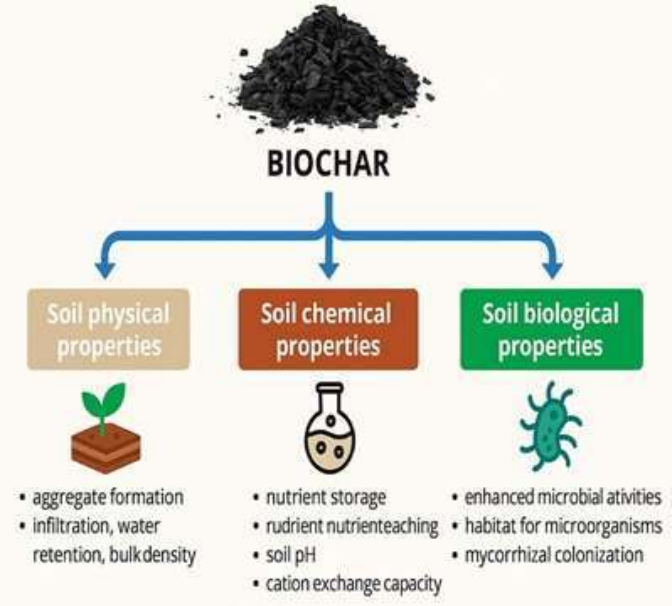
Impact on Soil Health



Physical Properties

- ✓ Improves soil structure
- ✓ Enhances aeration
- ✓ Increases water-holding capacity

Chemical Properties

- ✓ Raises soil pH (useful in acidic soils)
- ✓ Improves cation exchange capacity (CEC)
- ✓ Enhances nutrient retention

Biological Properties

- ✓ Promotes microbial activity
- ✓ Enhances beneficial soil organisms

Biochar-amended soils show improved physicochemical and biological characteristics.

Impact on Crop Productivity

Biochar contributes to increased agricultural productivity through:

- ✓ Improved nutrient availability
- ✓ Reduced nutrient leaching
- ✓ Enhanced root growth
- ✓ Better moisture retention

Studies show that biochar can significantly increase crop yields, especially in low-fertility soils.

Environmental Impacts

Carbon Sequestration: Biochar acts as a long-term carbon sink by stabilizing carbon in soil, helping mitigate climate change.

Greenhouse Gas Reduction

- ✓ Reduces methane (CH_4) emissions
- ✓ Reduces nitrous oxide (N_2O) emissions

High-temperature biochar is particularly effective in lowering greenhouse gas emissions.

Waste Management: Biochar production converts agricultural waste into a valuable resource, reducing:

- ✓ Open burning
- ✓ Environmental pollution

Economic Impact

Benefits

- ✓ Reduced fertilizer costs
- ✓ Increased crop yield and income
- ✓ Potential carbon credit benefits

Constraints

- ✓ High initial production cost
- ✓ Limited access to technology
- ✓ Scale dependency for profitability

Economic viability varies depending on farm size and resource availability.

Limitations and Negative Impacts

Despite its advantages, biochar has several limitations:

Potential Toxicity: Biochar may contain harmful compounds such as:

- ✓ Polycyclic aromatic hydrocarbons (PAHs)
- ✓ Dioxins and furans

Nutrient Imbalance

- ✓ Fresh biochar may absorb nutrients temporarily
- ✓ Requires pre-treatment (charging)

Variability in Performance: Effectiveness depends on:

- ✓ Soil type
- ✓ Climate
- ✓ Feedstock and production conditions

Heavy Metal Retention: Biochar can immobilize heavy metals, which may pose risks under certain conditions.

Role in Climate-Resilient Agriculture

Biochar enhances resilience by:

- ✓ Improving drought tolerance
- ✓ Enhancing water-use efficiency
- ✓ Stabilizing soil organic matter

It plays a vital role in climate-smart agriculture and sustainable farming systems.

Future Prospects

Future research and development should focus on:

- ✓ Standardization of biochar production
- ✓ Cost-effective technologies
- ✓ Integration with organic farming systems
- ✓ Policy support and incentives

Biochar is considered a key negative emission technology for future climate strategies.

Biochar production and application have transformative potential in agriculture. It improves soil health, enhances crop productivity and contributes to environmental sustainability. However, challenges such as economic feasibility, variability, and potential risks must be addressed. With proper management and technological advancements, biochar can become a cornerstone of sustainable agriculture.

Women's Role in Agroforestry and Nursery Entrepreneurship in Haryana

Kajal, Naresh Kaushik, Sandeep Arya and Krishma Nanda

Agroforestry is the practice of growing trees and crops in interacting combinations and is recognized worldwide as an integrated approach for sustainable land-use. The World Agroforestry Centre (ICRAF) defines it as "a dynamic, ecologically based, natural resources management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels." According to the UN Food and Agriculture Organization (FAO), more than 1.2 billion people around the world practice agroforestry on around 1 billion hectares (ha) of land (FAO, 2017). In Haryana, where agriculture forms the backbone of the rural economy, agroforestry has emerged as a promising approach to address challenges such as soil degradation, declining water tables, and climate variability. Within this evolving landscape, women are playing an increasingly vital role, particularly in agroforestry practices and nursery entrepreneurship. Their involvement not only contributes to environmental sustainability but also promotes socio-economic empowerment. Traditionally, women in rural Haryana have been actively engaged in farming activities such as sowing, weeding, harvesting, and livestock management. However, their role in agro-forestry is now expanding beyond labor contributions to active decision-making and enterprise development. Women are involved in planting and managing multipurpose tree species such as neem, shisham, eucalyptus, and fruit trees, which provide fuelwood, fodder, timber, and additional income. Their indigenous knowledge of plant species, soil conditions, and resource management plays a crucial role in maintaining biodiversity and ecological balance.

Role of Women in Agriculture and Agroforestry

Women have traditionally been an integral part of agriculture in Haryana. They contribute significantly to various farming activities such as:

- ✓ Seed selection and sowing
- ✓ Weeding and intercultural operations
- ✓ Harvesting and post-harvest processing
- ✓ Livestock management

However, their role in agroforestry is now expanding beyond labor contributions to active decision-making and enterprise development. Now, they are involved in

- ✓ Raising and nurturing tree seedlings

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- ✓ Managing tree-crop interactions
- ✓ Collecting fuelwood, fodder, and non-timber forest products
- ✓ Maintaining biodiversity through indigenous knowledge

Women possess deep-rooted knowledge of local ecosystems, plant species, and resource management. This knowledge is crucial for the success of agroforestry systems, particularly in selecting suitable tree species and maintaining ecological balance.

Nursery Entrepreneurship: An Emerging Opportunity

Nursery entrepreneurship is another area where women are making significant strides. It refers to the establishment and management of plant nurseries for producing seedlings of trees, fruits, ornamentals, and medicinal plants. It has emerged as a promising livelihood option for rural women in Haryana due to the following reasons:

- ✓ Low initial investment
- ✓ Short gestation period
  - High demand for quality planting material
  - Scope for year-round income generation

Women-led nurseries are increasingly supplying seedlings for agroforestry plantations, horticulture, and afforestation programs. These nurseries typically include:

- ✓ Timber species (e.g., eucalyptus, poplar and shisham)
- ✓ Fruit plants (e.g., guava, ber, amla)
- ✓ Medicinal and aromatic plants
- ✓ Ornamental plants for landscaping

Self-help groups (SHGs), government schemes, and agricultural universities are playing a significant role in training women in nursery techniques such as seed treatment, propagation, grafting, and plant protection.

Economic Contributions

Women's participation in agroforestry and nursery entrepreneurship contributes significantly to household and rural economies:

Income diversification: Tree-based systems provide additional income through timber, fruits, and other products.

Employment generation: Nurseries create employment opportunities for women and local communities.

Financial independence: Women gain control over income, improving their decision-making power within households.

Risk reduction: Agroforestry reduces dependency on single crops, minimizing risks associated with crop failure.

Additionally, women's control over income contributes to improved nutrition, education, and healthcare for their families. Socially, their involvement leads to increased confidence, leadership skills, and participation in community decision-making processes. Women entrepreneurs engaged in nursery raising often develop micro-enterprises, supplying planting material to farmers, government agencies, and NGOs.

Environmental Benefits

Women-led agroforestry initiatives contribute to environmental sustainability in multiple ways:

Soil conservation: Tree roots help prevent soil erosion and improve soil structure.

Carbon sequestration: Trees absorb carbon dioxide, helping mitigate climate change.

Biodiversity conservation: Women often prefer planting diverse species, enhancing ecological balance.

Water conservation: Agroforestry systems improve water infiltration and reduce runoff.

Their traditional knowledge ensures sustainable resource use and conservation of native species.

Challenges Faced by Women

Despite their contributions, women face several constraints:

Limited land ownership: Most women do not own land, restricting their decision-making authority.

Lack of access to credit: Financial institutions often require collateral, which women lack.

Limited technical knowledge: Inadequate training and extension support hinder adoption of advanced practices.

Market access issues: Women often face difficulties in accessing markets and getting fair prices.

Socio-cultural barriers: Gender norms restrict mobility and participation in economic activities.

These challenges limit the full potential of women in agroforestry and nursery entrepreneurship.

Way Forward

To enhance women's participation and effectiveness, the following measures are essential:

Capacity building: Regular training programs on agroforestry practices and nursery management

Access to finance: Simplified credit facilities and subsidies for women entrepreneurs

Land rights: Policies to ensure women's access to land and resources

Market linkages: Establishing cooperatives and digital platforms for better market access

Technology dissemination: Use of mobile apps and digital tools for knowledge transfer

Gender-sensitive policies: Inclusion of women in planning and implementation of agroforestry programs.

In conclusion, women in Haryana are emerging as key drivers of agroforestry development and nursery entrepreneurship. Their contributions are vital for achieving sustainable agriculture, environmental conservation, and rural development. Empowering women through education, resources, and supportive policies will not only enhance their livelihoods but also strengthen the overall agroforestry sector. Recognizing and promoting their role is essential for building a resilient and inclusive agricultural future. Encouraging women-led enterprises and strengthening institutional support can significantly boost rural development.

High Density Planting in Fruit Crops: Growing More Fruits in Less Space

G. Bhrijavasi and P. Vinaya Kumar Reddy

Introduction

Indian agriculture is changing rapidly, and fruit cultivation is becoming more modern than ever before. Farmers today face several challenges such as shrinking land holdings, shortage of labour, rising production costs, and unpredictable climate conditions. At the same time, the demand for fruits is continuously increasing because people are becoming more health conscious. Under these conditions, farmers cannot always depend on traditional orchard systems where trees are planted at very wide spacing and take many years to provide good income. This is where High Density Planting (HDP) has become a game changer in fruit cultivation. High Density Planting simply means growing more number of plants in a limited area by maintaining smaller tree size through scientific management practices. This technique allows farmers to harvest more fruits from the same land while improving fruit quality and profitability. Now a days HDP is becoming increasingly popular in fruit crops such as mango, guava, apple, banana, citrus, and grapes. Many progressive farmers are adopting this system because it provides early returns and better income.

What is High Density Planting?

In traditional orchards, trees are planted very far apart. During the first few years, a large portion of land remains unused until the trees grow fully. Farmers also have to wait many years for commercial production. High Density Planting solves this problem by planting trees closer together and managing them scientifically through pruning, training, drip irrigation, and fertigation. The main idea behind HDP is simple:

- ✓ More plants per unit area
- ✓ Better use of sunlight
- ✓ Early fruit production
- ✓ Higher yield and income

Instead of allowing trees to grow too large, farmers maintain compact canopies that are easier to manage.

Why is HDP Becoming Popular?

One of the biggest reasons for the popularity of HDP is the increasing pressure on agricultural land. Many farmers own only small land holdings and need technologies that can improve productivity. High Density Planting helps farmers:

- ✓ Harvest more fruits from less land
- ✓ Get income earlier
- ✓ Reduce wastage of water and fertilizers
- ✓ Improve fruit quality
- ✓ Manage orchards more efficiently

With the help of drip irrigation and fertigation, farmers can supply water and nutrients directly to the root zone, saving both water and fertilizers.

High Density Planting in Mango

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Mango is one of the most important fruit crops in India. Traditionally, mango trees are planted at wide spacing and become very large over time. Managing such orchards is difficult and harvesting operations also become expensive. Under HDP, mango trees are planted closer together and are regularly pruned to maintain manageable canopy size. Varieties such as Amrapali are highly suitable for HDP because of their compact growth habit. The benefits observed in HDP mango orchards include:

- ✓ Early fruit bearing
- ✓ Higher yield per hectare
- ✓ Better light penetration
- ✓ Improved fruit quality
- ✓ Easier spraying and harvesting

Many farmers in states like Uttar Pradesh, Andhra Pradesh, Maharashtra, and Telangana are gradually adopting this system.

High Density Planting in Guava

Guava responds extremely well to pruning and canopy management, making it one of the best fruit crops for HDP. Farmers can plant guava at closer spacing and maintain small trees through regular pruning. This not only improves productivity but also helps in obtaining quality fruits. In some ultra-high-density systems, thousands of guava plants are accommodated in one hectare. Guava growers prefer HDP because:

- ✓ Harvesting becomes easier
- ✓ Plants bear fruits early
- ✓ Fruits get better sunlight exposure
- ✓ Orchard management becomes simple

Apple Revolution through HDP

Apple cultivation in many countries has completely changed because of high-density orcharding. Traditional apple orchards used to take several years to start profitable production. Modern HDP orchards using dwarf rootstocks now produce fruits much earlier. In India, high-density apple cultivation is expanding rapidly in Jammu & Kashmir and Himachal Pradesh. These orchards provide:

- ✓ Better productivity
- ✓ Superior fruit quality
- ✓ Efficient land utilization
- ✓ Easier orchard operations

Many young farmers are now interested in modern apple orcharding because of its commercial potential.

Role of Modern Technologies

Modern technologies have made HDP more successful and profitable.

Drip Irrigation: Drip irrigation supplies water directly to the plant root zone and reduces water wastage.

Fertigation: Fertilizers are applied through irrigation water, improving nutrient efficiency.

Drones: Drones are now used for monitoring orchards and spraying pesticides.

Artificial Intelligence: AI-based systems help farmers detect diseases, nutrient deficiencies, and irrigation requirements.These technologies reduce labour dependency and improve orchard efficiency.

Challenges Faced by Farmers

Although HDP provides many advantages, farmers also face certain difficulties.The major challenge is the higher initial investment. Farmers need quality planting material, drip systems, and proper technical guidance. Regular pruning and canopy management are also necessary. Without proper management, overcrowding may reduce productivity. Some farmers may initially hesitate to adopt HDP because of lack of awareness and technical knowledge.

Future of High Density Planting

The future of HDP in India appears highly promising. As land availability decreases and fruit demand increases, more farmers are expected to adopt intensive orchard systems. Government departments, horticultural universities, and ICAR institutes are promoting HDP technologies through demonstrations and farmer training programs.

Future developments may include:

- ✓ AI-based orchard management
- ✓ Sensor-based irrigation
- ✓ Mechanized harvesting
- ✓ Improved dwarf varieties
- ✓ Smart orchard systems

These innovations will make fruit cultivation more profitable and sustainable.

Conclusion

High Density Planting has changed the way modern orchards are managed. It helps farmers produce more fruits from less land while improving fruit quality and income. Although the system requires scientific management and higher investment initially, its long-term benefits are very encouraging. With proper training, modern technologies, and efficient orchard management, HDP can play a major role in improving the future of fruit cultivation in India. As agriculture moves toward precision farming and sustainable production systems, High Density Planting is expected to become one of the most important technologies in modern horticulture.

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A Threat to Pulse Ecosystem, Spotted Pod Borer, *Maruca vitrata*

Priyakshi Buragohain, Sanghomitra Sarma and Goutami Kataki

One of the major biotic constraints for pulse production that can economically damage the plant parts such as flower buds, flowers and pods is *Maruca vitrata*, Spotted pod borer. This polyphagous pest feeds on about 39 host species of legume crops. Economically, pod borers are of considerable importance because of their potential to inflict substantial losses in legume production, which is a vital source of protein and nutrients in many global diets. The biology and ecology of pod borers encompass distinct developmental stages, each characterized by specific traits and time durations. During the egg stage, pod borer eggs exhibit specific morphological features that vary by species and their duration is influenced by environmental conditions. Eggs are laid singly or in small groups on the flowers or flower buds and also on the terminal shoots of young plants. It is oval, clear and light yellowish-white in colour. The eggs hatch into larvae in synchrony with host plant phenology, which is crucial for optimal larval growth and development, especially in species that feed on foliage. The larval stage consists of multiple instars, typically ranging from four to seven, depending on the species. Larval feeding habits vary but generally involve boring into pods, stems, or seeds, depending on host plant tissue specificity. Early instars may have limited feeding capacity but are critical for establishing developmental trajectories, whereas later instars consume more tissue and can cause significant crop damage. The larvae, or caterpillars, can grow up to 17-20 mm long. They are whitish to pale green in colour with irregular brown black spots and the head is dark brown. The young larvae can often be found in groups at this stage, but tend to be found individually later. Following larval development, the pupal stage occurs in concealed locations, such as within plant tissues or soil. Pupal duration is species- and temperature-dependent; for instance, the emerald ash borer pupates for approximately 20 days in chambers within the sapwood, with adults emerging in late spring. Adults often emerge conservatively from the pupal case, sometimes remaining temporarily within the pupal cells before emerging into the environment. The moth wings are blackish-brown with white markings on the forewings and a wingspan of 20-25 mm. The moths are active at night. During the day they can be found resting with their wings spread out on the undersides of leaves. Cowpeas can be attacked by the legume pod borer from early budding through to harvest. We can look for round holes on the flowers and also folded leaves that are stuck together.

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The pods will have a distinct hole where the larva entered. They may be eaten and bound together by webs made by the caterpillars; however, damage to these parts is not large in comparison to that done to the pods.

Pod borers inflict substantial damage on crops by affecting multiple plant parts, resulting in diminished yield and quality degradation of the crop. Feeding damage caused by pod borers predominantly affects pods, flowers and vegetative components, such as leaves and stems. The larvae penetrate the pods to consume the developing seeds, leading to direct seed loss and compromising pod integrity. Flower feeding by certain species diminishes reproductive success by destroying the floral tissues crucial for fruit set. Furthermore, larval feeding on vegetative parts debilitates plants by disrupting nutrient transport, reducing photosynthetic capacity and creating entry points for pathogens. Secondary effects on plant health include reduced vigor, stunted growth and increased susceptibility to secondary infections and pests. This damage disrupts physiological processes and can lead to heightened plant stress, resulting in decreased overall productivity. Additionally, multiple pest attacks on various plant parts may interact in a non-additive manner, sometimes exacerbating yield losses or, conversely, inducing compensatory growth in plants, thereby complicating the damage-yield loss relationships. Quality deterioration of harvested crops is a critical consequence of pod borer infestations. Damaged pods and seeds result in poor grain quality, reduced marketability and post-harvest losses due to increased susceptibility to pests and fungal infections. Effective pest management strategies, including integrated pest management approaches that combine host resistance, biological control and judicious pesticide use, are essential for minimizing such damage and maintaining crop health and quality.

Management strategies for pest control in agriculture encompass cultural, biological and chemical methods, often integrated within the framework of Integrated Pest Management (IPM) to achieve sustainable and effective crop protection.

Cultural practices are essential components of pest management, as they modify the cropping environment to hinder pest establishment, reproduction and survival. Techniques such as crop rotation and intercropping effectively disrupt pest life cycles and reduce host availability, thereby decreasing pest populations. Adjusting planting dates can help avoid peak pest periods, whereas trap cropping involves planting a preferred host crop to attract pests away from the main crop, thus minimizing damage. Field sanitation, which includes the removal of crop residues and destruction of infested plant material, reduces pest refuges and breeding sites and post-harvest management ensures the minimization of pest carryover to subsequent crops. Collectively, these cultural strategies constitute an integral part of Integrated Pest Management (IPM) approaches, reducing reliance on chemical inputs.

Biological Control uses the natural enemies of pests to regulate their populations. In the case of pod borers, these natural adversaries include predators such as lady beetles and lacewings, as well as parasitoids such as certain wasps, which can effectively reduce pest populations. Conservation biological control focuses on preserving and enhancing habitats to support these beneficial insects, including reducing broad-spectrum insecticide use, which adversely affects non-target organisms.

Chemical Control involves application of insecticides that continue to be a fundamental element of pest management strategies; however, their application should be judiciously integrated within Integrated Pest Management (IPM) frameworks to mitigate environmental and resistance-related concerns. Although conventional insecticides are effective in reducing pest populations, their excessive use can negatively impact beneficial organisms and the environment. In contrast, selective insecticides and insect growth regulators specifically target physiological processes in pests, providing precise control with minimal ecological disruption and reduced effects on non-target species. The management of insecticide resistance is crucial and involves strategies such as rotating insecticide classes with distinct modes of action, employing economic thresholds to limit applications and incorporating non-chemical methods to alleviate the selection pressure.

Future directions in pod borer management should emphasize the integration of emerging technologies, adaptation to climate change impacts and the adoption of sustainable, eco-friendly approaches. Advanced pest monitoring technologies, such as pheromone traps, remote sensing and precision agriculture tools, enable the accurate and timely detection of pod borer populations, facilitating targeted interventions and reducing unnecessary pesticide applications. Moreover, continuous research and farmer education are crucial for effectively implementing these sustainable strategies and enhancing long-term management success. Embracing emerging technologies, adapting to climate change and prioritizing sustainable practices will be crucial for future progress in managing this pervasive pest and ensuring crop production and food security.

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Structural Chromosomal Changes and their Applications in Crop Improvement

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Introduction

Chromosomes are the carriers of genetic information in all living organisms. They contain genes that regulate growth, development, reproduction and productivity. Any alteration in the number or structure of chromosomes can significantly influence the normal functioning of cells and organisms. Such alterations are known as chromosomal aberrations or chromosomal abnormalities (Goel *et al.*, 2017). Chromosomal aberrations may occur naturally during meiosis and fertilization or may be induced artificially through radiation, chemicals or tissue culture techniques. These abnormalities can affect plant morphology, fertility, adaptability and yield. While many chromosomal changes are harmful some can be effectively utilized in crop improvement programs to develop superior varieties with improved resistance, higher productivity and better adaptability. In plant breeding and genetics, chromosomal variations serve as important tools for understanding genome organization, gene transfer, evolution and the development of improved cultivars. Recent advances in molecular biology, genomics, fluorescence in situ hybridization (FISH), next-generation sequencing (NGS) and molecular marker technologies have greatly enhanced the detection and utilization of chromosomal changes in crop plants (Wang and Sun, 2025).

Chromosomal abnormalities Classification

Numerical Aberrations: It involves changes in the number of chromosomes due to improper chromosome segregation during cell division. These changes generally arise due to nondisjunction during meiosis. Common numerical chromosomal aberrations include monosomy, trisomy, triploidy, polyploidy and mosaicism. In plants, numerical changes sometimes contribute positively to evolution and crop improvement. Polyploid crops such as wheat, cotton, and potato have originated through chromosome number changes and exhibit enhanced vigor, adaptability and productivity. However, severe numerical abnormalities may also reduce fertility and disrupt normal growth.

Structural Chromosomal Aberrations: Structural aberrations occur due to breakage and rearrangement of chromosome segments. These changes alter chromosome organization and gene arrangement. Structural aberrations mainly include deletions, duplications, translocations, inversions, ring chromosomes and isochromosomes. These abnormalities may arise spontaneously or due to mutagens such as radiation and chemicals.

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Types of Structural Chromosomal Changes

Deletion refers to the loss of a chromosome segment when a broken fragment fails to rejoin with the chromosome. This may result in loss of genes, reduced viability, abnormal development and decreased fertility. However, small deletions are useful in crop improvement because they help in physical mapping of genes, identification of gene locations and chromosome engineering. In some cases, deletions are also used for removing undesirable genes (Balakrishnan *et al.,* 2019). Duplication occurs when a chromosome segment is repeated leading to extra copies of genes. Such changes may alter gene dosage increase the expression of certain traits and create genome imbalance. These are important in evolution because they provide additional genetic material that can develop new functions over time. Segmental duplications have contributed significantly to genome evolution and adaptability in crops such as cereals and cotton. Translocation involves the transfer of a chromosome segment from one chromosome to another. It may occur as reciprocal translocation where segments are exchanged between chromosomes called Robertsonian translocation, where entire chromosome arms fuse together. Translocations are highly useful in crop improvement because they facilitate the transfer of useful genes from wild relatives into cultivated species. They are used in introgression breeding and alien gene transfer particularly for developing disease resistant wheat varieties by transferring rust resistance genes from related species.

Inversion occurs when a chromosome segment breaks, rotates by 180° and rejoins in the reverse direction. Inversions are of two types: paracentric inversion, which does not involve the centromere and pericentric inversion, which includes the centromere. These rearrangements suppress recombination and alter gene arrangement. Despite this, inversions are important in maintaining desirable gene combinations, preserving adaptive gene complexes and studying chromosome evolution. Ring chromosomes are formed when the ends of a chromosome break and fuse together to form a circular structure. These chromosomes are generally unstable during cell division and may show abnormal segregation. Although they have limited direct use in crop breeding ring chromosomes are important in cytogenetic and chromosome behavior studies. Isochromosomes are chromosomes with identical arms formed due to abnormal centromere division. They are valuable in chromosome mapping and in understanding centromere function and chromosome evolution.

Detection of Structural Variations

Modern cytogenetic and molecular techniques have greatly improved the detection of structural chromosomal variations.

Karyotyping is the traditional microscopic examination of chromosome number and structure. It is simple and useful for detecting large abnormalities although its resolution is low.

Fluorescence in situ hybridization (FISH)

uses fluorescent probes to identify specific chromosome regions and is highly effective in detecting duplications, translocations, centromere positions and genome organization in crops such as wheat, rice and cotton.

PCR-based techniques such as qPCR and RT-qPCR are used for gene dosage analysis, copy number variation studies and gene expression analysis (Anderson *et al.,* 2026). Array-based comparative genome hybridization provides genome-wide detection of deletions, duplications and copy number variations.

In recent years, next-generation sequencing (NGS) technologies have revolutionized structural variation analysis by enabling high-resolution detection of chromosomal changes. Important NGS approaches include read-depth analysis, split-read methods, read-pair methods and de novo assembly. These techniques provide high precision, genome-wide detection and identification of even small structural variations making them essential tools in modern genomics and crop breeding programs (Gill, 2022).

Applications of Structural Chromosomal Changes (Balakrishnan *et al.*, 2019)

Transfer of Useful Genes: Chromosomal translocations facilitate transfer of disease resistance genes, abiotic stress tolerance genes and quality traits.

Evolutionary Studies: Structural rearrangements explain genome evolution, speciation and polyploid origin. Comparative genomics between diploid and polyploid species reveals evolutionary relationships.

Gene Mapping and Genome Analysis: Chromosomal aberrations assist in physical mapping, linkage analysis and identification of homologous chromosomes

Development of Hybrid Varieties: Structural changes influence recombination and fertility, thereby assisting hybrid breeding programs.

Improvement of Recombination Frequency: Chromosome rearrangements can increase recombination in low crossover regions, facilitating gene transfer and breeding efficiency.

Future Perspectives

Advances in whole genome sequencing, CRISPR/Cas genome editing, Molecular cytogenetics, Artificial intelligence and Precision breeding will further improve our understanding and utilization of structural chromosomal variations (Agarwal *et al.*, 2016). Modern breeding approaches integrating genomics and chromosome engineering can accelerate the development of climate-resilient, high-yielding, and disease-resistant crops.

Conclusion

Structural chromosomal changes play a major role in genome evolution, gene regulation and crop improvement. Although many chromosomal aberrations may negatively affect fertility and stability several structural variations have immense value in plant breeding and genetics. Translocations, inversions, duplications and segmental rearrangements have contributed significantly to the evolution of important crops such as wheat, rice, barley and cotton. Modern molecular and cytogenetic tools have

enabled precise detection and characterization of these variations thereby enhancing their application in crop improvement programs (Bhattacharya *et al.*, 2021). The integration of cytogenetics, genomics, molecular biology, and advanced sequencing technologies will continue to expand the role of structural chromosomal changes in developing superior crop varieties capable of meeting future agricultural challenges.

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From Gene to Field: The Long Road of Trait Deployment in Plant Breeding

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Abstract

Modern plant breeding integrates centuries-old, field-based selection with cutting-edge genomics and gene-editing tools. This article traces the pathway from gene discovery to on-farm deployment, highlighting how a single beneficial allele moves from initial identification in diverse germplasm through functional validation, introgression into elite backgrounds, trait stacking, multi-location testing and seed-system development. The discovery phase relies on QTL mapping, genome-wide association studies and functional assays to pinpoint and validate "good" genes, whereas introgression and pyramiding phases address linkage drag, genetic load and durability of resistance or tolerance traits. Although advances in genomics and genome editing have accelerated parts of this pipeline, deploying a validated trait into a stable, high-performing variety remains a multi-year, multi-stage process. The article underlines that successful trait deployment depends not only on scientific innovation but also on sound breeding strategy, rigorous field testing and strong seed-system support.

Introduction

Plant breeding today sits at the intersection of traditional field experience and cutting-edge molecular science. Behind every modern crop variety whether maize, rice, wheat, or a specialty vegetable there is a hidden journey that begins with a single gene or genetic region and ends in a farmer's field many years later. This journey is not just about discovering a useful trait, such as disease resistance or drought tolerance; it is about stabilizing that trait, integrating it into high-performing genetic backgrounds and confirming that it delivers consistent benefits across diverse environments and farming systems (Tester and Langridge, 2010). Advances in genomics, gene editing and data-driven selection have accelerated parts of this pipeline, but the core steps remain painstaking and time-consuming. From the initial screening of germplasm to marker-assisted backcrossing, multi-location trials, regulatory approval and seed multiplication, trait deployment is

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a carefully orchestrated process. (Varshney *et al*., 2018; Royo *et al*., 2020) This article walks through that pathway, explaining how a simple genetic change discovered in the laboratory can, over years of breeding and testing, become a real-world solution for farmers confronting climate stress, pests and market demands.

The discovery phase: finding the "good" gene/ allele

The journey of trait deployment begins long before the first cross is made in the field. It starts with the search for genetic variation that underlies a desirable characteristic, such as disease resistance, drought tolerance, improved grain quality, or early flowering. This initial phase, often called gene discovery or allele mining, is where researchers scan plant genomes to identify the specific DNA sequences that make a difference in performance (Mammadov *et al*., 2012; CGIAR/FAO, 2023). Modern discovery pipelines typically start with diverse germplasm, including landraces, farmer-saved varieties, wild relatives and genebank accessions. These collections are screened under controlled or field-like conditions to pinpoint accessions that stand out for the target trait. Once promising donors are identified, geneticists use tools such as quantitative trait locus (QTL) mapping, genome-wide association studies (GWAS), or transcriptome profiling to narrow the region of interest from whole chromosomes down to a few candidate genes or even a single causal variant. (Prasanna, 2021).

Functional validation then turns these candidates into "breeding-ready" alleles. Researchers may deploy gene editing (for example, CRISPR-Cas), RNA-interference, or near-isogenic lines to test whether altering or introducing the candidate sequence consistently changes the trait. (Zhang *et al*., 2014; Gao, 2021) Only after rigorous confirmation across multiple genetic backgrounds and environments is the gene or allele considered reliable enough to move from the laboratory to the breeding pipeline. In this way, the discovery phase bridges the gap between phenotype (what breeders and farmers can see in the field) and genotype (the underlying DNA code that produces it).

Introgressing the trait into elite germplasm

This is the core of "from gene to field" and where linkage drag and genetic load become real problems. Cover:

- ✓ Crossing the donor (often exotic or unadapted) with high-yielding elite lines.
- ✓ By using marker assisted backcrossing (MABC) or genic marker-assisted selection to recover the recipient genome as quickly as possible while keeping the target gene/allele (Varshney *et al.*, 2018; Prasanna, 2021).
- ✓ Explaining why simply adding a good gene is not enough: background effects, poor agronomy, or susceptibility to other stresses can still sink the new line.

Stacking and pyramiding: making traits more durable

Gene pyramiding (for disease resistance): Stack-

ing 2-3 resistance genes/QTLs into one background to slow down pathogen adaptation (Royo *et al*., 2020).

Multi-trait integration: Combining a resistance gene with a yield-boosting QTL or a stress- tolerance gene (Poland and Rutkoski, 2016).

Trade-offs: More genes can mean reduced fitness or yield unless the genetic background is carefully chosen (Borrell *et al*., 2021).

From the nursery to national trials

Pre-breeding / pre-varietal lines: Small-plot evaluation across a few environments.

Advanced trials (replicated yield trials): 2-3 years of multi-location testing to check stability, yield and adaptation (Varshney *et al*., 2018).

Quality and end-use testing: Grain quality, cooking quality, milling, or (in your case) baby-corn or sweet-corn ear quality (Mammadov *et al*., 2012).

Regulatory and biosafety checks for trans-genic or genome-edited traits, including dossier preparation, GMO committees and variety registration (Gao, 2021)

Conclusion

The journey from gene to field is a long, multi-stage process that links discovery in the laboratory with performance in the farmer's field. It begins with the identification of beneficial alleles through screening diverse germplasm and tools such as QTL mapping, GWAS and functional validation and continues through careful introgression into elite backgrounds using marker-assisted methods to minimize linkage drag and maintain agronomic quality. Gene pyramiding and multi-trait integration add durability and complexity, while extensive multi-location trials, quality assessments and regulatory checks ensure stable, safe and high-performing varieties. Ultimately, only when these scientific, institutional and seed-system steps align can a single genetic change translate into a practical, resilient crop variety that helps farmers cope with climate stress, pests and evolving market demands.

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Zero Tillage in Conservation Agriculture

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Introduction

Tillage is the first step in agriculture. It is an integral part of crop production. The basic objective of tillage is to modify soil condition in such a way that they become most favorable for the growth and yield of the crops. "Physical manipulation of soil called tillage" aimed improving soil conditions. Zero tillage is the process of no seed bed preparation and disturbing the soil where previous crop stubbles are present. Zero tillage is reducing cost of production and also reduces the soil erosion, crop duration and irrigation requirement. Zero tillage is also knows as no till or nill tillage. Conservation agriculture based on conserves natural resources and environment. It is improve soil fertility and builds up soil health in the long time. Three principles of conservation agriculture minimum disturbance of soil, permanent soil cover and crop diversification. Zero tillage practice was first initiated in USA. Glubler B. Triplet from USA is the father of zero tillage. In zero tollage primary tillage is completely avoided and secondary tillage is restricted to seedbed preparation only (Hashimi *et al.*, 2003).

Definition of zero tillage

Zero tillage is a method of crop cultivation in which seeds are sown directly into the soil without any prior land preparation such as ploughing, harrowing, or levelling. Special machines called zero till seed drills are used to place seeds and fertilizers into the soil with minimal disturbance. This method preserves soil moisture and reduces soil degradation.

History of zero tillage in India

Zero tillage approach started from 1960s by farmers in India. In India, research on zero tillage for wheat started almost three decades ago (Ekboir, 2002). In 1970 start of zero tillage research but lake of adequate planting equipment and weed control difficulties. In 1990 Peter Hobbs (Regional wheat agronomist, CIMMYT, Ludhiana) introduced inverted-T openers for drilling seed to Indian researchers. In 1991 first prototype of Indian zero tillage seed drill was developed at GBPUAT Pant-nagar. Zero tillage was more formally introduced and promoted in 1999-2000 in Haryana, and the area expanding rapidly to over 1.4 million hectares by 2005. In 1997 and 2004, about 620,000 farmers adopted zero tillage on 1.76 million in hectares in northern India. In 2008, zero tillage wheat covered around 1.76 million hectares in India, especially in Punjab, Haryana, and western Uttar Pradesh.

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Principles of Zero Tillage in conservation Agriculture

Farmers' increasingly adopting conservation agriculture practices. This conservation agriculture method is based on three principles, minimum soil disturbance, permanent soil cover with crop residues, and crop diversification.

Minimum soil disturbance: Conventional tillage is maximum harmful effect of soil structure, so Use of minimum tillage (primary tillage is totally avoid and secondary tillage apply only root zone) direct seeding involves growing crops without mechanical seedbed preparation and with minimal soil disturbance since the harvest of the previous crop. The term direct seeding is understood in Conservation agriculture system as synonymous with no-till farming, no tillage, direct drilling, etc.

Advantages of minimum soil disturbance

- ✓ Improve soil quality
- ✓ Increase water holding capacity
- ✓ Minimizes soil compaction and surface sealing
- ✓ Control soil erosion

Permanent soil cover with crop residues: Most important principle of zero tillage (CA) is permanent soil cover. This means keeping the soil covered with crop residues, mulching. This practice help are maintaining soil moisture, check soil erosion, which helps to maintain soil quality and reduce the need of irrigation.

Advantages of Permanent soil cover

- ✓ Improves infiltration and retention of soil moisture
- ✓ Maintains soil nutrients
- ✓ Check soil erosion
- ✓ Reduce weed growth

Crop diversification (crop rotation): Crop diversification is another most important principle of zero tillage (CA). it help farmers to maintain and boost yields and increase profits, while reversing land degradation, protection the environment and responding to growing challenge of climate change.

Advantages of crop diversification

- ✓ Brecks hardpan of soil
- ✓ Increases the use of available
- ✓ Ecological balance
- ✓ Soil quality is also improve

Role Zero tillage in conservation agriculture: Zero tillage play an important role in conservation agriculture. Zero tillage is help soil health (improve soil structure, increase organic matter, improve microbial activity and help nutrients cycling). It prevents destruction of soil aggregates and maintains soil porosity. Zero tillage reduces evaporation; increases water infiltration, and improves water retention. This is especially useful in dry and semi-dry regions. Zero tillage also useful for reduce soil erosion. Zero tilled soils are usually homogenous in structure containing greater number of beneficial earthworm. Earthworms are help to mixing of soil, as knows as biological tillage.

Type of Zero tillage

These are different types of zero tillage systems each with its variations and adaptation. There are mainly the following types:

Permanent Zero tillage: In this system, soil is never tilled for many years. Crops are sowing using in zero-till seed drill. This method helps improve soil structure, organic matter, and moisture conservation.

Strip tillage: In this method, only the planting row is tilled, not the whole field. This helps warm the soil in the planting zone, provides a clean seedbed, and still maintain residue cover between the rows.

Rotational no-tillage: Zero tillage is used for some crops in rotation, while occasional tillage is done for other. They might rotate between no-till and conventional tillage to manage different aspects of soil disturbance.

Vertical tillage: Vertical tillage is tillage method in which soil is loosened vertically with minimal disturbance to improve aeration, infiltration, and residue management.

Chemical zero tillage: In this method, weeds are controlled using herbicides instead of tillage. Soil disturbance is totally avoided.

Advantages of zero tillage in conservation agriculture

Cost effective: Zero tillage helps farmers reduce production costs, improve operational efficiency, and complete sowing on time. Timely sowing also contributes to better crop growth and higher yield.

Moisture conservation: Zero tillage plays an important role in moisture conservation by minimizing soil disturbance and maintaining crop residues on the soil surface. In conventional tillage using excessive tillage so causes high wind erosion, so loss of soil fertility.

Soil conservation: In zero tillage, use of mulching on the soil surface, so protect of soil and reduce of soil erosion and maintain of soil health. Zero tillage is an effective method for soil conservation under conservation agriculture.

Increase in soil organic matter: The retention of crop residues on the soil surface also adds organic material to the soil as it is decomposes. So increases organic matter also helps for soil fertility, microbial activity.

Reduced greenhouse gas emission: Conventional tillage practices release CO_2 into atmosphere from the decomposition of organic matter in the soil. Zero tillage helps sequester carbon in the soil, reducing greenhouse gas emission and contributing to climate change mitigation.

- ✓ Residues with no-tillage system keep the soil temperature cooler than under conventional, clean- tillage system by increasing albedo.
- ✓ Zero tillage is also help improves soil biological activity, Earthworms and beneficial micro-organisms increase in number.

Disadvantages of zero tillage

Zero tillage is more useful but some disadvantages.

Weed control: Practice zero tillage so grow more weed in field. Herbicides are required to control this weed. The Use of herbicides so adversely affects of plant and also soil.

Soil compaction: Continuous zero tillage may lead to soil compaction, especially in clayey soil (heavy soil). Adversely affects root growth and development.

Pest and disease management: Certain plant diseases and pests may find favorable conditions in the crop residues left in the field. This can lead to increased risks of diseases and pests affecting subsequent crops. Proper management practices, such as crop rotation and residue decomposition, are important to mitigate these risks.

Soil temperature: Crop residues on the soil surface keep the soil cooler, which may delay seed germination and early crop growth.

Conclusion

Zero tillage plays an important role in conservation agriculture like minimal soil disturbance, permanent soil cover and crop diversification. Zero tillage is also helpful for soil quality and soil health. The practice has gained recognition for its ability to preserve soil structure, reduce erosion and enhance moisture retention. The natural resources are precious and therefore demand an effective and sustainable use. Zero tillage is a potential technology in this scenario. The widespread adoption of zero tillage is not just an agricultural necessity; it is an ecological imperative. Adopting conservation agriculture practices, farmers can reduce their environment impact and improve their resilience to climate change while providing nutritious and affordable food growing population.

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From Fields to the Rivers: How Pesticides Affects Aquatic Ecosystem

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Introduction

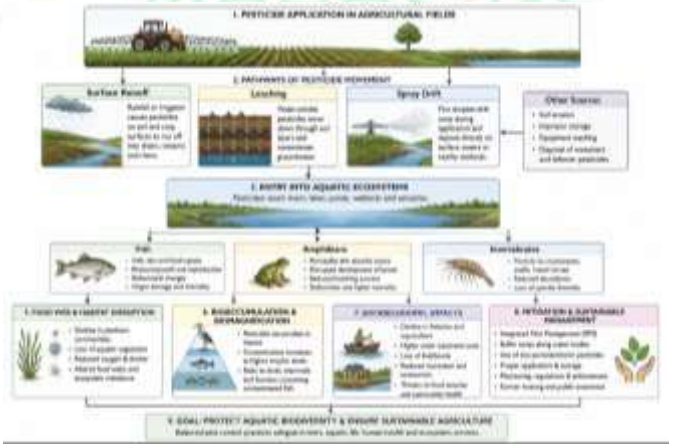
Modern agricultural farming systems rely extensively on pesticides to maintain crop yields and support global food security. Despite their benefits, the extensive use of these chemicals has led to unintended environmental impacts, especially within aquatic ecosystems. A large portion of pesticides applied in agriculture do not remain on the intended crops but are carried into nearby water bodies through various environmental processes. This contamination threatens biodiversity, disrupts ecosystem functions, and poses potential risks to human health (Carvalho, 2017). Numerous studies have reported the presence of pesticide residues in rivers, lakes, and wetlands, highlighting a strong connection between agricultural activities and aquatic pollution (Stehle and Schulz, 2015).

Pathways of Pesticide Movement

Pesticides reach aquatic ecosystems through multiple interconnected pathways. Among these, surface runoff is one of the primary routes, where rainwater or irrigation flow transports dissolved chemicals and contaminated sediments into nearby streams and rivers. This movement becomes more pronounced during periods of heavy rainfall, often resulting in sudden increases in pesticide concentrations (Stehle and Schulz, 2015).

Another important pathway is leaching, particularly for highly soluble pesticides that percolate through soil layers and contaminate groundwater, which may later contribute to surface water pollution.

Spray drift is an additional source of contamination, occurring when pesticide droplets are dispersed by wind during application and settle directly onto surrounding water bodies. Furthermore, poor management practices, including cleaning spraying equipment near water sources and improper disposal of pesticide containers, significantly elevate the risk of environmental contamination (Carvalho, 2017). Together, these pathways demonstrate how agricultural chemicals can extend far beyond their intended areas of use.



Impacts on Aquatic Fauna

Aquatic organisms are highly susceptible to pesticide contamination because of their continuous exposure to the surrounding water. In fish, toxic sub-

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stances can enter the body through the gills, skin, and food intake. Short-term (acute) exposure may cause large-scale mortality, whereas prolonged (chronic) exposure can impair growth, alter behaviour, and reduce reproductive capacity (Carvalho, 2017). Additional physiological impacts, including enzyme disruption and damage to internal organs, have also been documented. Most of the amphibians such as frogs and salamanders are especially vulnerable due to their highly permeable skin. Contact with pesticides can interfere with their hormonal systems, resulting in developmental defects and lower survival rates. Studies indicate that amphibian populations tend to decline in regions with intensive pesticide usage, suggesting a strong link between chemical exposure and loss of biodiversity (Stehle and Schulz, 2015).

Aquatic invertebrates, including crustaceans, molluscs, and insect larvae, are similarly affected. These organisms are essential for nutrient recycling and maintaining stable food webs. Exposure to pesticides can reduce their abundance, ultimately leading to decreased species diversity and disruption of ecosystem balance. Organophosphate pesticides like Chlorpyrifos a commonly used pesticide in agriculture fields (Yen *et al.,* 2011) and Bifenthrin which is not only used in agriculture but also in public health management like mosquito control (Ponepal *et al*., 2010). In a study it was found out that the mixture of both pesticides Chlorpyrifos and Bifenthrin causes genotoxic effect on Indian major carp, *Labeo rohita* (Bano *et al.,* 2021).

Chlorfenapyr a pyrrolebased halogenated insecticide used on agricultural crops for the insects and mites control (Bano *et al*., 2021). Acetamiprid is used in agriculture for management of paste in various countries (Zhang et al., 2011). Dimethoate a broad-spectrum organophosphate pesticide which is used to eradicate wide range of insects and mites (Tarbah *et al.,* 2007). Comparative effects of chlorfenapyr, dimethoate and acetamiprid on *Cirrhinus mrigala* under chronic exposure were studied and that study shows altered blood profile, disturbed thyroid hormones, elevated liver enzymes, and cause severe histological damage in gills and liver. The toxicity of these three pesticides where ranked as chlorfenapyr> acetamiprid > dimethoate (Ghayyur *et al*., 2021).

Copper sulfate a common used herbicides is toxic to the fishes in the same concentration which is being used to eradicate plants in terrestrial ecosystem. Malathion is an insecticide widely used in agriculture, and even small quantities entering aquatic ecosystems can significantly alter the abundance and composition of plankton and periphyton communities (Relyea and Hoverman, 2008).

Food Web Disruption and Habitat Degradation

Pesticide contamination impacts not only individual organisms but also disturbs entire aquatic food webs. Primary producers and consumers, such as phytoplankton and zooplankton, are particularly sensitive to chemical pollutants. A reduction in their populations limits the availability of food for higher trophical levels, including fish and amphibians. In addition, herbicides can harm aquatic vegetation that

plays a pivotal role in oxygen production and provides habitat for many organisms. The decline of these plants contributes to habitat degradation, promotes erosion, and reduces suitable breeding sites. Such alterations can significantly modify ecosystem structure and functioning, ultimately leading to a decline in biodiversity and ecological stability (Carvalho, 2017).

Bioaccumulation and Biomagnification

Some pesticides are highly persistent and gradually build up in the tissues of aquatic organisms. This process, referred to as bioaccumulation, intensifies as these chemicals are transferred through successive levels of the food chain, a phenomenon known as biomagnification. As a result, organisms at higher trophical levels, including birds and humans, may be exposed to elevated concentrations of toxic substances through the consumption of contaminated fish (Stehle and Schulz, 2015). Such accumulation can have serious health consequences, including neurological impairments, disruptions in hormonal function, and the development of chronic illnesses. The detection of pesticide residues in food sources underscores the wider public health concerns associated with aquatic pollution.

Socioeconomic Consequences

The effects of pesticide pollution are not limited to ecological damage but also have significant consequences for human societies. Declining fish populations and the deterioration of aquatic habitats often result in a reduction of fishery yields, directly impacting the livelihoods of communities that depend on fishing. Aquaculture operations that depend on natural water sources are similarly vulnerable, as contaminated water can trigger disease outbreaks and increase mortality rates among cultured species. Moreover, polluted water demands more advanced treatment processes to ensure its safety for consumption, thereby raising economic costs. The decline in water quality can also reduce opportunities for recreation and tourism associated with clean aquatic environments, further affecting local economies.

Key Prevention Strategies to reduce risk of pesticide poisoning in Fish

Physical Protection: Use a plastic sheet, tarp, or pond netting to cover the pond when pesticides are expected to be used nearby.

Buffer Zones: Plant shrubs or maintain tall grass between the pond and areas where chemicals are applied. These barriers help reduce spray drift and runoff from entering the water.

Avoid contamination through feed: Use pesticide residue free aqua feed materials. Ensure before use.

Integrated Pest Management (IPM): Integrated Pest Management is an environmentally friendly farming approach that reduces the use of harmful pesticides. Farmers use natural pest-control methods, crop rotation, and beneficial insects to manage pests. This helps protect rivers, lakes, and ponds from chemical pollution.

Turn off Equipment: Switch off waterfalls, fountains, and pond pumps while spraying is taking place. Water circulation can increase the absorption

of airborne toxins into the pond.

Proper Timing: Avoid applying lawn or agricultural chemicals on windy days or before rainfall, as wind and rain can carry pesticides into the pond through drift or runoff.

Monitor and Refresh: Regularly test your water for pH and chemical levels. In case of significant contamination, you may need to conduct a partial water change (replacing 20-25 % of the water).

Check toxicity of pesticide before application: Read pesticide labels to check their toxicity to fish, and prefer products that are less toxic or designed for aquatic use.

Conclusion

The movement of pesticides from agricultural fields to aquatic environments illustrates the interconnected nature of ecosystems. While pesticides contribute to agricultural productivity, their unintended impacts on aquatic species and human health cannot be ignored. Evidence from scientific studies highlights the need for sustainable practices and effective management strategies to minimize environmental risks. By adopting integrated approaches such as IPM and strengthening regulatory measures, it is possible to balance agricultural needs with environmental conservation.

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Silage: A Sustainable Solution for Fodder Preservation in Modern Agriculture

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Introduction

Livestock production plays a vital role in agricultural economies, particularly in countries like India where crop-livestock integration is a common farming practice. One of the major constraints to livestock productivity is the seasonal availability of green fodder, especially during dry seasons and also continuous reduction in farming area due to urbanization have a great impact on fodder shortage. Shortages in quality forage lead to reduced milk yield, poor animal growth, and economic losses for farmers.

What is Silage?

Silage is a high-moisture preserved forage produced through controlled anaerobic fermentation. During this process, naturally occurring lactic acid bacteria ferment soluble carbohydrates into organic acids, mainly lactic acid, thereby lowering pH and preserving the forage (Wilkinson and Davies, 2013). Unlike hay, which is dried before storage, silage retains much of the original nutrient value and palatability of fresh forage. Silage making provides a scientifically proven method to preserve green fodder through anaerobic fermentation, ensuring year-round availability of nutritious feed (McDonald *et al.*, 2011).

History of Silage: The concept of silage making originated in Europe during the 19th century. Early experiments were reported in France and Germany, where green crops were stored in airtight structures called silos to preserve their nutritional value. Over time, the technique spread globally and became an essential component of livestock production systems (McDonald *et al.*, 2011).

Importance of Silage

Silage plays a vital role in modern livestock-based agriculture by ensuring a continuous supply of quality fodder throughout the year. Its importance can be understood through the following points:

Year-Round Availability of Fodder: Silage allows farmers to preserve surplus green fodder during peak growing seasons and use it during periods of scarcity such as summer or drought. This ensures uninterrupted feeding and supports stable milk and meat production.

Nutritional Security for Livestock: Silage retains most of the nutrients present in fresh fodder, including carbohydrates, proteins, minerals, and vitamins. This supports better animal health, growth, reproduction, and higher milk yield.

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Improved Milk and Meat Production: Good-quality silage provides energy-rich feed that improves productivity of dairy and meat animals. It helps maintain body condition and production even during lean seasons.

Reduced Fodder Wastage: Surplus fodder often goes unused and spoils if not preserved. Silage making reduces wastage by storing excess green fodder safely for long periods.

Cost-Effective Feeding: Silage reduces dependency on expensive commercial feed and concentrates. By using farm-grown crops for silage, farmers can reduce feeding costs and increase profitability.

Climate Resilience: Silage making helps farmers cope with unpredictable weather conditions, droughts, and floods. It ensures feed security even when fresh fodder is unavailable.

Better Land and Resource Utilization: Farmers can grow fodder crops in rotation with other crops, improve soil health, and use available land more efficiently by storing surplus as silage.

Improved Digestibility and Palatability: Fermentation enhances the digestibility and taste of fodder, making it more palatable for animals and improving feed intake.

Suitable for Mechanization and Large-Scale Farming: Silage can be prepared and stored using mechanized systems, making it suitable for both small farms and large commercial dairy operations.

Nutritive Value of Silage

The nutritive value of silage depends on the crop species, stage of harvest, and fermentation quality. Good-quality silage is rich in:

- ✓ Energy (from carbohydrates)
- ✓ Moderate protein levels
- ✓ Digestible fiber
- ✓ Essential minerals and vitamins

Crops Suitable for Silage Making

Common crops used for silage include:

- ✓ Maize
- ✓ Sorghum
- ✓ Pearl millet
- ✓ Napier grass
- ✓ Oats
- ✓ Hybrid fodder crops

Stage of crop harvesting for silage making

The stage at which fodder crops are harvested is one of the most important factors influencing the quality, nutritive value, and fermentation success of silage. Harvesting at the correct stage ensures a balance between yield, nutrient content, and fermentable sugars, which are essential for good-quality silage.

Ensures Proper Fermentation: At the correct stage, plants contain sufficient water-soluble carbohydrates needed by lactic acid bacteria to produce acids that preserve the silage.

Optimal Nutrient Balance: Harvesting too early results in low dry matter and nutrients, while harvesting too late increases fiber and reduces digestibility.

Ideal Moisture Content: Silage crops should generally have 60-70% moisture. Correct harvesting ensures the crop is neither too wet (causing spoilage)

nor too dry (hindering compaction).

Better Animal Performance: Properly harvested crops produce silage that is more digestible and palatable, leading to improved milk yield, growth, and reproduction in livestock.

Maize: Milk to dough stage

Sorghum: Flowering to early grain stage

Grasses: Early vegetative stage

Different Methods of Silage Preparation

Pit or Trench Silage Method: The pit method is one of the most commonly used and cost-effective silage-making techniques, particularly suitable for small and medium-scale farmers. In this method, a pit or trench is dug in the ground at a slightly elevated site to prevent waterlogging. The size of the pit depends on the quantity of fodder to be preserved. The freshly harvested fodder is chopped into small pieces (2-3 cm) and filled into the pit in layers. Each layer is compacted manually or mechanically to remove trapped air, ensuring anaerobic conditions. After filling, the pit is covered with polythene sheets and a thick layer of soil to make it airtight. This method is simple, economical and requires minimal infrastructure. However, improper sealing or water seepage may lead to spoilage (FAO, 2017).

Bunker Silo Method: The bunker silo is an above-ground structure constructed using concrete, bricks, or compacted earth. It is widely used in commercial dairy farms due to its large storage capacity and ease of operation. In this method, chopped fodder is spread in layers inside the bunker and compacted using tractors or mechanical equipment. Once filled, the bunker is sealed with plastic sheets and covered with soil, sandbags, or used tires to maintain anaerobic conditions. Bunker silos are suitable for mechanized farming systems and large-scale operations. They allow easy filling and removal of silage but require proper drainage and management to prevent spoilage (Kung *et al*., 2018).

Tower Silo Method: Tower silos are vertical cylindrical structures made of concrete, steel or brick. They are more common in intensive dairy farming systems where large volumes of silage need to be stored. In tower silos, chopped forage is filled from the top and compacted under its own weight. The structure is designed to minimize oxygen entry, ensuring efficient fermentation. Although tower silos provide excellent storage conditions and reduce spoilage, their construction and maintenance costs are relatively high. This method is typically used in large commercial farms with advanced infrastructure (McDonald *et al*., 2011).

Silage Bag or Plastic Bag Method: The silage bag method is increasingly popular among small-scale farmers due to its low cost and convenience. In this method, chopped forage is filled into heavy-duty plastic bags, compacted tightly, and sealed to prevent air entry. This method is ideal for farmers with limited land and resources. It allows flexible storage and easy transportation. However, careful handling is required to prevent punctures and air leakage, which can spoil the silage (Wilkinson and Davies, 2013).

Bale Silage Method: In the bale silage method,

forage is compacted into bales using baling machines and then wrapped tightly with plastic film to create anaerobic conditions. This method is suitable for mechanized farms and areas where labor availability is limited. Bale silage is easy to handle, transport and store. However, it requires specialized equipment and higher initial investment.

Heap or Stack Silage Method: This is a traditional and simple method where, chopped fodder is piled on the ground in a heap. The heap is compacted manually or mechanically and then covered with plastic sheets and soil. Although inexpensive, this method has a higher risk of air exposure and nutrient loss compared to other methods. It is generally suitable for small-scale and temporary storage.

Characteristics of Good Quality Silage

Good-quality silage typically has:

- ✓ Pleasant aroma
- ✓ Light green to yellowish color
- ✓ Soft texture
- ✓ Low pH
- ✓ Absence of mold or foul smell

Limitations of Silage

- ✓ Requires initial investment
- ✓ Improper sealing may cause spoilage
- ✓ Requires technical knowledge
- ✓ Not ideal for low-moisture crops

Conclusion

Silage making is a scientifically proven and sustainable method of fodder preservation. It ensures consistent feed supply, improves livestock productivity and enhances farm profitability. With proper knowledge and adoption, silage can significantly strengthen livestock-based farming systems and contribute to sustainable agricultural development.

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Next-Generation GIS Technologies for Identification and Management of Degraded Landscapes

Vidhu Dixit and Arun Arya

Abstract

Geographical Information System (GIS) and advanced environmental databases play a vital role in monitoring, diagnosing, and mapping land degradation. These technologies assist in collecting, storing, analyzing, and interpreting spatial and non-spatial data related to soil, water, climate, vegetation, and land use. Databases such as SOTER, DSMW, ECOCROP, AQUASTAT, CLIMWAT, and CROPWAT provide scientific information for sustainable land and water resource management. Modern GIS platforms integrated with remote sensing, artificial intelligence (AI), Global Positioning System (GPS), drones, and cloud computing improve the accuracy of land degradation assessment and decision-making. These tools support agricultural planning, irrigation scheduling, soil conservation, crop suitability analysis, and environmental protection. GIS-based technologies are highly useful for researchers, planners, policymakers, and extension workers in promoting sustainable agriculture and restoring degraded landscapes.

Introduction

Land degradation is one of the most serious environmental challenges affecting agricultural productivity, biodiversity, water resources and ecosystem sustainability across the world. Degradation occurs due to soil erosion, deforestation, overgrazing, salinity, improper irrigation, mining activities, nutrient depletion, and unsustainable land-use practices. According to the United Nations Convention to Combat Desertification (UNCCD), nearly 40% of the world's land area is degraded, affecting about 3.2 billion people globally. In India, approximately 96.4 million hectares (about 29.3% of the total geographical area) are affected by land degradation and desertification. Soil erosion alone causes an annual loss of nearly 5.3 billion tonnes of soil in India, resulting in nutrient depletion and reduced crop productivity. Recent advancements in Artificial Intelligence (AI), Machine Learning (ML), Remote Sensing, Unmanned Aerial Vehicles (UAVs) and cloud-based GIS platforms have significantly improved the monitoring and management of degraded lands. High-resolution satellite imagery from platforms such as Landsat, Sentinel, MODIS, and Google Earth Engine enables real-time assessment of vegetation loss, soil moisture stress, erosion hotspots and land-use changes. Geographical Information System (GIS) is a powerful geospatial

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technology that helps in storing, analyzing, and mapping spatial information related to land resources. Various international databases and information systems have been developed to support land evaluation, crop planning, irrigation management, and environmental monitoring. These databases provide reliable and organized scientific information for sustainable land management, precision agriculture, and climate-resilient farming systems.

Soil and Terrain (SOTER) Database

The Soil and Terrain (SOTER) database is used for storing soil and terrain information at national and global levels. It helps in thematic mapping, monitoring changes in soil resources, and land-use planning. SOTER integrates GIS and Relational Database Management Systems (RDBMS) to create a world soil and terrain database with digitized maps and soil attributes.

Functions of SOTER

- ✓ Soil and terrain mapping
- ✓ Land-use planning
- ✓ Monitoring soil degradation
- ✓ Environmental assessment
- ✓ Support for policy-making

Digitized Soil Map of the World (DSMW)

The Digitized Soil Map of the World is a global soil database developed by FAO based on the FAO/UNESCO Soil Map of the World. It contains digitized maps and soil property data for different regions of the world.

Information Provided

- ✓ Soil classification
- ✓ Soil moisture storage capacity
- ✓ Soil drainage characteristics
- ✓ Effective soil depth
- ✓ Topsoil distribution

The DSMW database is useful for soil fertility evaluation, environmental studies, and teaching purposes.

FAO/ITC Land Use Database

The FAO/ITC Land Use Database stores information related to land use, agricultural activities, production systems, and socio-economic conditions. It helps in evaluating land productivity and monitoring land-use changes.

Components

- ✓ Data entry and storage module
- ✓ Query and search module
- ✓ Glossary of land-use classifications

This database assists in sustainable land-use planning and management.

ECOCROP 1 Database

ECOCROP 1 is a crop environmental requirements database used to identify suitable crop or tree species for specific environmental conditions. It provides information about minimum, optimum, and maximum environmental requirements for crops.

Uses

- ✓ Crop suitability analysis
- ✓ Environmental comparison of crops
- ✓ Agricultural planning
- ✓ Support for farmers and researchers

The database includes information on crops, grasses, trees, and other plant species.

ECOCROP 2 Database

ECOCROP 2 is used for crop modelling and environmental response analysis. It contains response information for important crops under different environmental conditions.

Applications

- ✓ Crop response analysis
- ✓ Statistical modelling
- ✓ Graphical presentation of crop responses
- ✓ Crop productivity assessment

WOCAT (World Overview of Conservation Approaches and Technologies)

WOCAT is an international tool that promotes sustainable land management and soil-water conservation. It helps in identifying suitable conservation practices to reduce land degradation.

Objectives of WOCAT

- ✓ Conservation planning
- ✓ Technology transfer
- ✓ Sustainable land management
- ✓ Soil and water conservation

WOCAT can be linked with other databases such as ECOCROP and AEZ for integrated land management.

Database Tool for Integrated Plant Nutrition Systems (DTIPNS)

DTIPNS provides information related to plant nutrient management and nutrient balance assessment. It supports environmentally friendly nutrient management practices.

Information Included

- ✓ Nutrient content of fertilizers & organic sources
- ✓ Nutrient uptake by crops
- ✓ Nutrient losses due to erosion and leaching
- ✓ Economic evaluation of nutrient management

This system helps in maintaining soil fertility and balanced plant nutrition.

AQUASTAT Database

AQUASTAT is a global water information system developed for water resource assessment and irrigation management.

Information Available

- ✓ Groundwater and surface water resources
- ✓ Irrigation potential
- ✓ Water withdrawal by sectors
- ✓ Irrigated and rainfed crop production
- ✓ Drainage and irrigation technologies
- ✓ Water-related diseases

AQUASTAT supports sustainable water-use planning and irrigation development.

Climatic Database (CLIMWAT)

CLIMWAT is a climatic database used for calculating crop water requirements and irrigation scheduling. It provides climatic data for agricultural planning.

Functions

- ✓ Estimation of crop water requirements
- ✓ Irrigation scheduling
- ✓ Drought assessment
- ✓ Agro-climatic evaluation

CROPWAT Program

CROPWAT is a computer program used for irrigation planning and management. It assists irrigation engineers and agronomists in efficient

water management.

Major Functions

- ✓ Calculation of evapotranspiration
- ✓ Determination of irrigation requirements
- ✓ Water supply planning
- ✓ Evaluation of drought effects

SIMIS (Scheme Irrigation Management Information System)

SIMIS is used for managing irrigation systems and providing information related to water delivery, crop production, maintenance, and irrigation scheduling.

Importance of SIMIS

- ✓ Irrigation management
- ✓ Crop monitoring
- ✓ Water fee management
- ✓ Agricultural planning

Important Emerging Technologies

Remote Sensing: Satellite imagery helps detect:

- ✓ Soil erosion
- ✓ Vegetation degradation
- ✓ Salinity
- ✓ Desertification
- ✓ Deforestation

Artificial Intelligence (AI) and Machine Learning (ML): AI algorithms analyze large geospatial datasets for:

- ✓ Predicting degradation hotspots
- ✓ Soil quality assessment
- ✓ Crop stress detection
- ✓ Automated land classification

Drone-Based Monitoring: Drones provide high-resolution images for:

- ✓ Precision agriculture
- ✓ Soil erosion mapping
- ✓ Gully identification
- ✓ Crop health assessment

Internet of Things (IoT): IoT-based soil sensors monitor:

- ✓ Soil moisture
- ✓ Nutrient status
- ✓ Temperature
- ✓ Water availability

Cloud Computing and Google Earth Engine: Cloud platforms allow:

- ✓ Large-scale geospatial analysis
- ✓ Real-time environmental monitoring
- ✓ Faster processing of satellite data

Land Qualities Used in Land Evaluation

Atmospheric Qualities: Atmospheric qualities influence crop growth and productivity.

Important Factors

- ✓ Rainfall
- ✓ Temperature
- ✓ Sunshine duration
- ✓ Growing season
- ✓ Dry spells

Cover Quality: Cover quality refers to the role of vegetation in protecting soil and maintaining ecological balance.

Major Components

- ✓ Biodiversity conservation
- ✓ Soil protection
- ✓ Climatic regulation

- ✓ Shelter for crops and livestock
- ✓ Regeneration capacity of vegetation

Land Surface and Terrain Qualities: These qualities describe the physical characteristics of land and terrain.

Important Terrain Features

- ✓ Surface receptivity
- ✓ Bearing capacity
- ✓ Stoniness
- ✓ Erosion susceptibility
- ✓ Accessibility of land
- ✓ Water storage capacity
- ✓ Runoff potential

Conclusion

GIS and environmental databases are essential tools for monitoring, diagnosis, and mapping of land degradation. Systems such as SOTER, DSMW, ECOCROP, AQUASTAT, CLIMWAT, CROPWAT and SIMIS provide valuable scientific information for sustainable management of soil, water, and agricultural resources. Modern technologies including AI, remote sensing, drones, IoT, and cloud computing have significantly improved the efficiency and accuracy of land degradation assessment. These technologies support sustainable land-use planning, precision irrigation, crop suitability analysis, and soil conservation practices. Proper utilization of GIS and advanced geospatial databases can help reduce land degradation, improve agricultural productivity, strengthen climate resilience, and ensure sustainable development for future generations.

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Cultivating Resilience: A Comprehensive Analysis of Crop Diversification and Sustainable Agriculture

Danveer Singh, Anjali Gangwar, Anupam and Rahul

The Global Imperative: Agriculture at a Critical Juncture

Global agriculture currently operates at a paradoxical nexus of unprecedented productivity and systemic fragility. While the sector's global economic valuation is estimated at approximately $3.8 trillion, this figure is increasingly divorced from the escalating environmental and social debt accrued by industrial intensification. Over the last several decades, the global food system has overseen a 70% surge in pesticide application and a corresponding reliance on the injurious use of chemical fertilisers. Despite this intensive input regime, the system has failed to meet the most basic metric of human welfare: 2.3 billion individuals remain in a state of moderate or severe food insecurity.

The core conflict of the 21st century lies in the "industrial simplification" of the agricultural landscape. Intensive monocultures have precipitated a global crisis of soil degradation, nutrient leaching, and catastrophic biodiversity loss. We are witnessing a transition where the natural capital required for future production the soil microbial community, the water cycle, and natural biocontrol mechanisms is being liquidated to sustain short-term caloric yields. Sustainable soil management is no longer a peripheral ecological concern; it is a strategic imperative for global food stability.

Key Global Agricultural Metrics

Total Global Agricultural Value: Approximately $3.8 trillion per annum.

Pesticide Application Growth: A 70% surge in global application rates since the mid-20th century.

Global Food Insecurity: 2.3 billion people lacking consistent access to nutritious food.

Productivity Erosion: A 34% reduction in agricultural productivity growth in Sub-Saharan Africa since 1961 due to climate-driven shocks.

Conceptual Framework: Transitioning from Monoculture to Diversity

The transition from simplified monocultures to Diversified Cropping Systems (DCS) represents a fundamental shift in agricultural architecture. DCS is defined as the intentional cultivation of various crops across different spatial or temporal dimensions encompassing intercropping, rotation, and replanting strategies. This is not merely an increase in species count; it is a sophisticated redesign of the agroeco-

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system to maximise internal biological regulation.

This framework is grounded in three core agroecological principles:

Biodiversity Integration: Replacing external chemical inputs with "functional biodiversity" that mimics natural ecosystem processes.

Plant-Microbe Interactions: Leveraging synergistic relationships where specific root exudates promote the growth of beneficial soil prokaryotes.

Soil Multifunctionality: Transitioning from a view of soil as a sterile substrate for fertiliser to a multifunctional living system capable of carbon sequestration, nitrogen fixation, and water filtration.

The strategic objective of DCS is a "triple win": increasing total system productivity, reducing reliance on fossil-fuel-derived agrochemicals, and embedding resilience against the increasing frequency of climate-induced and socio-economic shocks.

Implementation Typologies: Technical Architectures of Diversity

Diversification strategies are not monolithic; they are highly context-dependent architectures designed to leverage regional resource advantages. The following typologies represent the primary technical pathways for system complexification.

Intercropping and Strip Cropping: This involves the simultaneous cultivation of two or more crops in the same field, often alternating rows or strips to facilitate mechanical management. The Netherlands has emerged as a global leader in sophisticated strip cropping, using precision machinery to alternate cereals with legumes. This spatial arrangement maximises light capture and promotes interspecific facilitation, such as the nitrogen transfer between maize and soybean.

Agroforestry and Agrosilvopastoral Systems: These systems integrate woody perennials with annual crops and livestock. These architectures provide deep-root stabilization and microclimate regulation, protecting understorey crops from extreme heat and wind while providing long-term carbon sequestration.

Relay and Multiple Cropping: Temporal diversification strategies that maximise the land-use index. In relay systems, a secondary crop is sown into a standing crop before harvest (e.g. rice-wheat systems in subtropical regions). Multiple cropping involves sequential planting within a single calendar year, fully leveraging favourable heat and irrigation resources to eliminate fallow periods.

Typology	Spatial Arrangement	Resource Advantage	Ecological Service Provided	Typical Combinations
Intercropping	Simultaneous mixed or alternate rows	Complementary light and nutrient capture	Natural biocontrol and N-fixation	Maize-Soybean; Tea-Peanut
Agroforestry	Integration of trees with crops/livestock	Carbon sequestration and microclimate control	Deep-soil nutrient cycling; wind protection	Fruit trees with forage crops
Relay Cropping	Sequential overlap of crop lifecycles	Maximised use of residual soil moisture	Soil erosion prevention and land efficiency	Rice-Wheat; Tobacco-Potato
Multiple Cropping	Successive planting within one year	High annual land-use index	Weed suppression and year-round biomass	Rice-Maize-Mung bean

Ecological Mechanisms: Quantifying the Microbial and Geochemical Benefits

Soil Health Dynamics and Enzymatic Activity

Diversified systems provide a measurably superior environment for soil health indicators. Research consistently demonstrates that DCS leads to a +9% increase in Soil Organic Carbon (SOC) and a +12% increase in Microbial Biomass Carbon (MBC). However, the most profound changes occur in the enzymatic profile of the soil. Diversified systems exhibit twofold increases in crucial enzymes, including:

- ✓ **Dehydrogenase:** A key indicator of total microbial oxidative activity.
- ✓ **Alkaline Phosphatase:** Critical for the mineralization of organic phosphorus.
- ✓ **Fluorescein Diacetate Hydrolysis:** A proxy for total soil proteolytic activity.

The application of bioinoculants, such as *Bacillus* spp., in conjunction with modern nano-compounds like nanozeolite and nanochitosan, has been shown to increase NPK-solubilising bacteria by up to 57%. This is verified by quantitative PCR (qPCR) analysis showing significant increases in 16S rRNA gene copy numbers, indicating a robust and thriving bacterial population that can act as a sustainable alternative to traditional chemical fertilisers.

Resource Protection and Biogeochemical Cycles

The ecological return on diversification is expansive. Evidence suggests an +84% improvement in water quality due to the reduction of nutrient leaching and a +63% increase in pest suppression through natural biocontrol mechanisms. By maintaining continuous soil cover and varied root architectures, DCS mitigates greenhouse gas (GHG) emissions through carbon fixation while reducing soil erosion a critical factor in regions where intensive tillage has depleted the topsoil.

Economic Dimensions: Profitability and the Longevity Trade-off

The financial narrative surrounding diversification is often skewed by short-term yield obsession. A longitudinal analysis reveals that the true economic value of diversity is found in stability and input reduction.

The 20-Year Profitability Surge: When analysed over a 20-year horizon, diversified systems have demonstrated a 189% increase in profitability compared to conventional monocultures. This is driven by the internalisation of ecosystem services: farmers spend less on synthetic fertilisers and pest-

icides while their systems become less vulner-able to crop failure during drought.

The 50-Year Sustainability Trade-off: A critical observation in agricultural economics is the yield-profit trade-off that emerges at the 50-year mark. While short-term intensification in monocultures can produce extreme yield peaks, these systems eventually suffer from "yield decline" as soil biology collapses. In contrast, DCS prioritises long-term system stability. While a diversified farm may not reach the extreme peak yields of a high-input monoculture in a "perfect" year, it will consistently outperform monocultures in "marginal" years, ensuring the longevity of the enterprise.

Biofortified Cultivars and Market Value: The integration of biofortified crops adds a high-value dimension to the DCS model. By selecting cultivars designed for increased nutrient density, farmers can access premium markets and improve regional health outcomes. Key examples include:

- ✓ **Wheat:** Jingdong 8, Zhongyu 9507, and Zhongmai 175 (iron and zinc-enriched varieties suitable for North China).
- ✓ **Maize:** Yunyou 19 (high lysine and oil content) and Yunrui 8/21 (high oil) for Southwest China.
- ✓ **Rice:** Gongmi 2 (high zinc) for Southwest China.
- ✓ **Sweet Potato:** Zheshu 81 and Zheshu 255 (carotene-enriched) for East China.

These cultivars command higher prices and represent a strategic shift toward "nutrition-sensitive agriculture."

Barriers to Scaling: The Socio-Technical Lock-in: Despite the empirical evidence favouring diversification, the global agricultural system remains trapped in a state of "lock-in" a condition where social, political, and technological forces reinforce unsustainable practices.

Machinery and Infrastructure Lock-in: The industrial model is built on economies of scale that necessitate massive investment in specialised equipment. Large-scale tractors, planters, and harvesters are often designed for a single commodity crop (e.g. corn or soybean). This creates a "machinery lock-in" where the cost of transitioning to equipment capable of handling diverse crops or strip-cropping architectures is financially prohibitive for the individual operator.

The Agrichemical Business Model and Policy Distortions: We must critique the role of the agrichemical industry in maintaining this status quo. The industry's business model depends on the sale of maximum product volume, incentivising the very simplification that leads to pest and disease outbreaks. This is reinforced by global subsidy structures and federal crop insurance programmes that prioritise a handful of staple "commodity crops." For example, the 2007 Energy Independence and Security Act (the ethanol mandate) in the United States served as a massive force for "defensive simplification," encouraging farmers to abandon diverse rotations in favour of continuous corn production.

Pernicious Feedbacks and Defensive Planting: A particularly egregious example of lock-in is the case

of Dicamba-resistant crops. The decline in glyphosate effectiveness a result of the "pesticide treadmill" led to the development of "next-generation" herbicide-resistant traits for older, drift-prone chemicals like Dicamba. The use of these herbicides has triggered a "Pernicious Feedback": drift from one field damages neighbouring non-resistant crops, forcing those farmers into "defensive planting" adopting the resistant seed technology simply to protect their own yields from their neighbours' chemical applications. This dynamic rapidly collapses landscape diversity, reducing the Shannon diversity index and entrenching the technology package.

Digitalisation and the Future: Technical Enablers

To manage the inherent complexity of DCS, we must move beyond the "simplicity" of 20th-century management. Modern digitalisation offers the tools to manage complex architectures at scale.

DAKIS and Precision Management: Digital Knowledge and Information Systems (DAKIS) enable the regional precision management required for strip cropping and agroforestry. By utilizing remote sensing and satellite imaging, DAKIS allows for the real-time monitoring of crop patches, ensuring that inputs are applied with pinpoint accuracy, thus reducing waste and environmental impact.

The Resilience Booster Tool: Developed by the World Bank, the Resilience Booster Tool is instrumental in embedding climate resilience into project design. It allows planners to identify "resilience investments" that provide the highest return on adaptation, particularly in vulnerable landscapes where rainfed agriculture is the norm.

AI-Driven Biotechnology: Artificial Intelligence and predictive analytics are now being used to determine the optimal crop combinations for specific micro-climates. Simultaneously, gene editing is being utilised not for herbicide resistance, but for "facilitative traits" developing crops with shade tolerance or non-competing root architectures specifically designed for intercropping.

Regional Case Studies: Evidence from the Field

The theoretical benefits of diversification are corroborated by evidence from diverse geographical contexts.

Eastern Gangetic Plains (EGP) and Bangladesh: In the EGP, there has been a concerted push toward the intensification of grain systems through Conservation Agriculture. By adopting minimal soil disturbance and integrating high-value, biofortified crops, farmers have managed to stabilise yields. The PARTNER Programme in Bangladesh exemplifies this, linking smallholders to regional value chains and ensuring food security through the promotion of nutrient-dense cultivars.

Sub-Saharan Africa: The AFRI-RES Partnership : Agriculture in Africa is the continent's largest engine of economic growth, yet it remains extremely vulnerable, with 90-95% of production being rainfed. Since 1961, climate change has reduced agricultural productivity growth by 34%. Under 2°C-3°C warming scenarios, economic welfare in the

sector is projected to decline by 5-10%. Through the AFRI-RES partnership, governments are integrating landscape-level CSA approaches. By conserving natural forested areas adjacent to cultivated fields, farmers leverage ecosystem services like evapo-transpiration and wind protection to mitigate the probability of locust outbreaks and drought-induced crop failure.

Strategic Recommendations: A Roadmap for Transformation

To transition from a state of "lock-in" to a "virtuous feedback" cycle of sustainability, we must implement the following strategic directives:

Shift Research Priorities: Publicly funded research must move away from "propping up" unsustainable systems that serve the interests of the agrichemical industry. We must redirect funding toward systems-level research that addresses the "common good" focusing on nutrient density, soil health, and ecological stability. Scientists must move from being "neutral arbiters" of data to "honest brokers" who interpret the root causes of agricultural failure and project the externalities of production.

Policy Reform and Subsidy Realignment: We must demand a radical realignment of global subsidies. Financial incentives and crop insurance must be linked to the adoption of landscape-scale diversity, such as cover cropping and the maintenance of riparian buffers. Policies like the ethanol mandates must be re-evaluated for their role in landscape simplification.

Participatory Extension and On-Farm Research: To bridge the gap between science and practice, we must prioritise "farmer-initiated on-farm research." This ensures that diversification strategies are context-dependent and manageable at the farm scale, leveraging the experiential knowledge of the practitioners who manage these systems daily.

Market Reorganisation: Governments should encourage consumer-driven demand for biofortified and sustainably produced crops. Certification schemes for biodiversity-friendly agriculture and the development of local, intraregional value chains can provide the market signals necessary for farmers to invest in diversity.

By addressing the technical, economic, and political barriers to diversity, we can transform a fragile, simplified global food system into a resilient, multifunctional engine of health and environmental restoration.

Climate-Smart Seed Technologies for Sustainable Vegetable Production

Niranjan R., R. Saranya, K. Lakshanya and S. Ambika

Introduction

Climate-smart seed technologies play an important role in ensuring the sustainable production of vegetables amid climate change. Climate change poses many challenges to agriculture, including unpredictable rainfall, droughts, floods, high temperatures, soil salinity, and a higher incidence of pests and diseases. Vegetables are highly vulnerable to the mentioned environmental conditions, and their negative effects include germination, seedling growth, and the formation and production of flowers and fruits. To address such problems, climate-smart seed technologies have been adopted to improve crop seed performance. Climate-smart seed technologies include techniques such as seed priming, coating, pelleting, bio-priming, nanotechnology, precision seed production, and the development of stress- and disease-tolerant cultivars. The discussed technologies lead to improved seed germination, healthy seedling growth, and performance under challenging environments. Besides, these technologies ensure eco-friendly farming practices and reduce the use of chemicals in production processes. Improvements in seed performance contribute to food security, higher farmers' incomes, and environmental sustainability through increased production. Therefore, climate-smart seed technologies are viewed as integral components of modern agricultural practices, as they help to address existing and future agricultural problems.

Concept and Importance of Climate-Smart Agriculture (CSA)

"Climate-smart agriculture" includes both adaptation and mitigation. The technique seeks to lessen climate change exposure while boosting agricultural production. Cutting greenhouse gas emissions is also one of CSA's objectives. Seeds determine how crops establish themselves and perform, thus seed technology plays an important role in CSA. The seeds used for CSA can thrive in harsh climates, such as heat and drought. They require fewer inputs and boost yield stability.

Climate Change Impacts on Vegetable Seed Systems

By altering the environmental requirements for seed development and conservation, climate change affects the seed system. High temperatures decrease seed viability. Seed growth and germination are constrained by drought. Excess rain and floods lead to seed deterioration and a lack of oxygen. Furthermore, climate change makes seeds susceptible to pests and diseases. This reduces the quantity

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and quality of seeds produced. New pathogens can attack vegetable plants. Changes in temperature affect the storage process. Innovation in seed technology is required to address these issues. It is thus vital to adapt the seed system.

Climate-Resilient Vegetable Varieties

Crops with climate resistance have been developed to withstand unfavourable environmental conditions. They are resistant to high temperatures, low temperatures, droughts, and saline soils. In times of stress, they provide stable yields while minimizing chemical and irrigation use. Climate resistance characteristics are widely found in native landraces that are used as gene sources to produce improved genotypes. Therefore, they offer greater climate resilience and minimize production risks.

Seed Priming Technologies: Seed priming involves treatments applied before sowing seeds, and this process improves seed germination and seedling vigour. In seed priming, seeds are moistened with water or other liquids before planting. The use of chemical liquids for such processes is called osmo-priming, while the use of water is known as hydropriming. In biopriming, microbial agents are used. It helps boost seed metabolism; consequently, they germinate more efficiently and uniformly.

Seed Coating and Pelleting Technologies: Seed coating is a technique involving the application of protective coatings containing polymers and nutrients to seeds. It offers protection against diseases and insects while improving seed quality. Pelleting involves changes in seed size and shape to facilitate the process. They facilitate precise seed planting and improve seed moisture content. The germination process increases when seeds are exposed to stressful environments. Furthermore, seed loss decreases. Seed nutrient coating ensures early nutrition for young plants.

Protected Seed Production Technologies: The cultivation of crops under protective conditions, such as those provided by greenhouses and polyhouses, is considered protected seed production. In such a setting, crops are protected against adverse climatic factors like heat, cold, and rainfall. Additionally, there is easy control over other factors such as light, humidity, and temperature, thereby enabling the production of high-quality seeds. There are fewer pest attacks on crops grown in protective conditions, thus benefiting hybrid seed production. Pollination is easily controlled, leading to higher-quality seeds.

Molecular and Biotechnological Approaches: Through advanced methods, biotechnology has transformed seed development. Marker-assisted selection facilitates the rapid identification of desirable features. Certain genes for stress tolerance are introduced by genetic engineering. Precise gene editing is made possible by CRISPR technology. These techniques expedite the breeding process.

They aid in the development of crops resistant to heat, drought, and disease. Both yield and quality are enhanced by biotechnology. It shortens the time needed to generate new varieties. These methods are very dependable and effective. They are crucial for climate-smart agriculture in the future.

Seed Storage and Conservation Technologies: For seeds to remain viable and physically healthy, storage is essential. Seed degradation can be avoided with the right storage conditions. Vacuum packing and cold storage are popular techniques. Long-term conservation is accomplished through cryopreservation. Over time, these methods preserve seed quality. Local variations are preserved through community seed banks. In times of emergency, they guarantee seed availability. Sustainability and biodiversity are supported by conservation. It safeguards important genetic resources. For seed security, efficient storage is crucial.

Digital and Precision Seed Technologies: Digital tools enhance decision-making and seed management. Environmental conditions are monitored by devices such as Internet of Things sensors. Farmers can plan when to plant by using climate forecasts. Real-time agricultural information is available through mobile apps like Kisan Suvidha. These technologies lower hazards and increase efficiency. Precision farming guarantees the best possible use of resources. Crop performance is enhanced by data-driven decisions. Farmers are able to react swiftly to changes in the climate. Sustainable farming is supported by these instruments. Modern agriculture is changing as a result of digitalization.

Water-Smart Seed Technologies: Efficient utilization of water sources in farming operations is the primary objective of water-smart technology. Seeds that can survive despite a lack of water are designed for that purpose. Efficient watering techniques limit water losses. Anti-transpiration prevents evaporation from plant stems. This increases water efficiency and ensures the survival of crops in drought periods. Good water management is vital for sustainable farming practices. The described approaches reduce dependence on rainfall, ensuring steady crop production. Water-smart plants are critical for adapting to changing climate conditions.

Organic and Sustainable Seed Production: Organic seed production uses environmentally friendly, natural substances without any artificial chemical fertilizers or other chemicals. This process involves using manure, biological fertilizers, and plant-derived materials. Organic seeds are grown in accordance with specific organic certification criteria. This procedure helps avoid environmental contamination. It helps grow healthy food in an environmentally friendly manner and saves money.

Conclusion

To ensure sustainable cultivation of vegetables, climate-smart seed technology is necessary. This technology helps farmers be more resilient to the effects of climate change in agriculture, improving seed quality. It results in high productivity and efficient resource utilisation, thereby reducing the negative impacts of climate change.

The application of these concepts is important for food security by ensuring consistent yields and minimal losses, thereby helping farmers. Sustainable seed systems also help conserve the environment. Future development will depend on research.

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Nano Encapsulation in Food Industry

A. S. Nithishraam

Introduction

Nanotechnology is the scientific technology dealing materials with very small dimension basically they range about 1-100 nm. And the properties of the materials are thermal, optical, magnetic, mechanical and other materials are converted once they reduced less than 100 nm. Whose Particle size is very less and the Surface area is high. Hence it is the study of structures and materials in the scale at nanometers. In day today life nanoscience is involved in various sectors such as medical, agriculture, food industry, energy conservation, environment aspects etc. Among all of these Nanoscience plays a crucial role in Food industry where diet-based health problems are increasing day by day in worldwide based on the nature of food. Nanoscience transforms_the whole food system by production, storage, processing and value addition and also nanoscience increases the water solubility and temperature stability of the active ingredients of the food. Additional they also used in food packaging, nano biosensor etc... and these nano particles make sure of the human health and nutrition.

Nano Food: The Nanofoods are the nano technological tools used in crop cultivation, processing the food material, and the proper package practice of the food materials. The main objective of the Nanofood is to improving the quality of food nutrition, by the specific food additives and enhancement of the food material in the form of easily digestible and absorbs of food in the human body. And also, the biggest food corporates like Heinz, Unilever, Nestle, Kraft are initiating the research programs to bring the nanofood to the market and to feed every people with adequate nutrition containing food in future.

Need for Nano Encapsulation in the Food Industry

High Nutrient Loss during Processing and Storage: Important nutrients like vitamins, antioxidants, and probiotics degrade due to heat, oxygen, and moisture. Studies indicate 20-80% of some vitamins may be lost during processing and storage. Nano encapsulation helps protect these nutrients.

Growing Demand for Functional Foods: Demand for foods enriched with probiotics, omega-3 fatty acids and antioxidants is increasing. Conventional methods reduce their stability, creating a need for nano encapsulation.

Food Wastage and Limited Shelf Life: Around one-third of globally produced food is wasted, partly due to spoilage and oxidation. Nano encapsulation improves stability and extends shelf life.

High Cost of Bioactive Ingredients: Functional ingredients are expensive and losses during processing increase production costs. Nano encapsulation

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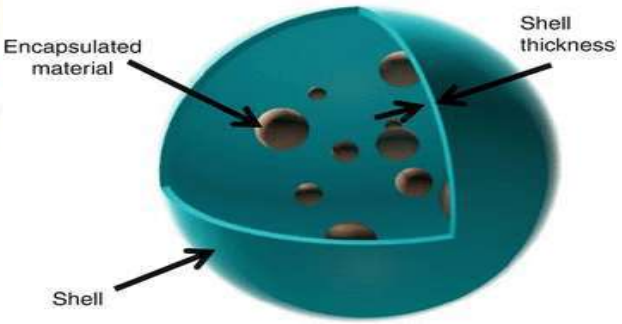
reduces wastage and improves utilization efficiency.

Poor Nutrient Absorption: Certain nutrients, such as omega-3 fatty acids and fat-soluble vitamins, have low bioavailability. Nano encapsulation enhances absorption and nutrient delivery efficiency.

Particle Size: Particle size is the main characteristic, which would govern the functional properties of the nano encapsulated product. A supplementary increase in polymer concentration or double-walled NPs gave rise to an increase in the particle size but also to a change in the physical appearance. And smaller particle size results in better dissolution behavior, mostly due to the increase in surface area to volume ratio of NPs in addition, polydispersity index (PDI) is considered as a major factor which indicates size distribution. It is fixed that values higher than 0.6 indicates polydispersity and values under 0.3 indicates monodisperses. Hence, this factor could indicate that size of NPs was or not distributed uniformly in suspensions.

Nano Encapsulation and Bioactives: Nanoencapsulation is a technology that the bio solubility, deliver nutrients, save us from environmental constituent when it is been stored for slow release of food active ingredient. There are various food active ingredients such as Vitamins, thiamine, riboflavin, omega 3 fatty acid, carotenoids like lycopene and other basic stuff like iron, calcium, protein etc. Nanoencapsulation- process is combining the food bio actives in nanoscale structured wall materials. The wall materials should be consumable biopolymers such as proteins, vitamins, lipids, polysaccharides to deliver in the nanoscale structures. The major advantage of the nanoencapsulation is the particle size is reduced to nano structure, solubility of the food bio actives (active ingredients) is enhanced by increasing the surface area and it makes the food to digest easily. Bioactive in nano foods are biologically active compounds, such as phytochemicals, vitamins, minerals, antioxidants, probiotics, peptides, and essential fatty acids, incorporated into nano-scale delivery systems (1-100 nm). Used to enhance their physicochemical stability, bioavailability, controlled release, and therapeutic or functional efficacy in food matrices. These nano encapsulated bio actives contribute to improved nutritional quality and targeted health benefits beyond basic nutrition.



Nano Encapsulated Food's- Active Ingredients and Suitable Wall Material with Uses

Food Bioactives	Wall Material Used for Encapsulation	Benefits of the Wall Material
Resxevatrol	Gelation complex	Improved aqueous solubility and stability
Rosemary oil	Gum Arabic	Improved flavor retention up to 30%
Epigallactocatechin gallate	B-Lactoglobulin complex	Reduces the degradation due to hydrolyzing enzymes
Melatonin	Cholesterol, Phosphatidyl-choline	Improved bioavailability
Curcumin	Casein complex micelle	Increased aqueous solubility and antioxidant activity.

Techniques of Nanoencapsulation: The nanoencapsulation technology has been classified into two mechanisms for the progression of the nano particles: 'top-down' and 'bottom-up'. In "top-down" technique, particle size is decreased and the encapsulation done by the application of suitable tools] Meanwhile, the "bottom-up" method where the does not increase particle size; it builds nanoparticles from molecules or atoms. And the techniques of bottom-up approach are self-assembly and self-organization of molecules, supercritical-fluids, coacervation, inclusion complexation and nanoprecipitation are referred as bottom-up methods where emulsification is a top-down approach. But occasionally, both approaches can be combined to receive the ideal results. This classification is not used at the present but nano encapsulated systems are liable to be separated into liquid-liquid, solid-liquid and solid-solid systems. The main liquid-liquid process, which is commonly used for solubilization, is oil-water emulsion-based system. There are diversified nanoencapsulation processes for food nutraceuticals have been carried in the few years. For example, methods similar to nanostructured lipid carriers, nano emulsions, nanosuspensions, nanoliposomes, biopolymer nanoparticles or micelles made of polysaccharides or proteins have been developed and the liquid-based processes (nanoprecipitation), emulsification-solvent evaporation, coacervation, ionotropic gelation, supercritical fluid extraction of emulsion) and electrochemical-based techniques (electrospinning and electro spraying) as appropriate techniques for nanoencapsulation. Additionally, nanostructures are also classified into two main classes: single-core and multicore. Specifically, the nanocarriers, carries two mechanisms namely nanosphere and nano capsule. The nanoencapsulation techniques are further classified into five groups, which involves in the main procedure or the component used for building the nano capsules, are:

- ✓ Lipid formulations (nanoliposomes and nano-structured lipid carriers, nano emulsions,)
- ✓ Natural nanocarriers (caseins, cyclodextrins, nanocrystals, amylose nanostructures and caseins)
- ✓ Specialized equipment (electro spun nanofibers, electro sprayed NPs and nano spray dried particles)
- ✓ Functional biopolymeric NPs and
- ✓ Disparate techniques (carbohydrate nanogels and protein nanotubes).

The uses of these nano delivery systems have been determined by the compatibility of NPs properties and the properties of the BACs with the suitable implementation; they provide their usage in a huge variety of solid foods and beverages. It is necessary to consider various parameters for optimal NP preparations, pH, suitable organic solvents, processing time, type of polymers, surfactants, target compounds, polymers ratio and methods of drying. And also, NPs delivered from these encapsulation methods differs in size, shape, mechanical properties and composition, because they involve in regulating their absorption, distribution, metabolism and excret-

ion.

Advantages

Enhanced Bioavailability: Nanoencapsulation can improve the solubility and absorption of poorly soluble nutrients, and bioactive components increase their bioavailability.

Targeted delivery: Nanoparticles can be designed to target specific cells or tissues in the body limiting off-target effects and improving nutrient utilization and functional efficacy.

Controlled release: Nanoencapsulation allow controlled and sustained release of active ingredients, providing an easily trackable with prediction and providing prolonged functional and nutritional benefits.

Protection: Nanoparticles can protect sensitive compounds from degradation in the gastrointestinal tract or while storage, increased stability and shelf-life.

Lower side effects: On targeting specific cells or tissues and reducing undesirable interactions and improving the stability of functional food formulations.

Nano Encapsulated Food Products Used in Day-to-Day Life

Fortified milk and dairy products: Vitamins like Vitamin D, A, and Omega-3 fatty acids are nano-encapsulated to improve absorpt-ion and prevent degradation. Example: fortified milk with better nutrient bioavailability.

Fruit juices and health drinks: Nano-encapsulated antioxidants, vitamins, or minerals are added to increase stability during storage. Example: vitamin-enriched energy drinks.

Probiotic yogurt: Beneficial bacteria (probiotics) are nano-encapsulated so they survive stomach acid and reach the intestine effectively.

Bakery products (bread, biscuits and cakes): Iron, zinc, omega-3, or antioxidants may be nano-encapsulated to avoid changes in taste and improve nutrient retention.

Cooking oils: Nano-encapsulation protects sensitive compounds like omega-3 fatty acids from oxidation.

Tea and coffee premixes: Flavors or nutraceutical compounds can be nano-encapsulated for controlled release and longer flavour retention.

Functional foods and nutrition bars: Protein bars or health bars may contain nano-encapsulated vitamins, minerals, or herbal extracts.

Infant formula products: Essential fatty acids and micronutrients may be nano-encapsulated for improved digestion and absorption.

Dietary supplements and nutraceutical capsules: Though supplements, many are consumed like foods; compounds such as curcumin (turmeric extract) or omega-3 are nano-encapsulated to increase bioavailability.

Ice cream and desserts: Nano-encapsulation helps preserve flavours and sensitive nutrients without affecting texture.

Conclusion

In conclusion, nanoencapsulation provides promising scope to transform nutrient delivery and enhance the functional properties of food bioactive

by overcoming traditional limitations. With its ability to increase bioavailability, enhance targeted delivery, enable controlled release, and deliver with proper protection to sensitive compounds, nano-encapsulation has high potential for improving nutritional outcomes while minimizing nutrient degradation and improving efficacy. Though, constrains such as complex manufacturing processes, High toxicity concerns, regulatory barriers scalability problems, and cost implications should be carefully addressed to track the benefits of this innovative technology. Sustainable research, development, and collaboration across multidisciplinary fields are necessary to unclose the full potential of nanoencapsulation and make aware of its extensive clinical and commercial applications in the future.

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Phosphate-Solubilizing Bacteria as Next-Generation Biofertilizers for Sustainable Phosphorus Management

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Abstract

Phosphorus is indispensable for energy transfer, root proliferation, nucleic-acid synthesis and yield formation, but its availability in soil is restricted by fixation with calcium under alkaline conditions and with iron and aluminium under acidic conditions. Phosphate-solubilizing bacteria represent a practical biological option for improving plant-available phosphorus without claiming to create new phosphorus in soil. They mobilize insoluble inorganic and organic phosphorus through organic-acid secretion, proton extrusion, chelation, phosphatase and phytase activity, and associated plant-growth-promoting effects. Recent fertilizer statistics show that global agricultural use of inorganic fertilizer nutrients remained high in 2023, including about 41 million tonnes of phosphorus expressed as P_2O_5, indicating the continuing need to improve phosphorus-use efficiency. This review, prepared in the style of the Indian Journal of Agronomy, synthesizes the mechanisms, agronomic benefits, field limitations and research priorities of phosphate-solubilizing bacteria for Indian and global nutrient-management systems. Available evidence supports their use as a component of integrated nutrient management with soil testing, organic amendments, balanced fertilization and quality-controlled inoculant application.

Introduction

Phosphorus (P) is the second most limiting macronutrient after nitrogen in many cropping systems, yet its soil chemistry is more complex because phosphate ions are weakly mobile and readily precipitate or adsorb on reactive mineral surfaces. In calcareous and alkaline soils, soluble phosphate commonly forms sparingly soluble calcium phosphates, whereas in acidic soils it is fixed by iron and aluminium oxides. Consequently, repeated fertilizer application can increase total soil P while the fraction immediately available to crops remains small. Phosphate-solubilizing bacteria (PSB) are rhizosphere or endophytic bacteria capable of converting insoluble phosphate compounds into soluble orthophosphate ions, mainly $H_2PO_4^-$ and HPO_4^{2-}. Their agronomic value lies in improving the biological availability and recovery efficiency of existing soil P and added fertilizer P. This distinction is essential: PSB do not

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manufacture phosphorus; they alter its form, location and accessibility in the root zone.

Current relevance and global fertilizer context

The interest in PSB has increased because phosphate rock is finite, fertilizer prices are volatile and nutrient losses contribute to eutrophication. FAOSTAT's 2025 analytical brief reported that world agricultural use of inorganic fertilizers reached about 190 million tonnes of nutrients in 2023, of which 112 Mt was N, 41 Mt was P_2O_5 and 38 Mt was K_2O. World production in the same year was estimated at 120, 45 and 43 Mt for N, P_2O_5 and K_2O, respectively. The 2002-23 trend further shows a 20% rise in agricultural use of P_2O_5, despite a short-term decline from 2022 to 2023.

Table 1: Global inorganic fertilizer nutrient use and production in 2023 (compiled from FAOSTAT Analytical Brief, 2025).

Indicator (2023)	Nitrogen (N)	Phosphorus (P_2O_5)	Potassium (K_2O)
Agricultural use (Mt nutrient)	112	41	38
World production (Mt nutrient)	120	45	43
Change in agricultural use since 2002	+32%	+20%	+62%

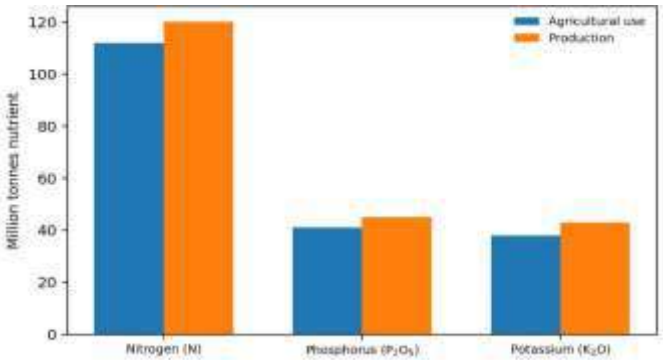

Fig. 1: Global agricultural use and production of N, P_2O_5 and K_2O fertilizer nutrients in 2023

Mechanisms of phosphate solubilization: The dominant mechanism of inorganic phosphate solubilization is organic-acid production. Genera such as Bacillus, Pseudomonas, Enterobacter, Burkholderia, Rhizobium, Serratia and Klebsiella release gluconic, citric, oxalic, malic, lactic and acetic acids. These acids lower rhizosphere pH and dissolve calcium-, iron- and aluminium-bound phosphate complexes. Gluconic acid is frequently reported as a major product because it strongly acidifies the micro-zone around bacterial colonies and roots. Mineralization of organic P is equally important in soils with considerable organic matter. Phosphatase and phytase enzymes hydrolyse organic phosphate esters and phytate, thereby releasing orthophosphate. Siderophores, extracellular polymeric substances, proton extrusion and root-growth-promoting compounds such as indole acetic acid may indirectly enhance P acquisition by increasing root surface area and microbial activity in the rhizosphere.

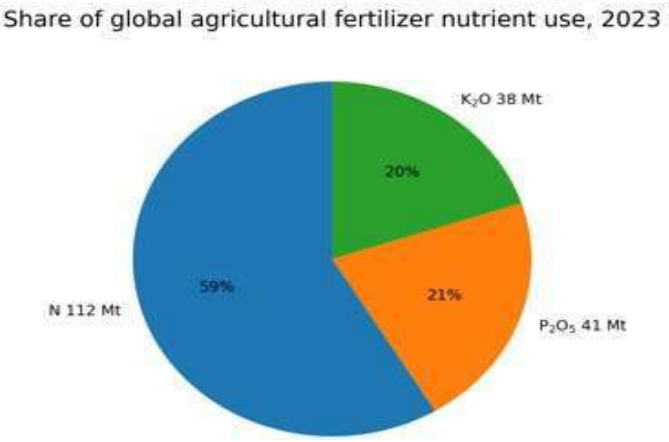

Fig. 2: Share of N, P_2O_5 and K_2O in global agricultural fertilizer nutrient use in 2023.

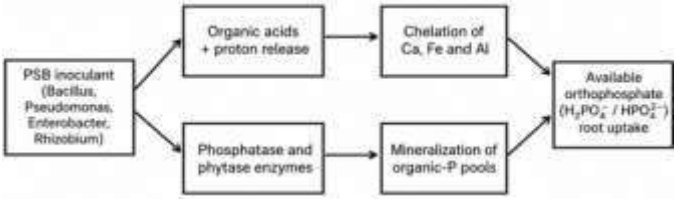

Fig. 3: Main biochemical pathways through which PSB mobilize unavailable phosphorus in soil

Major PSB groups and functional traits

Table 2: Functional diversity of major phosphate-solubilizing bacterial groups

Bacterial group	Commonly reported trait	Likely agronomic role	Precaution
Bacillus spp.	Spore formation, organic-acid production	Better shelf life; suitable for carrier-based formulations	Field response depends on strain and soil moisture
Pseudomonas spp.	Organic acids, siderophores, root colonization	Rapid rhizosphere activity and root-growth support	Sensitive to formulation and storage conditions
Enterobacter/Serratia spp.	Strong solubilization in vitro in some strains	Useful candidates for screening and consortia	Biosafety and strain authentication are essential
Rhizobium/Bradyrhizobium with PSB traits	Symbiosis plus P mobilization	Useful in pulses and legume-based systems	Compatibility with host genotype is required
Burkholderia-related taxa	Multiple plant-growth-promoting traits	Potential under stress-prone environments	Use only well-characterized safe strains

Agronomic benefits in crop production

Table 3: Agronomic contribution of PSB in integrated nutrient management

Benefit	Scientific basis	Field implication	Best practice
Higher available P	Solubilization of fixed Ca-P, Fe-P and Al-P fractions	Improves early root growth and crop establishment	Apply near seed/root zone with recommended P source
Improved fertilizer-use efficiency	Better synchrony between P release and root demand	May reduce avoidable fertilizer wastage	Use with soil-test-based fertilizer recommendation
Improved root architecture	Phytohormone and rhizosphere effects	Greater soil exploration and stress tolerance	Combine with organic matter and adequate moisture
Soil biological activity	Enhanced microbial cycling and enzyme activity	Supports long-term soil health	Avoid incompatible pesticide or fertilizer mixing
Climate-resilient nutrient management	Lower dependence on blanket fertilizer escalation	Useful in low-input and rainfed systems	Use quality inoculants with viable cell count

Table 4: Suggested treatment structure for field validation of PSB under Indian agronomic conditions

Treatments	Nutrient management option	Expected comparison	Key observations	Statistical design
T_1	Absolute control	Baseline nutrient response	Yield, P uptake, soil available P	Randomized block design
T_2	Recommended NPK	Full fertilizer reference	Yield and economic benchmark	3 replications minimum
T_3	75% recommended P + PSB	Fertilizer saving potential	P-use efficiency and root traits	Plot size crop-specific
T_4	Recommended P + PSB	Additive biological effect	Available P, phosphatase activity	ANOVA with LSD/CD
T_5	Rock phosphate/ compost + PSB	Mobilization of low-solubility P source	Soil enzyme activity and benefit:cost ratio	Multi-season validation

Suggested field evaluation format for Indian conditions

For publishable agronomic evaluation, PSB should be tested under multi-location field conditions rather than relying only on halo-zone formation on agar media. A robust design should include soil-test status, initial available P, pH, organic carbon, microbial count, crop variety, fertilizer placement, irrigation/rainfall and economic analysis.

Correct interpretation of soil-test results

A scientifically correct interpretation is that PSB increase available phosphorus, not total phosphorus, unless a P-containing material is added. Therefore, a successful PSB response may be observed as higher Olsen-P or Bray-P, greater plant P uptake, improved root length density and better yield, while total soil P remains unchanged.

This interpretation avoids the misleading claim that biofertilizers create new phosphorus.

Limitations and precautions

Field performance of PSB is affected by soil pH, temperature, moisture, organic carbon, native microbial competition, pesticide compatibility, inoculant carrier, viable cell count, shelf life and crop genotype. Laboratory phosphate-solubilization indices do not always predict field performance. Quality assurance should include strain identity, contamination testing, viable count at expiry, crop-specific recommendation and clear instructions on seed treatment, soil application or root dipping.

Future research priorities

Future research should move from single-strain claims to well-characterized microbial consortia that combine phosphate solubilization with nitrogen fixation, potassium mobilization, stress tolerance and biocontrol. Experiments should report phosphorus-use efficiency, root morphology, soil enzyme activity, microbial persistence, yield stability, benefit:cost ratio and environmental indicators. Integration with precision nutrient management, soil-test mapping, remote sensing and weather-based advisories can help identify where PSB will deliver the highest agronomic return.

Conclusion

Phosphate-solubilizing bacteria are credible next-generation biofertilizers for improving phosphorus availability and fertilizer efficiency. Their action is based on biochemical mobilization of insoluble and organic P pools through acidification, chelation and enzymatic mineralization. For Indian agriculture, their best role is not as a complete substitute for phosphate fertilizer but as a biological component of integrated nutrient management with soil testing, organic amendments, balanced fertilization and site-specific recommendations. Reliable field performance requires strain selection, quality formulation, correct application and multi-environment validation.

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Nano fertilizers: The Next Frontier in Sustainable Agriculture

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Abstract

Nano fertilizers have emerged as a promising innovation in modern agriculture, offering solutions to major challenges associated with conventional fertilizers, such as low nutrient-use efficiency, soil degradation, and environmental pollution. By utilizing nanoscale materials with enhanced reactivity and controlled-release properties, nano fertilizers improve nutrient delivery, strengthen plant physiological functions, and enhance resilience against abiotic stresses. Their production through top-down, bottom-up, and biological synthesis methods allows for tailored formulations suited to various crops and soil conditions. This article discusses the science behind nano fertilizers, their advantages, applications, limitations, and their growing significance in building climate-resilient and sustainable agricultural systems. While their potential is substantial, further research is needed to address environmental safety, long-term impacts, and high production costs to ensure responsible and widespread adoption.

Global Need for Advanced Fertilization Technologies

The global agricultural and horticulture sectors are under significant pressure as the world population moves steadily toward an estimated 9.6 billion by the year 2050 (Tilman *et al*., 2011). Traditional farming systems rely heavily on chemical fertilizers to increase productivity, but their prolonged use has resulted in declining soil health, reduced nutrient-use efficiency, and environmental degradation. Conventional fertilizers release nutrients rapidly, often exceeding the rate at which plants can absorb them. This imbalance causes substantial nutrient losses through leaching, volatilization, and soil fixation, leading to groundwater contamination, eutrophication, and increased financial strain on farmers (Zhang *et al*., 2015). With nutrient-use efficiency frequently falling below 50%, there is an urgent need for more efficient and environmentally responsible nutrient delivery systems (Chen *et al*., 2017). In this context, nano fertilizers represent a breakthrough technology capable of addressing many of these persistent challenges.

Mechanism and functional advantages of nano fertilizers

Nano fertilizers operate at the nanoscale typically within the 1-100 nm range where materials exhibit enhanced surface area, reactivity, and mobility. These properties allow nano fertilizers to improve nutrient solubility, facilitate slow and susta-

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ined release, and promote deeper penetration into plant roots and leaves. Unlike conventional fertilizers, which often release nutrients in large pulses, nano fertilizers ensure a consistent and controlled supply, closely matching plant uptake needs and reducing overall nutrient wastage (Prasad *et al*., 2018). Their improved delivery efficiency directly contributes to healthier plant growth, higher biomass accumulation, and enhanced physiological functions, including better chlorophyll production, nitrogen metabolism, and seedling vigor (Singh *et al*., 2020).

Nano fertilizers and plant stress tolerance

In addition to boosting plant growth under ideal conditions, nano fertilizers play a crucial role in enhancing tolerance to abiotic stresses, which are becoming increasingly common due to climate change. Stress factors such as drought, salinity, extreme temperatures, and waterlogging negatively affect crop metabolism and yield potential. Nano fertilizers help plants withstand these stresses by strengthening cellular membranes, improving water uptake, stimulating antioxidant enzyme activity, and supporting osmotic balance. These improvements allow crops to maintain productivity even under adverse environmental conditions, making nano fertilizers a valuable tool for climate-resilient agriculture (Hussain *et al*., 2019).

Production Techniques and Application Methods

The production of nano fertilizers is achieved through three major methods: top-down, bottom-up, and biological synthesis. The top-down approach involves physically breaking down larger particles into nanosized structures through milling or grinding, though it may result in irregular particle sizes and impurities. In contrast, the bottom-up method constructs nanoparticles atom by atom or molecule by molecule, enabling precise control over particle uniformity and structure. The third method, biological or green synthesis, employs micro-organisms, algae, and plant extracts to produce nanoparticles in an environmentally friendly and less toxic manner (Prasad *et al*., 2018; Hussain *et al*., 2019; Singh *et al*., 2020). These approaches allow for versatile formulations tailored to specific crop needs and soil conditions. Nano fertilizers can be applied through soil incorporation, foliar sprays, or fertigation. Soil application ensures gradual nutrient release in the rhizosphere, foliar sprays enable rapid correction of deficiencies, and fertigation allows uniform distribution while minimizing nutrient loss.

Environmental and Practical Challenges

Despite their wide-ranging benefits, nano fertilizers also present certain limitations and concerns. Environmental risks arise from the possibility that nanoparticles may accumulate in soil, potentially affecting beneficial microorganisms and altering soil chemistry (Prasad *et al*., 2018). Incorrect dosage or poorly designed formulations could also lead to phytotoxicity, damaging plant tissues and hindering growth (Zhang *et al*., 2015). Additionally, the advanced technology required for nanoparticle synthesis contributes to high production costs, which may limit accessibility for small and marginal farm-

ers (Chen *et al*., 2017). Perhaps the most significant limitation is the lack of comprehensive long-term research on their ecological and human health impacts. As nanotechnology in agriculture is still relatively new, more studies are needed to evaluate its long-term sustainability and safety, emphasizing the requirement for strong regulatory frameworks (Hussain *et al*., 2019).

Conclusion

Nano fertilizers offer a transformative solution to many challenges faced by modern agriculture. Through improved nutrient efficiency, enhanced plant growth, and greater resilience to climate-induced stresses, they hold immense promise for building sustainable and productive farming systems. Their ability to deliver nutrients in a controlled and targeted manner reduces environmental contamination while supporting higher yields and better crop quality. However, despite their potential, it is essential to address concerns related to production costs, environmental safety, and long-term impacts before their widespread adoption. Continued research, standardized regulations, and advancements in cost-effective synthesis technologies will play a vital role in shaping the future of nano fertilizers. With responsible development and application, nano fertilizers could become a cornerstone of climate-smart and sustainable agriculture in the years to come.

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Botanical Features and Economic Importance of Cashew

S. Ranjith Raja Ram, M. Velmurugan and K. Thirukumaran

Introduction

The cashew tree (*Anacardium occidentale*) belongs to the family *Anacardiaceae*, primarily grows in tropical and subtropical regions with warm climates. Portuguese traders introduced cashews to India in the 16th century. Today, India, Vietnam, Brazil, and various West African countries are top producers. In countries such as Brazil, India, and Thailand, it is eaten fresh and also processed into juice, jam, chutney, or alcoholic beverages. Due to its rapid spoilage, fresh cashew apples are not exported; it is packed with heart-healthy fats, essential proteins, and minerals like magnesium. The species is native to south America The dwarf cultivars, growing up to 6 m (20 feet height), maturing sooner and it produce greater yield and most profitable to farmers. In 2023, 3.9 million tonns of cashew nuts were harvested globally. In contrast, the seed itself is toxic in its raw state. The primary compound responsible for this toxicity is an organic substance called Cardol, chemical name 5-(8,11-pentadecadienyl)-resorcinol. Pure Cardol, which belongs to the chemical group of phenols, is an oily liquid that varies in color from light yellow to brown depending on its purity. Its odor is characteristically phenolic, described as pungent and slightly smoky. Cardol is highly irritating. Contact with the skin causes inflammation, itching, and blistering. Reports from Brazil indicate a high prevalence of contact dermatitis among industrial workers handling cashews. Similar effects have been observed in consumers who have eaten untreated nuts from local markets. If Cardol comes into contact with the eyes, it can cause redness, tearing, and potential corneal damage. Inhaling Cardol vapors, such as those released during industrial processing, can lead to the aerosolization of irritating substances. This can cause respiratory irritation and severe coughing in workers, potentially even triggering shortness of breath. Ingestion of Cardol typically results in nausea, vomiting, and diarrhea, while severe cases may lead to systemic effects. Commercially sold cashew nuts are generally safe, as the outer shell, containing the highest levels of Cardol, is removed. The kernels are then either roasted or steamed, further reducing Cardol levels since the compound begins to degrade at temperatures above 200 °C. The cashew tree is cultivated in the tropics between 25°N and 25°S, and is well-adapted to hot lowland areas with a pronounced dry

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season, where mango and tamarind trees also thrive well. The traditional cashew tree is tall, up to 46 ft height, requiring three years from planting before it starts production, and eight years before economic harvests. More recent breeds, such as the dwarf cashew trees, are up to 20 ft tall and start producing after the first year, with economic yields after three years. The cashew nut yields for the traditional tree are about 0.25 t ha^{-1}, in contrast to over a ton per hectare for the dwarf variety. Grafting and other modern tree management technologies improve and sustain cashew nut yields in commercial orchards.

Botanical description

Common name

- ✓ Engish : Cashew nut
- ✓ Tamil : Mundiri
- ✓ Hindi : Kaju
- ✓ Telugu : Munthamamidi

Scientific Name: *Anacardium occidentale*

Family: *Anacardiaceae*

Habit: Generally trees and shrubs and rarely woody vines containing resin passage with gum/acrid juice.

Root: Deep tap root system.

Stem: Hard stem with resinous bark. The cashew tree is large and evergreen, growing to 14 metres (46 feet) tall, with a short, often irregularly shaped trunk.

Leaves: The leaves are spirally arranged, leathery textured, elliptic to obovate, 4-22 centimetres long and 2-15 cm broad, with smooth margins. Alternate, simple, pinnately compound, estipulate.

Inflorescence: A terminal or axillary panicle.

Flower: The flowers are produced in a panicle or corymb up to 26 cm (10 in) long; each flower is small, pale green at first, then turning reddish, with five slender, acute petals. Flower Small, complete, usually actinomorphic rarely zygomorp, pentamerous, hermaphrodite but often unisexual by reduction of androecium or gynoecium, a nectar secreting disc or gynophores present hypogynous.

Calyx: Usually 5 sepals, sometimes 3 to 7, free or basally connate imbricate.

Corolla: Petals 5-3 or absent (pistacia) polypetalous rarely connate imbricate, sometimes fused with the receptacle to from a hypanthium.

Androecium: Stamens ten in whole of 5 each all fertile in anacardium 10-7 of which only is functional and the rest are staminodes, filaments free, basally, connate stamens arise from the base of on intrastaminal disc, this disc may sometimes be modified into gynophores, anther bithecous, introrse.

Gynoecium: Tricarpellary rarely pentacarpellary, syncarpous, unilocular, superior one pendulous ovule, ovary pentacarpellary and pentalocular with only one ovule, style 1-5 widely separated.

Fruit: The fruit of the cashew tree is an accessory frit, sometimes called a pseudocarp or false fruit. Fruit is an oval or pear-shaped structure, a hypocarpium, that develops from the pedicel and the receptacle of the cashew flower. Called the cashew apple.

Seed: Cotyledon thick with little or no endosperm and curved embryo.

Floral formula

$$Br, \oplus \, ♀ \, K_{(4-5) \text{ or } 5} \, C_5 \, A_{1-10} \, \underline{G_{(1-5)}}$$

Pollination: Entomophilous

Economical Importance

Edible Uses: The fleshy peduncle called cashew apple when ripe is used in beverages. The kernel is consumed as raw nuts, roasted nuts, fried nuts, salted nuts, dry fruit, and is added to cakes and deserts. The wood of the tree is used as fuel.

Commercial Uses

- ✓ The bark of cashew tree is used in tanning industry.
- ✓ It is also used as an insecticide, and an adhesive for book binding.
- ✓ It is used in pharmaceutical industry as substitute for gum Arabic and is also used in making ink.
- ✓ The juice of cashew apple is used for making wine. The cashew apple is used in preparing various juices, syrups, candies and pickles.
- ✓ The residue of cashew apple is used to extract pectin.
- ✓ Vinegar is prepared from fresh fruit of cashew.
- ✓ The cashew nut shell is used in the cosmetic industry, pharmaceutical industry, textile industry, paper industry, and ink making.
- ✓ Cashewnut shell yields a vesicant juice known in trade as Cashewnut Shell Liquid (CNSL). CSNL is used in preservation of boats, nets, and wood. CNSL is used in insulating varnishes and resins.
- ✓ It is also used in paint industry, particle board adhesives, thermo-plastic resins, thermo setting resins, and plastic industry.
- ✓ The shell oil is also used as insecticide against mosquito larvae.

Cold Plasma Treatment on Seed Germination

R. Saranya, S. Ambika and R. Niranjan

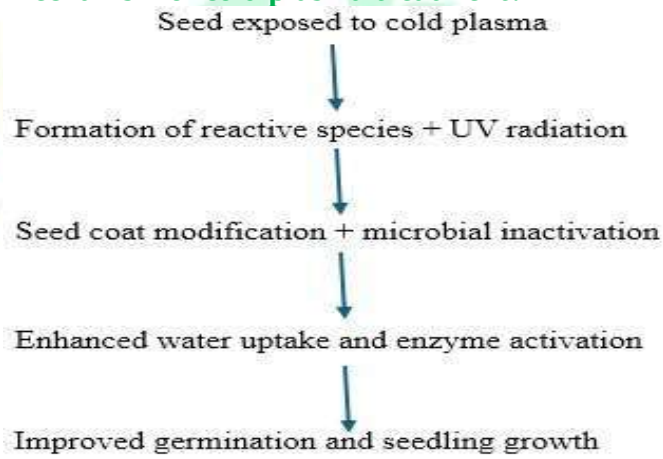
Introduction

Seed is essential in agriculture for crop production. Favourable climatic conditions are required for the production of good-quality seed. Every crop starts with a seed, and using high-quality seeds for planting produces higher yields. Scientists and farmers mainly focus on improving the seed germination, uniform crop growth and resistance to pests and diseases. Traditional methods of seed treatment are priming and hardening with organic and inorganic substances. In modern agriculture, cold plasma treatment is a new technology for improving seed germination, seedling growth and development.

What is cold plasma?

There are four states of matter, such as solid, liquid, gas and plasma, used. Cold plasma is a new technology used to improve seed germination and performance. Plasma is a non-chemical technique in which seeds are treated with an ionised gas at low temperature. It is made up of electrons, ions, reactive with oxygen and nitrogen species and lower UV photons. It contains charged particles and reactive molecules. Under controlled conditions, the use of electrical discharge generated the cold plasma. When seeds are exposed to plasma, the outer seedcoat is slightly altered. It helps to improve the water imbibition in seeds. At the same time, it reduces the microbial load on the seed surface.

Mechanism of cold plasma treatment?



How cold plasma works on seeds

When seeds are treated with cold plasma for a short time, several changes happen in seed 1. In the first stage (Imbibition phase), water enters the seeds, and the outer seedcoat is more permeable to water uptake. Some physical changes occur in the seedcoat.

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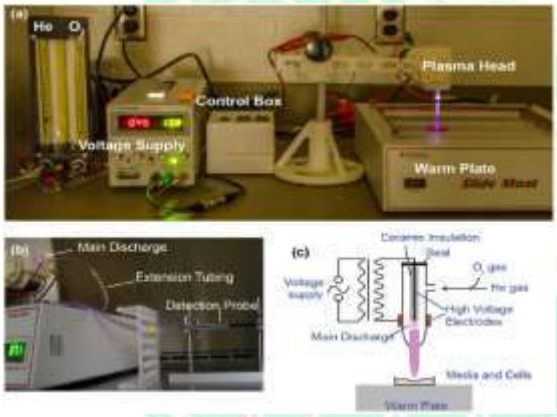
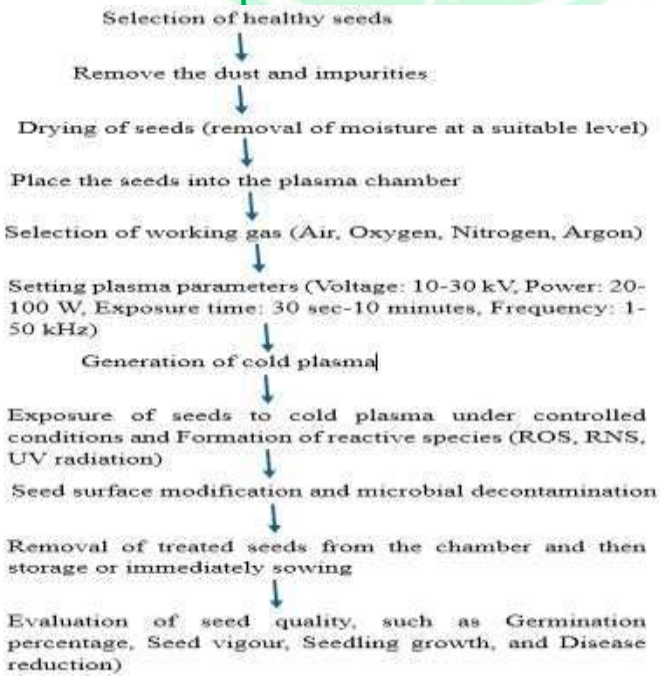
In the second stage (breakdown of food material), water activates the enzymes that help to break down the stored food material. Some reactive molecules in plasma that interact with the seed surface and can trigger biochemical reactions inside the seed. The third stage, cold plasma, contains antimicrobial properties that help to reduce the microbial activities on the seed surface, which can protect the seeds from microbial attack during seedling growth and germination. It is a non-chemical, environmentally safe method. Excess exposure of seeds to the cold plasma treatment may affect the seed performance.



Procedure of cold plasma treatment



Benefits of cold plasma treatment

Improved Germination: Seeds are exposed to cold plasma to improve the germination and overall plant growth and yield compared to untreated seeds. It ensures the faster emergence of uniform plant performance.

Enhanced seedling growth: Treated seeds produce better root and shoot growth. Vigorous seedlings are better suited for survival under field conditions.

Better water uptake: Treated seed coats are slightly modified to absorb water quickly and efficiently. During sowing, it helps to activate the metabolic processes early.

Increased enzyme activity: Breakdown of stored food material into energy for better seedling growth.

Efficient stress tolerance: Seeds treated with plasma have significantly higher tolerance to abiotic stress such as drought, salinity, flooding, etc. This is more useful under climate change conditions.

Reduce the seed-borne disease: Antimicrobial properties help to reduce the microbial activities on the seed surface and protect the seeds from microbial attack during seedling growth.

Eco-friendly and does not harm the environment.

Limitations and challenges

- ✓ The plasma generation equipment is costly
- ✓ Exposure time (duration) may affect the performance
- ✓ Limited adoption at the field level
- ✓ Lack of standardised procedures for different crops
- ✓ Lack of skilled professionals

Examples of cold plasma treatment in vegetable seeds with dosage

Vegetable crop	Dosage	Effects
Tomato	30-60 W for 1-3 minutes	Improved germination
Chilli	20-50 kV for 2-5 minutes	Increased seed vigour
Brinjal	1-4 minutes	Better seedling growth
Okra	3-5 minutes	Enhanced water uptake
Cucumber	30 sec- 2 minutes	Faster germination

Conclusion

Cold plasma treatment is an emerging and innovative technology for seed treatment. It helps improve seed germination, seedling growth and tolerance to abiotic stress without the use of chemicals. It is more important in modern agriculture because of its sustainability and eco-friendly approach. But more focus needs to be on reducing cost, wider use by farmers, and in large-scale applications. Nowadays, agriculture increases the demand for sustainable and eco-friendly practices. Cold plasma treatment plays a major role in improving seed germination and seedling growth, and better crop production without causing hazards to the environment.

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Native Grasslands and Orans: Backbone of Livestock-Based Livelihoods in Arid Rajasthan

Shirish Sharma and Sandeep Kumar Bangarwa

The arid zone of Rajasthan is characterized by low rainfall, extreme temperatures, sandy soils, and frequent drought conditions. In this fragile ecosystem, livestock plays a crucial role in supporting the livelihood and economy of rural communities. Crop production and animal husbandry are complementary to each other, and sustainable livestock production largely depends upon the availability of quality fodder resources. Fodder not only provides nutrition to animals but also contributes to improved milk, meat, and wool production, thereby strengthening the rural economy of the arid region. Rajasthan possesses one of the largest livestock populations in India. According to recent livestock statistics, the state has more than 56 million livestock, including cattle, buffaloes, sheep, goats, and camels. Animal husbandry contributes significantly to the state economy, particularly in arid districts where crop farming is highly risky due to erratic rainfall. Livestock rearing provides regular income through milk, wool, meat, manure, and draft power. However, increasing livestock population and shrinking grazing lands have created severe pressure on fodder resources. The fodder requirement in arid Rajasthan is fulfilled through multiple sources such as cultivated fodder crops, crop residues including straw and stover, pasture grasses, fodder trees and shrubs, weeds, and community grazing lands like Orans and Gauchars. Traditionally, local communities protected Orans and Gauchars as common grazing lands for livestock. These areas supported native grasses, perennial shrubs, and trees that provided nutritious fodder throughout the year. However, due to overgrazing, encroachment, and lack of proper management, these grazing resources are presently in degraded condition and their productivity has declined significantly. The annual availability of feed and fodder in Rajasthan is estimated at about 60.11 million tonnes dry matter against a requirement of nearly 76.27 million tonnes, indicating a deficit of around 21 percent. In arid Rajasthan alone, the total annual fodder availability has been estimated at 38.46 million tonnes compared to a requirement of 58.39 million tonnes, showing a very high fodder shortage. This shortage becomes even more severe during drought years when natural vegetation dries up and crop residue production declines sharply. The shortage of fodder directly affects livestock productivity. Feed and fodder account for nearly 60-70 percent of the total cost of

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milk production in dairy farming systems. Poor-quality fodder results in low digestibility, protein deficiency, mineral imbalance, and reduced energy intake, ultimately decreasing animal health and productivity. Insufficient nutrition leads to lower milk yield, poor reproductive efficiency, delayed maturity, weak immunity, and higher disease incidence among livestock. Milk production is highly dependent on the quantity and quality of fodder available to dairy animals. Animals receiving balanced green fodder, legumes, and nutritious grasses produce significantly higher milk compared to animals dependent only on dry crop residues. In Rajasthan, indigenous and non-descript cows produce an average of about 2.79 kg milk per day, while buffaloes produce about 4.29 kg and crossbred cows about 5.31 kg per day under improved feeding and management conditions. Scientific studies also indicate that green fodder improves milk fat percentage, protein content, and overall milk quality due to better nutrient availability. Fodder quality is equally important as fodder quantity. High-quality fodder contains adequate crude protein, digestible nutrients, vitamins, and minerals essential for animal growth and lactation. Native grasses like Sewan and Dhaman are highly nutritious and palatable, making them suitable for sustainable livestock production in arid regions. Green fodder also improves rumen activity and feed conversion efficiency in ruminants. In contrast, poor-quality dry fodder such as weathered straw contains low protein and high fiber, resulting in poor digestion and low milk production.

Native grass species are highly important for the sustainability of arid ecosystems because they are naturally adapted to drought, low fertility soils, and harsh climatic conditions. Among the important indigenous grasses of Western Rajasthan, Sewan grass (*Lasiurus sindicus*) is considered the most valuable perennial grass due to its high palatability, drought tolerance, and nutritive value. Dhaman grass (*Cenchrus ciliaris*) is another important species widely used for grazing and pasture development because of its high biomass production and adaptability. Other native grasses such as Marvel grass (*Dichanthium annulatum*), Buffel grass (*Cenchrus setigerus*), and Anjan grass (*Cenchrus biflorus*) also contribute significantly to fodder availability and soil conservation in arid regions. Apart from grasses, fodder trees and shrubs are equally important in sustaining livestock during drought and lean periods when herbaceous vegetation becomes scarce. Khejri (*Prosopis cineraria*) is regarded as the lifeline of the desert because its leaves provide nutritious fodder and the tree improves soil fertility. Desi Ber (*Ziziphus nummularia*) is widely browsed by goats and sheep, while shrubs like Phog (*Calligonum polygonoides*), Khimp (*Leptadenia pyrotechnica*), and Lana (*Haloxylon salicornicum*) are important for browsing animals in sandy areas. Multipurpose species such as Neem, Moringa, Mulberry, and Bael are also being promoted for their fodder, medicinal, and ecological benefits. India presently has around 8 million hectares under cultivated fodder and about 11.5 m ha

under grasslands and pastures. In addition, approximately 97 million hectares of degraded land have the potential to be utilized for fodder production and pasture development. However, lack of quality seed material, poor extension services, water scarcity, climate variability, and degradation of common grazing lands remain major constraints in fodder development. To overcome fodder scarcity, several innovative and sustainable fodder production technologies are being promoted in arid regions. Hydroponic fodder production systems are gaining attention because they require less water and provide green fodder throughout the year. Sprinkler and drip irrigation systems are being recommended to improve water-use efficiency in fodder cultivation. Silage preparation and fodder conservation techniques are also important for ensuring feed availability during drought periods. Researchers have further emphasized the restoration of Orans and Gauchars through reseeding of native grasses, controlled grazing, and plantation of fodder trees and shrubs. The promotion of thornless cactus, fodder beet, and moringa has shown promising results in arid Rajasthan. Thornless cactus cultivated under watershed development programmes has performed well in districts like Bikaner and is increasingly being used in feed pellet production as a substitute for molasses. Rapid multiplication techniques for cactus and improved pasture grasses are also being developed for wider dissemination among farmers. Agroforestry and silvipasture systems involving Khejri, Ber, Neem and perennial grasses are emerging as sustainable models for fodder and environmental security in dryland regions. Experts have also stressed the importance of road water harvesting and utilization of runoff water for developing roadside fodder plantations and nurseries. Such initiatives can help in creating live fodder banks in drought-prone regions of Rajasthan. Integration of fodder development programmes with schemes like Watershed Development, MGNREGA, and Panchayati Raj can further strengthen pasture restoration and community participation in grazing land management. In conclusion, fodder resources are the backbone of livestock production and ecological sustainability in the arid zone of Rajasthan. Native grasses such as Sewan and Dhaman, along with indigenous trees and shrubs like Khejri and Ber, are highly valuable for maintaining animal productivity and restoring degraded ecosystems. The increasing livestock population and declining fodder availability have created a serious fodder deficit that adversely affects milk production, animal health, and rural livelihoods. Therefore, there is an urgent need to revive Orans and Gauchars, improve the availability of quality fodder seed, promote sustainable grazing practices, and adopt modern fodder production technologies. These measures will not only improve livestock productivity and milk quality but will also contribute towards environmental conservation, rural livelihood security, and sustainable agricultural development in the arid regions of Rajasthan.

CRIPSR-Cas 9: Revolutionising Modern Plant Breeding

Sandeep Kumar Bangarwa and Shirish Sharma

Climate change, population growth, and shrinking arable land pose severe threats to global food security. Traditional plant breeding methods are often slow and imprecise, taking decades to develop resilient crops. CRISPR-Cas9 technology has emerged as a game-changing tool, allowing scientists to edit plant genomes with unprecedented speed, accuracy, and efficiency.

How CRISPR-Cas 9 Works in Plants?

The CRISPR-Cas9 system operates as a pair of molecular scissors guided by a programmable GPS tracker.

sgRNA Guidance: A custom-designed single guide RNA molecule matches a specific DNA sequence in the plant genome.

Cas9 Cleavage: The Cas9 enzyme follows the guide RNA to the target site and creates a precise double-stranded break in the DNA.

Cellular Repair: The plant's natural repair mechanisms fix the break. This process can be harnessed to knock out undesirable genes or insert beneficial traits.

CRISPR-Cas 9 methodology

The CRISPR-Cas9 methodology functions as a highly precise, two-component molecular system adapted from a natural bacterial defense mechanism. It allows researchers to target, cut, and alter specific DNA sequences within an organism's genome.

Target Selection and Guide Design

The first step requires identifying the precise genomic sequence (typically 20 nucleotides long) that needs editing. This target site must lie immediately upstream of a Protospacer Adjacent Motif (PAM). For the widely used *Streptococcus pyogenes* Cas9 protein, the mandatory PAM sequence is 5'-NGG-3' (where N represents any nucleotide).

Guide RNA (gRNA) Construction

Scientists synthesize a custom single guide RNA (sgRNA) by combining two elements:

Spacer (CrRNA): A customizable 20-nucleotide region matching the target gene sequence.

Scaffold (TracrRNA): A constant RNA structural loop that physically binds into the Addgene CRISPR Guide structural groove of the Cas9 enzyme.

Cargo Delivery into Target Cells

The sgRNA and Cas9 enzyme are introduced into the host cell. They can be delivered via different biological formats:

Plasmid DNA: DNA vectors expressing both Cas9 and sgRNA.

mRNA + RNA: Direct translation of the components

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inside the cell cytoplasm.

Ribonucleoprotein (RNP) Complexes: Pre-assembled, active Cas9 protein bound directly to sgRNA, which reduces off-target errors and avoids foreign DNA integration

Common delivery methods, especially when overcoming rigid plant cell walls, include Agrobacterium-mediated transformation, biolistic particle bombardment (using gold nanoparticles), or polyethylene glycol (PEG)-mediated transfection of protoplasts.

Genomic Recognition and Cleavage

Once inside the cell nucleus, the active Cas9-gRNA complex scans the genome:

- ✓ It locates and loosely binds to an accessible PAM site.
- ✓ It melts the local DNA double helix, allowing the 20-nt guide RNA to base-pair with the complementary target strand.
- ✓ If the match is perfect, two distinct catalytic domains on the Cas9 enzyme (HNH and RuvC) undergo a conformational shift and act as molecular scissors.
- ✓ The enzyme introduces a clean, double-stranded break (DSB) exactly 3 base pairs upstream of the PAM site.

The Cas9 complex detaches, and the host cell's internal repair machinery automatically activates to fix the broken DNA via one of two natural paths:

Key Applications in Agriculture

CRISPR-Cas9 is transforming agriculture by introducing traits that improve crop yield, quality, and climate resilience.

Repair Pathway	Mechanism	Main Application Outcome
Non-Homologous End Joining (NHEJ)	Joins the broken DNA ends back together. It is error-prone and frequently introduces random insertions or deletions (indels).	Gene Knockout: Disrupts the open reading frame to completely silence or deactivate a target gene.
Homology-Directed Repair (HDR)	Uses a matching donor template (co-delivered by the researcher) to seamlessly patch the broken DNA strands.	Gene Insertion / Editing: Allows precise point mutations, sequence corrections, or the introduction of entirely new traits

Climate Resilience and Abiotic Stress Tolerance: Extreme weather events require crops that can survive harsh environments. Researchers use CRISPR to engineer drought-tolerant rice, salinity-resistant wheat, and heat-tolerant maize by modifying genes responsible for water retention and stress signaling.

Pest and Disease Resistance: Biotic stresses like viruses, bacteria, and fungi cause massive annual crop losses. CRISPR allows scientists to silence susceptibility genes (S-genes). For example, editing the *MLO* gene locus has successfully produced powdery mildew-resistant varieties of wheat, tomatoes, and grapes without using chemical pesticides.

Enhancing Nutritional Value and Yield: Beyond survival, CRISPR improves food quality. It has been used to create high-oleic acid soybeans, gluten-reduced wheat for celiac sufferers, and golden rice with enhanced Vitamin A content. It also optimizes

plant architecture such as grain size and tilling number to maximize yield per acre.

Advantages over Traditional Methods

Speed: Lowers breeding cycles from over a decade to just a few years.

Precision: Edits specific nucleotides without disrupting other desirable traits.

Non-Transgenic Options: Can produce "DNA-free" edits that do not contain foreign DNA, distinguishing it from older GMO technologies.

Challenges and Future Horizons

Despite its massive potential, CRISPR-Cas9 faces technical and regulatory hurdles. Off-target mutations, where the enzyme cuts unintended genomic sites, remain a technical concern, though newer variants of Cas9 are drastically reducing these errors. Regulatory frameworks vary globally. Some countries regulate CRISPR crops as traditional varieties, while others subject them to strict GMO legislation. As these policies evolve, CRISPR-Cas9 stands out as an indispensable tool to build a sustainable, food-secure future.

Unraveling the Water Needs of Broilers and Layers

G. Sri Manjula Reddy, I. Suresh Kumar Reddy and K. Madan Mohan Reddy

Abstract

Water is an essential nutrient in poultry production, playing a vital role in digestion, thermoregulation, and overall bird health. The water needs of poultry vary depending on their growth stage, breed, and environmental factors. Broilers and layers require specific water intake levels to maintain optimal productivity, with water consumption closely linked to feed intake. Proper hydration is especially crucial for egg-laying hens, as it influences eggshell quality and internal egg composition. Understanding these water requirements and ensuring proper water management is key to enhancing poultry health and farm efficiency.

Introduction

Water stands as a fundamental and often overlooked nutrient in poultry production, serving diverse functions crucial for bird health and productivity. From softening feed in the crop to aiding digestion, supporting temperature regulation and contributing to blood, lymph, and egg composition, water plays a pivotal role. Proper hydration is paramount for chickens, influencing their overall well-being. Water needs vary throughout different phases of poultry production, making it essential to understand these changing requirements. Here, we will discuss about the varying water requirements across poultry production stages.

Requirement of water in Broilers: 9.24 lit water is required from chick stage to slaughter age.

Water requirement based on type of bird (Ravindran, 2007)

Type of bird	Lit/100 birds day^{-1}
Layer pullets (growing birds)	10-13
Layer hens (Mature)	22
Breeder pullet (growing)	12-16
Breeder hen (Mature)	30
Broiler chicken	16-25

Based on feed intake: Water requirement is 2 times that of feed intake.

Age (Broilers)	Feed consumed (kg week^{-1})	Water intake (lit week^{-1})
1st week	0.13	0.26
2nd week	0.28	0.56
3rd week	0.47	0.94
4th week	0.64	1.28
5th week	0.85	1.7
6th week	1.07	2.14
7th week	1.18	2.36

Requirement of water in Layers: In laying hens, water is essential for optimal egg production. As, hydration directly affects the quality of eggshell and

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internal egg composition. Water is also required for calcium transport to the eggshell. In general, the water temperature for mature birds should be in between 10-15^{0}C for adequate consumption of water by birds.

	Feed consumed (g week^{-1})	Water intake (ml week^{-1})
1st week	77	154
2nd week	119	238
3rd week	175	350
4th week	224	448
5th week	259	518
6th week	294	588
7th week	322	644
8th week	350	700
9th week	378	756
Chick stage requires 4.4 lit day^{-1}		
Grower		
10th week	406	812
11th week	427	854
12th week	448	896
13th week	469	938
14th week	490	980
15th week	511	1022
16th week	532	1064
Grower stage requires 6.6 lit day^{-1}		
Pre lay		
17th week	560	1120
18th week	644	1288
19th week	742	1484
20th week	777	1554
21st week	826	1652
Pre lay stage requires 7.1 lit day^{-1}		

Laying hens take 4 lit water/12 eggs produced (North *et al.*, 1990)

Conclusion

Water is definitely one of the most vital nutrients in poultry production. Understanding its versatile role in crop function, digestion, thermo-regulation and complete health is of supreme significance. It is very essential to understand the growing water needs at each stage of poultry production to ensure that birds obtain the necessary hydration required for their well-being and efficiency. Adequate water management is not simply a duty; it is the basis of successful poultry production.

Cotton Crop: Cultivation Practices and Physiological Factors Affecting Growth and Yield

Pratiksha J. Goswami, Nachiket T. Chothani and Chandrakant Singh

Introduction

Cotton, popularly known as "White Gold," is one of the world's most important commercial fiber crops. It belongs to the genus Gossypium and family Malvaceae and is mainly cultivated for its lint fiber used in the textile industry. Cottonseed is also economically important because it is used for oil extraction and cattle feed. Major cotton-producing countries include India, China, United States, Brazil and Pakistan. In India, important cotton-growing states are Gujarat, Maharashtra, Punjab, Haryana and Rajasthan. Cotton is a tropical and subtropical crop that grows best in warm temperatures of 20°C-30°C with adequate sunshine and frost-free conditions. It performs well in deep black and well-drained loamy soils with a pH of 6.0-8.0. Proper water, nutrient and temperature management are essential because physiological factors such as photosynthesis, respiration, water relations, nutrient uptake and hormonal balance greatly influence germination, flowering, boll development, fiber quality and overall yield.

Botanical and Agronomic Information of Cotton

Scientific Classification

- ✓ Kingdom: Plantae
- ✓ Family: Malvaceae
- ✓ Genus: Gossypium
- ✓ Common species:
  - *Gossypium hirsutum* (American cotton)
  - *Gossypium arboreum*
  - *Gossypium barbadense*

Climatic Requirements: Cotton grows best in tropical and subtropical regions. Important climatic conditions include:

- ✓ Temperature: 21°C to 30°C
- ✓ Frost-free period: At least 180-200 days
- ✓ Rainfall: 50-100 cm annually
- ✓ Bright sunshine during boll formation and maturation
- ✓ Excess rainfall or cloudy weather negatively affects flowering and boll opening.

Soil Requirements: Cotton performs well in:

- ✓ Deep black cotton soils
- ✓ Well-drained loamy soils
- ✓ Soil pH between 6 and 8
- ✓ Waterlogging is harmful because it reduces oxygen availability to roots.

Growth Stages of Cotton Crop: Cotton growth can

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be divided into five major stages:

- ✓ Germination and emergence
- ✓ Seedling establishment
- ✓ Vegetative growth
- ✓ Flowering and boll formation
- ✓ Boll maturation and opening

Each stage is controlled by several physiological processes that determine final yield and fiber quality. The package of practices for cotton cultivation includes all scientific recommendations required for achieving higher yield and better fiber quality. Proper land preparation is the first important operation in cotton cultivation. The field should be deeply ploughed and followed by repeated harrowing and leveling to obtain a fine seedbed. Incorporation of farmyard manure or compost improves soil fertility, water-holding capacity and microbial activity. Good quality certified seeds should always be selected for sowing. Seed treatment with fungicides such as carbendazim or thiram helps protect the crop from seed-borne and soil-borne diseases, while insecticidal treatment helps in reducing early infestation of sucking pests.

Timely sowing and proper spacing are important for good cotton growth and reducing pests and diseases. Cotton needs balanced nutrients: nitrogen for plant growth, phosphorus for roots and flowering, and potassium for boll and fiber quality. Excess nitrogen should be avoided. Micronutrients like zinc, boron, and magnesium are also necessary. Proper irrigation, especially during germination, flowering, and boll development, is essential. Drip irrigation saves water and improves fertilizer efficiency. Weed control through weeding, inter-cultivation, and herbicides helps reduce competition.

Cotton is affected by pests like aphids, whiteflies, jassids, thrips, and bollworms. IPM practices such as resistant varieties, pheromone traps, natural enemies, and limited pesticide use are recommended. Diseases like wilt, root rot, blight, and leaf curl virus can be controlled through crop rotation, seed treatment, and sanitation. Harvesting is done in several pickings when bolls are fully open and dry to maintain fiber quality.

Physiological factors play a central role in determining cotton growth, development, yield and fiber quality. Photosynthesis is one of the most important physiological processes because it is responsible for the synthesis of carbohydrates required for plant growth and boll development. Cotton requires high solar radiation and healthy green leaves for efficient photosynthesis. Light intensity, chlorophyll content and leaf area index greatly influence the rate of photosynthesis. Excessive vegetative growth causes self-shading and reduces light penetration to lower leaves, thereby decreasing photosynthetic efficiency.

Physiological Factors Affecting Cotton Crop

Physiological factors are internal and external conditions influencing plant growth, metabolism and productivity. These factors directly affect photosynthesis, respiration, water balance, nutrient uptake, flowering and fiber development. The most specific physiological factors affecting cotton crop

are discussed below.

Photosynthesis

Photosynthesis is the process through which green plants convert sunlight into chemical energy.

$$6CO_2 + 6H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6O_2$$

Importance in Cotton

- ✓ Cotton is highly dependent on efficient photosynthesis for boll development.
- ✓ Leaves act as the primary source of carbohydrates.
- ✓ Photosynthates are transported to developing bolls and fibers.

Factors Affecting Photosynthesis

Light Intensity: High sunlight increases carbohydrate production. Cloudy weather reduces yield.

Leaf Area Index: Larger healthy leaf area enhances photosynthetic efficiency.

Chlorophyll Content: Nitrogen deficiency reduces chlorophyll formation and lowers photosynthesis.

Temperature: Optimal temperature improves enzymatic activity involved in photosynthesis.

Effect on Yield: Reduced photosynthesis causes:

- ✓ Boll shedding
- ✓ Smaller bolls
- ✓ Poor fiber quality
- ✓ Lower lint yield

Respiration

Respiration is the process of energy release from food materials inside plant cells.

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Energy}$$

Role in Cotton

- ✓ Provides energy for growth and metabolism
- ✓ Supports flowering and boll formation
- ✓ Helps nutrient transport

Physiological Impact; Excessively high temperatures increase respiration rates, causing:

- ✓ Loss of stored carbohydrates
- ✓ Reduced boll retention
- ✓ Lower productivity

Balanced respiration is essential for efficient growth.

Water Relations and Transpiration

Cotton is moderately drought-tolerant but requires sufficient moisture during flowering and boll development.

Transpiration: Transpiration is the loss of water vapor through stomata.

Importance

- ✓ Maintains plant temperature
- ✓ Helps nutrient transport
- ✓ Maintains cell turgidity

Water Stress Effects

Drought Stress	Excess Moisture	Critical Stages for Water
Leaf wilting	Root suffocation	Square formation
Reduced photosynthesis	Reduced nutrient uptake	Flowering
Flower and boll shedding	Increased disease incidence	Boll development
Reduced fiber elongation	Root suffocation	

Mineral Nutrition: Cotton requires balanced nutrients for physiological activities. Nutrient physiology is highly important in cotton production. Nitrogen is essential for protein synthesis and vegetative growth, phosphorus supports root development and energy transfer and potassium regulates stomatal movement, water balance and enzyme activation.

Potassium deficiency adversely affects boll opening and fiber quality. Micronutrients such as boron are necessary for pollen germination, flower retention and fiber development, while magnesium is a major component of chlorophyll and directly influences photosynthesis.

Nitrogen (N)

Functions	Deficiency Symptoms	Excess Nitrogen
Chlorophyll synthesis	Yellow leaves	Excess vegetative growth
Vegetative growth	Reduced leaf area	Delayed maturity
Protein formation	Poor growth	Increased pest attack

Phosphorus (P)

Functions	Deficiency Symptoms
Root development	Stunted growth
Energy transfer	Delayed maturity
Flowering and boll formation	

Potassium (K)

Functions	Deficiency Symptoms
Water regulation	Weak stems
Enzyme activation	Poor boll opening
Fiber development	Inferior fiber quality

Potassium is especially important for high-quality cotton fiber production.

Temperature: Temperature strongly influences cotton phys-iology. Extremely high temperatures increase respir-ation rates and reduce carbohydrate accumulation in reproductive parts. High temperatures also reduce pollen viability and increase flower and boll shedding. On the other hand, low temperatures delay germination, slow metabolic activities and delay crop maturity. Water availability strongly affects physiological activities because water is essential for nutrient transport, cell expansion and photosynthesis. Drought stress causes stomatal closure, reducing carbon dioxide uptake and photosynthesis. Severe moisture stress leads to flow-er drop, boll shedding, poor fiber elongation and reduced yield. Excessive water or waterlogging creates oxygen deficiency around roots, resulting in poor respiration, nutrient imbalance and root decay. Extreme temperatures reduce productivity signific-antly.

Optimum Temperature	High Temperature Effects	Low Temperature Effects
Germination: 18-30°C	Increased flower abortion	Delayed germination
Vegetative growth: 25-35°C	Reduced pollen viability	Reduced root activity
Fiber development: around 27°C	Faster respiration	Slow growth
	Poor boll retention	

Hormonal Regulation: Plant hormones regulate growth and development in cotton. Plant hormones also regulate various physiological processes in cotton. Auxins promote cell elongation and boll retention, gibberellins encourage stem elongation and cytokinins support cell division and delay leaf senescence. Excessive production of ethylene can result in premature leaf fall, flower shedding and boll abscission. During stress conditions, abscisic acid accumulates and induces stomatal closure to minimize water loss. Growth regulators such as mepiquat chloride are often used to control excessive vegetative growth and improve boll retention.

Auxins

- ✓ Promote cell elongation
- ✓ Help root development

Gibberellins

- ✓ Stimulate stem growth
- ✓ Enhance flowering

Cytokinins

- ✓ Promote cell division

- ✓ Delay leaf senescence

Ethylene: Excess ethylene causes:

- ✓ Leaf drop
- ✓ Boll shedding
- ✓ Premature aging

Abscisic Acid (ABA)

ABA increases during drought stress and causes stomatal closure to reduce water loss. Hormonal balance is critical for proper crop growth.

Flowering and Boll Retention

Factors Affecting Boll Retention; Cotton plants naturally produce more flowers than they can retain. Poor boll retention directly reduces yield.

- ✓ Moisture stress
- ✓ Nutrient imbalance
- ✓ High temperature
- ✓ Insect damage
- ✓ Hormonal imbalance

Fiber Development Physiology

Cotton fiber develops from epidermal cells of the seed coat. Fiber development has four stages:

- ✓ Fiber initiation
- ✓ Elongation
- ✓ Secondary wall thickening
- ✓ Maturation

Factors Affecting Fiber Quality

Temperature: Moderate temperatures improve fiber length.

Potassium Nutrition: Improves fiber strength and maturity.

Water Availability: Adequate moisture supports fiber elongation.

Photosynthate Supply: Carbohydrates are essential for cellulose deposition.

Stomatal Regulation

Stomata regulate gas exchange and water loss.

Importance

- ✓ Controls CO_2 entry
- ✓ Maintains transpiration balance
- ✓ Influences photosynthesis

Stress Conditions; under drought

- ✓ Stomata close
- ✓ CO_2 entry decreases
- ✓ Photosynthesis declines

Efficient stomatal regulation improves water-use efficiency.

Light and Photoperiod

Cotton is generally considered a day-neutral plant, but light intensity greatly influences growth.

Physiological Effects of Light

- ✓ Enhances photosynthesis
- ✓ Promotes flowering
- ✓ Improves boll opening

Shaded conditions reduce

- ✓ Dry matter production
- ✓ Fiber quality
- ✓ Yield

Root Physiology

Healthy root systems are essential for nutrient and water uptake.

Important Root Functions

- ✓ Water absorption
- ✓ Nutrient uptake

- ✓ Hormonal signaling
- ✓ Anchoring the plant

Factors Affecting Roots

Soil Compaction: Restricts root growth.

Waterlogging: Reduces oxygen supply.

Salinity: Causes osmotic stress and ion toxicity. Poor root development limits overall crop productivity.

Stress Physiology in Cotton

Cotton faces several environmental stresses. Stress conditions disturb physiological balance and reduce yield.

Abiotic Stresses	Biotic Stresses
Drought	Insect pests
Most common stress affecting cotton.	Diseases
Heat Stress	Nematodes
Causes pollen sterility and flower drop.	
Salinity	
Reduces germination and growth.	

Another important physiological aspect in cotton is the source-sink relationship. Leaves act as sources by producing carbohydrates through photosynthesis, while bolls, roots and shoots act as sinks by utilizing these assimilates. Cotton plants continuously produce vegetative and reproductive structures simultaneously, leading to competition for nutrients and carbohydrates. Excessive vegetative growth diverts assimilates away from developing bolls, thereby reducing yield. Balanced assimilate partitioning improves boll retention, lint yield and fiber quality. Source-Sink Relationship; Leaves are the "source" of carbohydrates, while bolls are the "sink." A strong source-sink relationship improves:

- ✓ Boll growth
- ✓ Fiber elongation
- ✓ Seed development

Flowering and boll development are highly sensitive stages in cotton physiology. Environmental stresses such as drought, high temperature, nutrient deficiency and pest attack can lead to heavy shedding of flowers and young bolls. Fiber development occurs through stages of initiation, elongation, secondary wall thickening and maturation. Adequate potassium supply, proper moisture availability and favorable climatic conditions are essential for obtaining superior fiber quality. Root physiology is equally important because healthy roots ensure efficient absorption of water and nutrients. Soil compaction, salinity, poor aeration and waterlogging negatively affect root growth and reduce overall plant productivity.

Modern Physiological Management Practices

Farmers and scientists use several practices to improve cotton physiology and productivity.

- ✓ Improved Irrigation
  - Drip irrigation
  - Scheduled watering
  - Moisture conservation
- ✓ Balanced Fertilization; Application of: NPK and Micronutrients
- ✓ Plant Growth Regulators; Used to:
  - Control excessive vegetative growth
  - Improve boll retention
  - Enhance maturity
- ✓ Stress-Tolerant Varieties

Development of drought- and heat-tolerant cotton cultivars helps maintain productivity under

changing climate conditions.

Conclusion

Cotton is one of the world's most important commercial fiber crops and its productivity largely depends on efficient physiological functioning and proper agronomic management. Physiological processes such as photosynthesis, respiration, water relations, nutrient uptake, hormonal regulation and assimilate partitioning directly influence plant growth, flowering, boll development, fiber quality and final yield. Among these factors, efficient photosynthesis, balanced mineral nutrition, proper water management and good boll retention are considered the most critical for achieving higher productivity. Environmental stresses such as drought, high temperature, salinity and waterlogging adversely affect these physiological activities, resulting in reduced growth, poor fiber development and lower yields. Therefore, successful cotton cultivation requires the integration of scientific farming practices with a sound understanding of crop physiology. Balanced fertilization, timely irrigation, effective weed management, integrated pest control and the use of stress-tolerant varieties are essential for maintaining healthy crop growth and maximizing yield potential. Understanding the physiological behavior of cotton plants enables farmers, agronomists and researchers to improve crop management strategies, enhance fiber quality and ensure sustainable cotton production under changing environmental conditions.

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Effect of Climate Change on Cropping Patterns in India

Himani Sharma and Banti

India is an agrarian country where agriculture supports the livelihood of millions of people and contributes significantly to the national economy. However, climate change has emerged as a major challenge for Indian agriculture. Rising temperatures, irregular rainfall, droughts, floods, and extreme weather events are directly affecting agricultural productivity and altering cropping patterns across different regions of the country. Climate change not only impacts crop yields but also influences the choice of crops, sowing time, irrigation practices, and farming systems. According to recent studies, increasing temperature and changing monsoon patterns are among the most important factors affecting crop production in India.

Meaning of Cropping Pattern

Cropping pattern refers to the proportion of area under different crops at a particular time and place. It depends on several factors such as climate, soil type, rainfall, irrigation facilities, market demand, and technological advancement. In India, cropping patterns vary from region to region due to diverse agro-climatic conditions. Climate change is now becoming one of the major factors influencing these cropping patterns.

Major Effects of Climate Change on Cropping Patterns in India

Changes in Rainfall Pattern: The Indian monsoon has become highly unpredictable due to climate change. Some regions experience excessive rainfall and floods, while others suffer from droughts and prolonged dry spells. This variability affects sowing and harvesting periods. Farmers are shifting from water-intensive crops like rice and sugarcane to drought-resistant crops such as millets, pulses, and oilseeds in many semi-arid regions.

Rise in Temperature: Increasing temperatures negatively affect crop growth and productivity. High temperatures accelerate crop maturity, reduce grain filling duration, and increase evapotranspiration. Studies indicate that wheat productivity may decline significantly under future warming scenarios. Similarly, maize yields are also expected to decrease due to heat stress.

Shift in Crop Seasons: Climate change is altering the traditional crop calendar in India. Delayed monsoon arrival and early withdrawal affect sowing schedules. Farmers are forced to modify planting dates and adopt short-duration crop varieties. For example: Delayed monsoon affects kharif crop sowing. Warmer winters reduce the duration of *rabi* crops like wheat and mustard. Some farmers are shifting towards multiple cropping or mixed cropping systems.

Regional Changes in Cropping Patterns: Different regions of India are experiencing different impacts:

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In northwestern India, declining groundwater and rising temperatures are reducing the sustainability of the rice-wheat system. In dry regions of Rajasthan and Maharashtra, farmers are increasingly adopting millets and pulses. Coastal regions face salinity intrusion and flooding, affecting paddy cultivation. Himalayan regions are witnessing changes in horticultural crops due to warming temperatures.

Increased Pest and Disease Incidence: Warmer temperatures and humidity create favorable conditions for pests, insects, and diseases. This increases crop losses and forces farmers to change cropping systems or crop varieties. For instance, pest outbreaks in cotton and rice-growing regions have become more frequent under changing climatic conditions.

Impact on Major Crops

Rice: Rice production is highly dependent on monsoon rainfall and water availability. Irregular rainfall and floods reduce rice productivity, especially in eastern India.

Wheat: Wheat is sensitive to temperature rise during grain filling stages. Even a small increase in temperature can reduce yield significantly.

Maize: Heat stress and moisture scarcity negatively affect maize productivity.

Pulses and Millets: Pulses and millets are relatively more climate-resilient and are gaining importance in drought-prone areas.

Adaptation Strategies

To reduce the adverse effects of climate change on cropping patterns, several adaptation measures are necessary:

- ✓ Adoption of climate-resilient crop varieties
- ✓ Promotion of millets and drought-tolerant crops
- ✓ Efficient water management through drip and sprinkler irrigation
- ✓ Crop diversification and mixed farming
- ✓ Use of weather forecasting and early warning systems
- ✓ Conservation agriculture practices
- ✓ Integrated nutrient and pest management

The Government of India has also launched initiatives such as the National Innovations in Climate Resilient Agriculture (NICRA) to help farmers adapt to climate variability.

Biochar as a Negative Emissions Technology: Science, Applications and Policy Dimensions

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Abstract

Biochar, a stable carbon-rich material produced by pyrolysis of organic biomass under oxygen-limited conditions, has re-emerged as a multifunctional tool for sustainable agriculture, climate change mitigation, and circular waste management. Rooted historically in the Amazonian terra preta soils, modern biochar is recognized as a negative emissions technology (NET) by the IPCC and is gaining traction in voluntary carbon markets and national climate policies. This article synthesizes current evidence on biochar's production pathways, physicochemical properties, agronomic and environmental benefits, socioeconomic relevance, and innovation frontiers, underscoring its transformative potential for a climate-resilient future.

Introduction

Global environmental pressures accelerating soil degradation, biodiversity loss, climate change, and mounting organic waste demand innovative, ecologically sound interventions. Among these, biochar has re-emerged as a versatile solution with ancient origins. A portmanteau of "biomass" and "charcoal," biochar is produced by thermochemical decomposition of organic matter under oxygen-limited conditions a process called pyrolysis. Indigenous peoples of the pre-Columbian Amazon basin exploited this principle over 2,000 years ago to create the extraordinarily fertile dark soils known as terra preta do Índio ("Indian dark earth"), which retain their remarkable productivity to this day (Lehmann and Joseph, 2015). Modern research has rediscovered biochar as a powerful tool in climate-smart agriculture, carbon sequestration and environmental remediation. Its alignment with circular bioeconomy principles and growing recognition in international policy frameworks including the IPCC Sixth Assessment Report (AR6) as a NET have elevated it from a niche agronomic amendment to a mainstream sustainability strategy (IPCC, 2022). This article provides a concise synthesis of biochar's science, applications, limitations and future directions.

Production and Properties

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Pyrolysis Pathways: Biochar is produced by heating biomass feedstocks including crop residues, wood chips, animal manure, sewage sludge, and organic municipal waste at 300-700°C in an oxygen-limited environment, yielding three co-products: biochar (solid), bio-oil (liquid), and syngas (H_2, CH_4, CO; gaseous). Slow pyrolysis (300-500°C, extended residence time) maximises solid biochar yield and is preferred for agricultural use; fast pyrolysis and gasification are optimised for liquid fuel and syngas generation, respectively (Bridgwater, 2012). Hydro-thermal carbonisation (HTC) is a complementary wet-process route producing "hydrochar" from high-moisture feedstocks, though its carbon stability is generally lower than pyrolytic biochar (Kambo and Dutta, 2015). Figure 1a illustrates comparative product yields across pyrolysis modes.

Physicochemical Properties: Biochar's agronomic and environmental utility stems from its distinctive physicochemical profile. Its highly porous, honeycomb-like microstructure confers a surface area that, depending on feedstock and temperature, typically ranges from 10 to over 400 $m^2\ g^{-1}$ (higher temperatures and woody feedstocks yield larger surface areas) (Downie *et al.*, 2009). Its fused aromatic carbon lattice is chemically recalcitrant key to long-term carbon storage while labile aliphatic fractions may decompose over shorter timescales, so reported mean residence times (MRTs) span decades to millennia depending on feedstock, temperature, and soil conditions (Singh *et al.*, 2012). Additional defining properties include alkaline pH (7-10), high cation exchange capacity (CEC; 10-50 cmol kg^{-1}), surface functional groups (carboxyl, hydroxyl, phenolic) that enhance contaminant sorption, and low bulk density that improves soil aeration (Lehmann and Joseph, 2015).

Agricultural and Environmental Benefits

Soil Health and Crop Productivity: Biochar improves soil physical, chemical, and biological properties through multiple mechanisms: increased water retention in sandy or drought-prone soils; enhanced nutrient retention via high CEC, reducing nitrogen and phosphorus leaching; pH correction in acidic soils; and provision of microhabitats for beneficial bacteria, fungi, and mycorrhizae (Atkinson *et al*., 2010). A landmark meta-analysis of 103 studies by Jeffery *et al*. (2011) found mean crop yield increases of 10-25% in nutrient-poor tropical and acidic soils; however, responses in temperate soils are frequently negligible or mixed, under-scoring the importance of soil-specific application guidelines. A more recent meta-analysis by Biederman and Harpole (2013), synthesising 114 studies, confirmed significant improvements in aboveground productivity, soil microbial biomass, and plant nutrient uptake.

Carbon Sequestration and Climate Mitigation: Biochar's aromatic carbon lattice renders it far more resistant to microbial mineralisation than compost or crop residues. Woolf *et al*. (2010) estimated that a global sustainable biochar programme could sequester up to 1.8 Gt CO_2-equivalent per year under optimistic feedstock assumptions a modelled theoret-

ical upper bound, not a near-term projection. Beyond direct carbon storage, biochar-amended soils consistently show reduced emissions of nitrous oxide (N_2O; global warming potential 273 × CO_2 over 100 years, per IPCC AR6) and methane (CH_4; 27.9 × CO_2, 100-year; 81.2 × over 20 years) (IPCC, 2021; Liu *et al.*, 2022). Figure 1b summarises key GHG mitigation pathways.

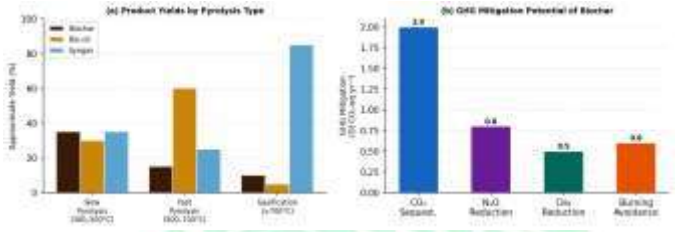

Figure 1. (a) Approximate product yields (%) by pyrolysis process type. (b) Estimated GHG mitigation potential (Gt CO_2-eq yr^{-1}) of global biochar application across major emission pathways (after Woolf *et al*., 2010; Liu *et al*., 2022).

Waste Valorisation and Circular Bioeconomy: Pyrolysis converts agricultural residues, forestry by-products, sewage sludge, and urban organic waste into high-value co-products, diverting biomass from open-field burning, landfill, or uncontrolled decomposition all significant sources of greenhouse gases (Roberts *et al.*, 2010). The resulting biochar, bio-oil, and syngas embody circular bioeconomy principles, transforming waste liabilities into soil amendments, energy carriers and chemical feed-stocks. Figure 2 illustrates this integrated value chain.

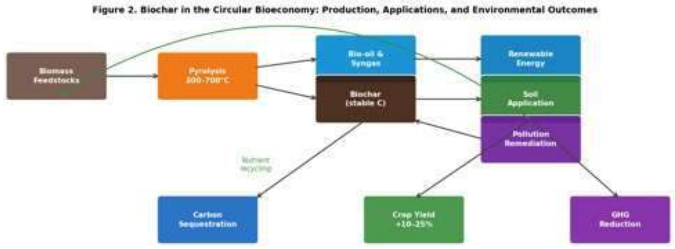

Figure 2: Schematic of biochar within the circular bioeconomy, from feedstock collection through thermochemical conversion to agronomic and environmental outcomes.

Pollution Remediation: Biochar's high surface area and surface charge facilitate immobilisation of heavy metals (Pb, Cd, As), persistent organic pollutants, and pesticides in soils and water. Beesley *et al.* (2011) demonstrated significant reduction in Pb and Cd mobility in contaminated soils, while Mohan *et al.* (2014) documented effective As removal from aqueous systems using wood-derived biochar. Applications span constructed wetlands, stormwater bioretention filters, and brownfield rehabilitation.

Socioeconomic and Policy Dimensions: For smallholder farmers in Sub-Saharan Africa and South Asia, low-cost kiln technologies including flame curtain kilns and cone kilns enable on-farm biochar production from locally available residues (Whitman *et al.*, 2011). Field programmes in Kenya (ICRAF, 2013) and India (Suman *et al.*, 2016) reported measurable improvements in soil fertility, crop yields, and in some cases farm income, alongside rural employment benefits in feedstock collection and processing. At the policy level, the IPCC AR6 formally recognises biochar as a viable NET (IPCC, 2022). Countries including the UK, Germany, and Australia are exploring biochar's inclusion in Nationally Determined Contributions (NDCs) under the Paris Agreement. Standardised carbon accounting methodologies are being developed by registries including Puro.earth and Verra (BCM0001), enabling biochar-linked carbon

credits in voluntary markets and potentially unlocking substantial private investment (Fuss *et al*., 2018).

Limitations and Challenges

Economic barriers: Capital costs for pyrolysis systems remain prohibitive for smallholders without financing or subsidy support.

Feedstock logistics: Collecting, drying, and transporting dispersed biomass is labour-intensive and economically marginal in many regions.

Standardisation gap: Absence of universally accepted quality standards (carbon content, heavy metal thresholds, pH, surface area) causes product variability and undermines market confidence. The European Biochar Certificate (EBC) and IBI Biochar Standards are steps toward harmonisation, but global adoption remains incomplete.

Land-use conflicts: Dedicated energy crops for pyrolysis feedstock could compete with food production or incentivise land-use change in deforestation-sensitive regions.

Evidence gaps: Long-term field trials across diverse agroecological zones and cropping systems are still needed to validate decadal-scale performance and establish robust application guidelines (Jeffery *et al.*, 2017).

Overcoming these barriers will require coordinated investment in R&D, enabling policy environments, accessible financing, and inclusive stakeholder engagement.

Innovations and Future Prospects

Engineered biochars with tailored properties represent a rapidly expanding research frontier: nutrient-enriched biochars (N, P, K-loaded) function as slow-release fertilisers; magnetised biochars enhance heavy metal removal from water; alkali-activated biochars target specific pollutant streams; and co-pyrolysis with sewage sludge recovers phosphorus in plant-available forms (Rajapaksha *et al.*, 2016). Integrated pyrolysis-bioenergy systems co-producing bio-oil and syngas for local heat and power alongside marketable biochar substantially improve economic viability, particularly for off-grid rural communities (Woolf *et al.*, 2010). Urban applications are gaining momentum: biochar-amended tree pit substrates improve stormwater management and urban heat island mitigation in cities including Stockholm and Singapore (Veg Tech, 2020). Evaluation as a concrete and asphalt additive for embodied carbon reduction is ongoing (Gupta and Kua, 2017). Collectively, these innovations broaden biochar's societal reach well beyond agricultural contexts.

Conclusions

Biochar stands at a productive convergence of environmental science, agronomy, and sustainable development. Its capacity to improve soil health, sequester atmospheric carbon, valorise organic waste, and remediate contamination offers a rare combination of co-benefits. With formal recognition as a NET by the IPCC, growing integration into carbon markets, and an expanding body of evidence from field trials and meta-analyses, biochar is transitioning from a niche amendment to a main-

stream sustainability tool. Realising its full potential requires sustained research investment to close evidence gaps, enabling regulatory frameworks, accessible financing for smallholder producers, and harmonised international quality standards. This ancient "black earth" may yet prove indispensable to a climate-resilient future.

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Next-Gen Farming: Integrating AI, IoT and Drones

Brijesh Kumar Yadav, Beena Khorwal, Omkar Gupta and Dattatraya V. Patil

Introduction

Agriculture is one of the oldest and most important sectors in the world, providing food and raw materials for human life. With the increase in population and the growing demand for food, traditional farming practices alone are no longer sufficient to meet future requirements. Farmers face several challenges such as climate change, shortage of water resources, increasing labour costs, pest attacks, and soil degradation. Therefore, modern agriculture is gradually shifting toward advanced technological solutions that can improve productivity and ensure sustainable use of resources.

Next-generation farming is an advanced approach that integrates modern technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and drones into agricultural practices. These technologies work together to create smart farming systems capable of collecting real-time information, analysing field conditions, and helping farmers make accurate decisions. Unlike conventional farming methods, smart farming allows farmers to manage crops with greater precision and efficiency. The combination of AI, IoT, and drones helps in reducing wastage, improving crop quality, and increasing overall farm productivity.

Artificial Intelligence in Agriculture

Artificial Intelligence refers to the ability of computer systems and machines to perform tasks that normally require human intelligence. AI systems can learn from data, recognize patterns, analyse information and make predictions. In agriculture, AI has become an important technology because it helps farmers manage their fields more effectively and make informed decisions.

AI can process a large amount of agricultural data collected from different sources, including sensors, weather stations, satellite images, and drones. The technology analyses this information and identifies patterns that may not be easily recognized by humans. For example, AI systems can detect crop diseases at an early stage by examining images of plants and identifying symptoms before they become visible to the human eye. Early detection helps farmers take corrective measures quickly and reduce crop losses.

AI can also predict crop yields by analysing weather conditions, soil properties, and historical data. Such predictions help farmers plan harvesting activities and estimate production levels more accurately. Additionally, AI-based systems can recommend suitable fertilizers, irrigation schedules, and pest control measures according to crop requirements. The use of AI in agriculture improves efficiency and reduces human effort. Farmers can save time, reduce operational costs, and increase

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productivity by using AI-based solutions.

Internet of Things in Agriculture

The Internet of Things is a technology that connects various devices and sensors through the internet, enabling them to collect and exchange data automatically. In agriculture, IoT devices are used to monitor field conditions continuously and provide real-time information to farmers.

Different types of sensors are installed in agricultural fields to measure factors such as soil moisture, temperature, humidity, light intensity, and nutrient levels. These sensors collect information and transmit it to cloud-based platforms through internet connectivity. Farmers can access this information through mobile applications or computer systems and monitor field conditions from any location.

IoT technology plays a major role in smart irrigation systems. Traditional irrigation methods often lead to excessive water use and resource wastage. However, IoT-based irrigation systems can monitor soil moisture levels continuously and supply water only when necessary. This approach conserves water and improves crop growth. IoT also helps farmers monitor environmental conditions in green-houses and livestock farms. Real-time monitoring improves efficiency and helps prevent crop damage due to sudden changes in environmental conditions.

Drones in Agriculture

Drones are unmanned aerial vehicles that are increasingly being used in agriculture for monitoring and managing agricultural activities. Agricultural drones are equipped with cameras, sensors, GPS systems and imaging technologies that help farmers observe field conditions from above.

Fig. 1: Crop Monitoring using Drone

Drones can capture high-resolution images and videos of crop fields, allowing farmers to monitor crop growth and detect problems more efficiently. They provide detailed information about plant health, soil conditions, irrigation issues, and pest infestations. One important application of drones is crop health monitoring. By capturing images of crops at different growth stages, drones help identify stressed areas where plants may be suffering from nutrient deficiency, disease, or water shortage. Early identification of such problems allows farmers to take immediate action. Drones are also used for spraying pesticides and fertilizers. Compared to traditional methods, drone spraying is more precise and reduces the amount of chemicals used in the field. This improves efficiency and minimizes environmental impact. In addition, drones help in field mapping and yield estimation. Farmers can use aerial images to create maps of their fields and analyse crop conditions more effectively.

Integration of AI, IoT and Drones

The true potential of smart farming is achie-ved when AI, IoT, and drones work together as an

integrated system. IoT devices collect data from the field continuously, while drones gather aerial images and visual information about crop conditions. Artificial Intelligence then processes and analyses this data to generate useful recommendations. For example, sensors installed in the soil may detect low moisture levels in a particular section of the field. At the same time, drones may identify poor crop growth in that area through aerial images. AI systems analyze both datasets and suggest irrigation or fertilizer requirements for that specific location.

This integrated approach supports precision agriculture, where farming practices are applied according to the specific needs of individual sections of a field rather than treating the entire field uniformly. Precision agriculture improves efficiency and increases crop yield.

Advantages of Next-Generation Farming

Next-generation farming offers several benefits for modern agriculture. It helps increase productivity by enabling better crop management practices. Farmers can use resources such as water, fertilizers, and pesticides more efficiently, reducing waste and lowering production costs. These technologies also improve decision-making by providing accurate and real-time information. Labour requirements can be reduced because many farming operations become automated. Furthermore, smart farming supports sustainable agricultural practices by reducing environmental impacts and promoting efficient use of natural resources.

Challenges of Next-Generation Farming

Despite its advantages, next-generation farming faces certain challenges. The initial cost of implementing AI systems, IoT devices, and drones can be high, making adoption difficult for small-scale farmers. Technical knowledge and training are also required to operate these technologies effectively. Internet connectivity is another important factor because many smart farming systems rely on online data transmission. In rural areas, limited internet access may create difficulties. Data security and privacy concerns may also arise due to the large amount of information being collected and stored.

Future Scope

The future of agriculture is expected to become more advanced with the development of intelligent machines and automation systems. Technologies such as robotic harvesting, autonomous tractors, machine learning algorithms, and advanced drone systems will further improve agricultural productivity. Future farming systems may become capable of performing most operations automatically with minimal human intervention. These innovations will help meet increasing food demands and contribute to sustainable agricultural development.

Fig. 2: Application of Drones in Agriculture

Conclusion

Next-generation farming through the integration of Artificial Intelligence, Internet of Things, and drones is revolutionizing modern agriculture. These technologies provide efficient and intelligent solutions for crop monitoring, resource management, and decision-making. They improve productivity, reduce operational costs, and support sustainable farming practices. Although certain challenges exist, continuous technological advancement and increased awareness among farmers will make smart farming more accessible and beneficial in the future.

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Urban Horticulture: Turning Small Spaces into Big Opportunities

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Abstract

Urban horticulture has emerged as a transformative approach to food production in response to unprecedented urbanization rates. This article examines how confined urban spaces balconies, rooftops, abandoned lots, and vertical wall surfaces can be converted into productive growing systems that generate significant economic, nutritional, and environmental returns. Evidence indicates that small scale urban horticulture is not merely a recreational hobby but a viable strategy for enhancing food security, improving public health, mitigating urban heat islands, and creating micro enterprise opportunities. This synthesis demonstrates that with appropriate method selection, spaces as small as four square feet can yield substantial produce annually, while advanced hydroponic systems achieve productivity multiple times higher than traditional soil based methods.

Introduction

The twenty-first century has witnessed an unprecedented demographic shift toward urban living. As cities expand vertically and horizontally, green spaces per capita continue to decline, creating what researchers term the "urban green deficit." This reduction in accessible natural space coincides with growing concerns about food system vulnerabilities, supply chain disruptions, and the carbon footprint associated with long-distance food transport. The COVID-19 pandemic served as a critical wake-up call, exposing the fragility of just-in-time food supply chains and prompting renewed interest in localized food production. Empty supermarket shelves and volatile produce prices drove both policymakers and citizens to reconsider the potential of urban agriculture.

In response, cities across Europe and North America have passed "right to grow" motions, granting communities access to public land for horticultural purposes. Urban horticulture refers specifically to the cultivation of fruits, vegetables, herbs, and ornamental plants within city limits, utilizing both traditional and innovative growing methods adapted to space constraints. Unlike conventional agriculture, which requires extensive land holdings, urban horticulture prioritizes spatial efficiency, rapid crop turnover, and integration with built infrastructure.

Why urban horticulture matters

Urban horticulture provides multiple benefits:

Food Security: Fresh vegetables and herbs can be grown at home, reducing dependence on market supply.

Health Benefits: Access to pesticide-free produce

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improves nutrition and well-being.

Environmental Impact: Green spaces reduce heat, improve air quality, and support biodiversity.

Economic Potential: Sale of fresh produce, seedlings and gardening services can generate income.

This combination of personal, environmental and economic gains makes urban horticulture highly relevant in modern cities.

Productive potential of small spaces

Contrary to conventional wisdom, small urban spaces can achieve remarkable levels of food production when properly managed. The key lies in shifting from two dimensional thinking (square footage) to three-dimensional thinking (cubic volume), utilizing vertical space, stacking systems, and rapid succession planting. Hydroponic systems have demonstrated significant performance advantages over traditional soil cultivation in confined urban settings. Static hydroponic methods produce fresh weight increases exceeding ten percent and dry weight increases exceeding fifty percent compared to soil controls. Circulating hydroponic systems achieve even higher quality improvements, enhancing vitamin C content and sensory quality by substantial margins. At a larger scale, container-based vertical farming using Nutrient Film Technique (NFT) systems retrofitted into standard shipping containers with LED lighting and climate control enables continuous year-round production cycles independent of external weather conditions.

Economic opportunities

Microgreens Enterprise: Microgreens production requires only 10 to 20 square feet of space yet generates 20 to 20 to 40 per tray, with 5 to 7 harvest cycles possible annually.

Mushroom Cultivation: Specialty mushrooms grown in basements or spare closets yield 10 to 10 to 20 per square foot per year using low-cost substrate materials such as straw or coffee grounds.

Restaurant Supply Contracts: Culinary herbs and edible flowers sold directly to restaurants command premium prices of 15 to 30 per pound, with continuous harvest cycles in controlled environments.

Vertical Farm Profitability: Retrofitted shipping container farms (320 square feet) achieve annual revenues of 50,000 to 100,000 for leafy greens and herbs in dense urban markets.

Value-Added Products: Dried herbs, pickled vegetables, and hot sauces increase per-unit value by 200 to 500 percent compared to raw produce, while extending shelf life significantly.

Environmental and health benefits

- ✓ Reduces the urban heat island effect, lowering ambient temperatures and building cooling costs.
- ✓ Enhances environmental quality through carbon sequestration, air purification, and storm water management.
- ✓ Supports biodiversity by providing habitats for pollinators, birds, and beneficial insects.
- ✓ Creates ecological corridors by integrating edible and ornamental plants within urban spaces.
- ✓ Improves public health by promoting mental well-being, social interaction, physical activity, and environmental awareness.

Challenges and evidence-based solutions

- ✓ Manages soil contamination through raised beds with protective barriers, use of certified clean soil, and long-term phytoremediation using species like sunflower and mustard.
- ✓ Addresses limited sunlight by selecting shade-tolerant crops (lettuce, spinach, mint, chard), using reflective surfaces and applying supplemental LED lighting.
- ✓ Improves water efficiency through rainwater harvesting, self-watering wicking beds, and hydroponic systems that significantly reduce water use.
- ✓ Reduces theft and vandalism with community signage, protective plantings, and engagement of local residents to build stewardship.
- ✓ Navigates regulatory constraints by promoting ornamental edibles, highlighting property value benefits, and advocating for supportive urban agriculture policies.

Conclusion

Urban horticulture has evolved from a niche activity into a vital component of modern urban sustainability. Even small spaces can achieve high productivity through methods such as hydroponics and controlled environment systems, contributing to household food security and potential income generation. Its benefits extend far beyond food production, encompassing improved mental and physical health, stronger social cohesion, climate change mitigation, biodiversity support and effective storm water management.

At the same time, technological advancements in LED lighting, sensors, and automation are making urban food production more efficient and economically viable. Integrating urban horticulture into mainstream urban planning can transform underutilized spaces into productive assets, enhancing resilience, sustainability, and overall quality of urban life.

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Common Drone Failures in Agriculture and How to Fix Them

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Introduction

Agriculture is becoming more advanced with the use of modern technologies such as Artificial Intelligence (AI), Internet of Things (IoT), robotics, and drones. Among these technologies, agricultural drones have become one of the most useful tools in modern farming. Drones are unmanned aerial vehicles (UAVs) that help farmers in crop monitoring, pesticide spraying, field mapping, irrigation management, and yield estimation. These drones improve farming efficiency, reduce labour costs, save time, and support precision agriculture. Agricultural drones are equipped with advanced technologies such as cameras, GPS systems, sensors, and spraying equipment. They can collect real-time information from fields and help farmers identify crop diseases, pest attacks, nutrient deficiencies, and water stress at an early stage.

Fig. 1: Drone Failure

This allows farmers to make better decisions and improve crop productivity. However, despite their advantages, agricultural drones may face several technical and operational failures during use. These failures can interrupt agricultural operations, reduce efficiency, increase maintenance costs and sometimes lead to accidents or crop damage. Therefore, understanding common drone failures and learning how to fix them is important for farmers and drone operators.

Battery Failure and Power Problems: Battery failure is one of the most common problems faced in agricultural drones. Since drones depend completely on batteries for flight operations, poor battery performance can seriously affect agricultural activities. Batteries may fail because of overcharging, excessive discharge, overheating, long working hours, or improper storage conditions. Sometimes the drone may suddenly lose power during operation, which can cause crashes or incomplete spraying tasks. Old or damaged batteries also reduce flight time and affect drone performance. In agricultural fields, where large areas need to be covered, battery issues can delay farming operations and reduce efficiency.

Battery failure also increases maintenance costs because damaged batteries are expensive to replace. Poor battery management may additionally

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affect other electronic components of the drone. To solve battery-related problems, farmers should use high-quality batteries recommended by the manufacturer. Batteries should be charged properly and should not be overcharged. It is important to store batteries in cool and dry places because high temperatures reduce battery life. Operators should regularly inspect batteries for swelling, leakage, or physical damage. Carrying backup batteries during field operations also helps avoid interruptions. Proper battery maintenance improves flight safety, increases drone lifespan, and ensures smooth agricultural operations.

GPS and Communication Failure: Agricultural drones depend heavily on GPS systems and communication technology for navigation, automated flight paths, field mapping, and spraying operations. Weak GPS signals or communication failures can affect drone stability and reduce operational accuracy. GPS problems usually occur because of poor weather conditions, weak satellite connectivity, tall trees, mountains, electromagnetic interference, or flying near high-voltage power lines. Communication failures may also happen because of weak controller signals, low battery levels, software glitches, or long-distance operations. When GPS signals become weak, drones may lose navigation accuracy and spray chemicals unevenly across fields. In some cases, drones may drift away from their intended flight path or completely lose control. Communication failure between the drone and remote controller may delay commands or interrupt operations. These problems can lead to poor field coverage, wastage of pesticides and fertilizers, reduced crop protection, and higher chances of accidents. To prevent GPS and communication failures, operators should always fly drones in open areas with minimal interference. GPS systems should be calibrated before every operation, and signal strength should be checked carefully. Drone firmware and software should be updated regularly because updates improve connectivity and navigation performance. Farmers should also avoid operating drones near communication towers or strong electromagnetic sources. Maintaining the drone within the recomm-ended operating range improves communication quality and operational safety.

Motor, Propeller and Spraying System Problems: Motors and propellers are among the most important components of agricultural drones because they help maintain stable flight and lifting power. Similarly, spraying systems are essential for applying pesticides, fertilizers, and herbicides accurately on crops. Motor and propeller failures may occur because of dust accumulation, loose connections, physical damage, excessive vibration, or wear and tear caused by continuous operation. Damaged propellers reduce flight stability and may cause the drone to crash. Faulty motors also reduce spraying accuracy and increase energy consumption. Spraying system problems are also common in agricultural drones. These failures may happen because of clogged nozzles, pump malfunction, leakage in pipes

or tanks, and chemical residue buildup. Uneven spraying reduces crop protection and may result in poor pest control and lower agricultural productivity.

If spraying systems fail during operation, chemicals may not be distributed equally across the field, causing wastage of pesticides and fertilizers. Leakage problems can also harm the environment and increase operational costs. To solve these problems, farmers should regularly inspect motors, propellers, pumps, and spraying equipment. Propellers should be replaced immediately if they are damaged. Motors should be cleaned regularly to remove dust and dirt. Spraying tanks, pipes, and nozzles should also be cleaned after every operation. Using filtered chemicals and clean water helps prevent nozzle blockage. Operators should carry spare propellers and essential repair tools during field operations. Proper maintenance improves spraying efficiency, drone stability, and overall farming performance.

Software, Sensor and Weather-Related Problems : Modern agricultural drones depend on advanced software systems, cameras, and sensors for automated flight operations, crop monitoring, and data collection. Software or sensor failure can seriously reduce the effectiveness of precision agriculture. Software problems may occur because of outdated firmware, installation errors, system bugs, or corrupted files. These errors may cause unstable flight, navigation failure, delayed responses, or system crashes. Sometimes the drone may stop functioning properly during operation because of software malfunction. Cameras and sensors may also fail because of dust, water exposure, improper calibration, or physical damage. Malfunctioning sensors reduce the accuracy of crop analysis, field mapping, and disease detection. Poor image quality may affect farmers' decision-making ability and reduce farming efficiency. Weather conditions are another major reason for drone failure. Strong winds, heavy rainfall, fog, high humidity, and extreme temperatures can affect drone stability and damage electronic components. Flying drones in bad weather increases the risk of accidents and reduces operational efficiency. To fix software-related problems, operators should install regular firmware and software updates from official manufacturer websites. Drones should be recalibrated after updates to ensure smooth operation. Cameras and sensors should be cleaned regularly and protected from water or dust exposure. Farmers should always check weather forecasts before operating drones. Drone flights should be avoided during storms, heavy winds, or rainfall. Operating drones under suitable weather conditions improves safety, efficiency and equipment lifespan.

Importance of Maintenance and Prevention: Regular maintenance is one of the most effective ways to prevent drone failures in agriculture. Proper maintenance improves operational safety, reduces repair costs, increases drone lifespan, and ensures better farming performance. Maintenance activities include battery inspection, cleaning motors and propellers, checking spraying systems, calibrating

sensors, updating software and testing communication systems. Regular inspections help identify problems before they become serious. Farmers and drone operators should maintain maintenance records and follow manufacturer instructions carefully. Training programs should also be provided to operators so that they can handle drones safely and solve technical problems effectively. Preventive maintenance not only reduces equipment failure but also improves agricultural productivity and resource efficiency. Well-maintained drones provide better spraying accuracy, improved crop monitoring, and more reliable field analysis

Conclusion

Agricultural drones are transforming modern farming by improving crop monitoring, reducing labour requirements, and supporting precision agriculture. However, common failures such as battery problems, GPS signal loss, motor damage, spraying system malfunction, software errors, and weather-related issues can affect drone performance and agricultural operations. Understanding these failures and applying proper maintenance practices help farmers operate drones safely and efficiently. Regular inspections, timely repairs, software updates, and correct operational methods can significantly reduce drone failures and improve productivity. With continuous advancements in drone technology, agricultural drones are expected to become more intelligent, reliable, and efficient in the future. These improvements will support sustainable agriculture, increase food production, and help farmers manage resources more effectively.

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Good Bugs vs Bad Bugs

Rohit Raman and Rittik Sarkar

Abstract

This article examines the complicated and often misunderstood role of insects in agriculture. It points out that less than 1% of insect species are harmful pests. The article contrasts the negative effect of herbivorous pests, which damage about 18% of global agricultural production, with the significant economic and ecological value of beneficial insects. These helpful species offer important ecosystem services, such as pollination and natural pest control, contributing hundreds of billions of dollars to global agriculture each year. It concludes that protecting and fostering beneficial insects is vital for global food security, reducing environmental harm, and creating resilient agricultural systems.

Introduction

When we think about farming, we often picture golden wheat fields, long rows of corn, or orchards full of fruit. Yet beneath this scenic beauty lies a hidden world of constant activity a complex ecosystem where billions of tiny creatures engage in daily struggles that determine the fate of our food supply. Insects are the most diverse group of organisms on Earth, with over one million known species. In agricultural settings, they play remarkable roles. Less than 1% of insect species are harmful pests, but these few cause billions of dollars in crop damage each year. The majority of insects in our fields and orchards are either beneficial to agriculture or harmless onlookers.

Understanding the fragile balance between beneficial and harmful insects is essential for the future of sustainable agriculture. As farmers around the world face the challenges of climate change, pesticide resistance, and a growing demand for food, the natural services provided by beneficial insects are more important than ever.

Fig. 1: The ladybug (ladybird beetle) is one of agriculture's most valuable allies, consuming up to 5,000 aphids in its lifetime

The Good: Beneficial Insects and their Value

Beneficial insects provide valuable services to agriculture, worth billions of dollars each year. These services mainly include pollination and pest control. Together, they form the base of much of our food production.

Pollinators: Nature's Crop Boosters

Pollination is one of the most visible and well-known services insects offer. According to the

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Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the economic value of pollination services to global agriculture ranges from $235 to $577 billion annually. This impressive figure reflects the contributions of honey bees, native bees, butterflies, moths, flies, and other pollinators to crop production worldwide.

Figure 2: Honey bees are the most valuable agricultural pollinators, responsible for pollinating over 100 commercial crops in North America

The relationship between pollinators and crops is very specific. About 35% of global crop production relies on animal pollinators to some extent. Crops such as almonds, apples, blueberries, cherries, coffee, and cocoa heavily depend on insect pollination. Some of these crops need pollinator visits for successful fruit development.

Predators and Parasitoids: Natural Pest Control

While pollinators work during the day, predatory and parasitic insects tirelessly fight against agricultural pests at all hours. A major study by Losey and Vaughan (2006) estimated that the pest control services provided by beneficial insects to U.S. agriculture are worth around $4.5 billion annually.

Figure 3: Green lacewings are voracious predators of aphids, mites, and other soft-bodied pests

Lady beetles (ladybugs), lacewings, predatory mites, parasitic wasps, and ground beetles are some of the most important natural enemies of agricultural pests. A single lady beetle can eat up to 5,000 aphids in its lifetime. Parasitic wasps, despite their small size, have a significant impact by laying eggs inside pest insects. Their larvae eventually kill the host.

The Bad: Agricultural Pests and their Impact

In spite of natural enemies, agricultural pests pose a major challenge for farmers globally. Herbivorous insects damage about 18% of world agricultural production, leading to losses worth hundreds of billions of dollars every year. Recent data from the Crop Protection Network highlights the effects of invertebrate pests on U.S. crop production. In 2024, these pests reduced soybean yields by 1.4% across reporting states, with total management costs surpassing $843 million.

The Balance: Integrated Pest Management

The path to sustainable agriculture does not lie in eradicating all insects but in managing the balance between helpful and harmful species. Integrated Pest Management (IPM) is a broad appro-

ach that combines biological, cultural, and chemical methods to control pests while reducing environmental harm.

IPM strategies that focus on beneficial insects have shown notable success. Studies indicate that diverse landscapes with flowering plants encourage higher populations of natural enemies, which leads to better pest control. Farmers can support beneficial insects through various practices: planting strips of flowering plants, minimizing the use of broad-spectrum pesticides, providing habitats like beetle banks, and considering beneficial insects when choosing pest control products. These methods not only assist with natural pest management but can also lower costs and improve long-term sustainability on farms.

Conclusion

The relationship between farmers and insects is intricate and often misunderstood. Instead of seeing all insects as threats, successful agriculture involves recognizing the essential roles that beneficial species have in pollination and pest control. The economic value of these services, amounting to hundreds of billions of dollars, highlights their significance for global food security. As we work to feed a growing population while minimizing environmental impact, the natural services offered by beneficial insects become more important. By understanding and supporting these small allies, farmers can develop more resilient, sustainable, and productive agricultural systems. The message is clear: good bugs are not just nice to have; they are crucial partners in agriculture. Protecting and promoting beneficial insects is not merely an act of kindness toward nature. It is a wise business choice that benefits farmers, consumers, and the environment.

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Chlorine: An Essential Micro-nutrient for Higher Plants

Mrinal Choudhury and Britan Rahman

Abstract

Chlorine (Cl) occurs predominantly as Cl^- in soil and plant. It is an essential micronutrient of higher plants and participates in several physiological metabolic processes. Its functions in plant growth and development include osmotic and stomatal regulation, evolution of oxygen in photosynthesis, and disease resistance and tolerance. At adequate levels of supply, Cl improves the yields and quality of many crops such as onions and cotton if the soils are deficient in this nutrient. When excessive, Cl can be a major component of salinity stress and toxic to plants.

Introduction

Natural inputs of Cl to soils come mainly from rainwater, sea water, dust, and air pollution. In addition, human practices, such as irrigation and fertilization, contribute significantly to Cl deposition. The rates of Cl deposition to soils range from 1 to >1000 kg ha^{-1}, depending on location and cultural practices.Chlorine occurs predominantly as Cl^- in soil and plants. Chlorine is an essential micronutrient for higher plants and participates in several physiological processes. It is also ascribed as a main resource of salinity stress. This article provides a brief review of current progresses on Cl nutrition of higher plants.

Availability of chlorine in soils: The content of Cl^- varies greatly in soils. The plant available form of Cl is mainly Cl^- anion. Plants may be able to take up some metal-Cl complex such as $CdCl^+$, but with a minimal percentage. The Cl^- anion does not form complexes readily and since mineral soils mainly carry negative charge, Cl^- tends to be repelled from the surfaces of soil particles. Thus the concentration of Cl^- in the bulk solution is greater than in the diffuse layers surrounding soil particles. The movement of Cl^- within the soil is determined by water fluxes, and in particular, the relationship between precipitation and evapo-transpiration. During mineral weathering and soil development, Cl^- is readily leached out at early stages. Therefore, Cl^- concentration in most well-developed soil is low unless there is good input from rainfall, fertilizers, and irrigation. In the arid and semi-arid areas, Cl^- tends to be accumulated in the soil due to high evaporation/rainfall ratio, which drives salts from deeper soil layers to the surface. In these regions, salt stress and Cl toxicity may pose a challenge to crop production. In contrast, in the humid area, particularly tropical and subtropical regions, high rainfall often results in thorough leaching of Cl^- from soils and subsequent deficiency of Cl^- for plants. Fortunately, the internal requirement of Cl^- for most crop plants is small, and the inputs of Cl^- from

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rainfall, air pollution, fertilizers as secondary element, and irrigation may suffice their needs for normal growth. Therefore, Cl^- deficiency in crops does not occur frequently. However, with the cleaning of air, water, and increased purity of fertilizers, Cl^- deficiency may become an issue in the tropical and subtropical regions, particularly for those sensitive crops such as onion and kiwi. For some crops such as wheat, barley, and maize, application of Cl^- fertilizers may increase their yield, and for cotton, Cl fertilizer can improve fibre quality if the soil is deficient in Cl.

Function of chlorine in higher plants: Chlorine plays an essential role in stomatal regulation. The opening and closure of stomata is mediated by the fluxes of potassium and accompa-nying anions such malate and chloride. Cl is necessary for the water splitting reaction, or Hill reaction, in photosystem II. Besides manganese, chloride plays a fundamental role in the water-splitting system of PSII. Chlorine may either act as a bridging ligand for stabilization of the oxidized state of manganese, or as a structural component of the associated (extrinsic) poly-peptides. Chlorine in plants mainly accumulates in chloroplast, and is essential to photosynthetic function. The chlorine-deficient plant showed leaf symptoms of wilt, chlorosis, necrosis, and an unusual bronze discoloration. The critical level of Cl deficiency is approximately 2 mg kg^{-1} dry weight. However, Cl concentrations in plants generally exceed this critical deficiency level by two orders of magnitude and become important in osmotic adjust-ment and plant water relations. Chloride, together with potassium (K^+), has a particular function in osmoregulation in the grass stigma. The stigma of grasses such as *Pennisetum americium* L. often extend within minutes at anthesis by cell elongation and this is mainly mediated by the rapid transfer of K^+ and Cl^- from the surrounding tissue into the stigma primordium. In conclusion, Cl− has important functions in osmoregulation at different levels.

Disease resistance and tolerance in higher plants: Cl plays a major role against salinity stress, which may reduce plant tolerance to pathogens, if not its resistance directly. However, there is also literature reporting Cl enhancing plant resistance to disease, in which fairly large amounts of Cl^- were required. These amounts are far greater than those required to fulfill its role as a micronutrient, but far less than those required to induce effects of salinity. Many diseases in different crops were reported to be suppressed by Cl at the levels of macronutrients. These include: corn (*Zea mays* L.) stalk rot, *Gibberella zeae* or *G. fujikuroi*; stripe rust on wheat, *Puccinia striiformis* and downy mildew (*Sclerophthora macrospora*) of millet (*Pennisetum typhoides* L.). Chloride may also suppress septoria in wheat, either directly or indirectly through its effects on take-all. A number of these studies have distinguished the effects of Cl^- from the other accompanying cations. However, the mechanism of Cl^- effect on resistance is largely unknown.

Chlorine and crop yield: Several studies have demonstrated the importance of fertilizing crops with

Cl to maintain grain yields. Cl applied in the form of KCl, improved the productivity of wheat and other crops. It was also reported that chloride fertilizer could promote better vegetative growing conditions, yielding a greater grain number per unit surface. The studies on onion showed onion seems a high Cl-requiring plant, and the onions which received Cl application through irrigation water have healthier, darker green foliage. Rice, wheat, rape, Chinese cabbage, and asparagus, yield can be increased through applying more chlorine-containing fertilizer. Yield response to Cl^- follows the concept of response of crops to mobile nutrients. This means the yield can be related directly to the amount of Cl, given that this nutrient is the most limiting one in the soil. It is also important to note that Cl is mobile and subject to leaching, so crops grown in soils where the soil Cl is low, such as sandy and sandy loam soils, would benefit more from Cl fertilizer.

Chlorine deficiency symptoms: Wilting of leaves, especially at leaf margins, is a typical symptom of Cl deficiency when plants are exposed to full sunlight. With severe deficiency, curling of the youngest leaves followed by shriveling and necrosis may occur. In palm trees which have a particularly high Cl^- requirement, besides wilting and premature senescence of leaves, frond fracture and stem cracking are typical symptoms of Cl deficiency. In leaves and roots, besides cell division, cell extension is particularly impaired in Cl-deficient plants, and in roots this is associated with sub-apical swelling and enhanced formation of short laterals, giving the roots a stubby appearance. In plant species such as red clover with relatively low Cl^- requirements the demand can be met by a low concentration nutrient solution indicating that the selectivity of Cl uptake is not very high as compared. Highly leached soils with a low Cl input from rain and other sources, Cl deficiency may occur even in plant species with low Cl requirements. The probability of Cl deficiency and, thus response to chloride fertilizers, increases in plant species with a high Cl requirement such as kiwifruit and palm trees in particular.

Conclusions

As a yield- and growth-limiting nutrient, the physiological functions of Cl in higher plants include osmotic regulation, stomatal regulation, evolution of oxygen in photosynthesis, disease resistance and tolerance. Except for some plant species, the average concentrations of chlorine in plants are in the range of 2-20 g kg^{-1} dry matter (DM), which is easy to be met by irrigation, rain, fertilizers, and air pollution. However, the practices of avoiding fertilizers containing metallic salts of Cl may enhance the possible deficiency of Cl in some areas, especially in high-yielding deep sandy soils with low organic matter. Furthermore, plants differ in their responses to Cl fertilizer and limited information is available on the internal and external requirement of major crops for Cl and previous studies were mainly limited to few cultivars. Future studies on crop yield and quality-Cl availability relationships should be expanded to a wide range of soils and cultivars of crop plants.

Digital Extension as a Tool for Environmentally Sustainable Agriculture

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Abstract

Indian agriculture is facing increasing pressure from declining natural resources, climate variability and rising cost of cultivation. In this context, digital extension has emerged as an effective tool to support environmentally sustainable agricultural practices. Digital extension uses information and communication technologies such as mobile phones, internet platforms and social media to provide timely and location-specific advisories to farmers. These digital tools improve nutrient management, water-use efficiency, integrated pest management and climate-smart decision-making. The article discusses the role of digital extension in reducing environmental degradation, improving resource-use efficiency and strengthening farmers' decision-making while highlighting key challenges and future directions.

Introduction

Agriculture in India is undergoing a period of rapid transformation due to increasing population pressure, shrinking land resources and growing environmental concerns. Intensive farming practices, excessive use of fertilizers and pesticides, and inefficient water management have resulted in soil degradation, water pollution and declining biodiversity. Farmers increasingly require timely and locally relevant information to manage crops sustainably. Traditional extension systems often face limitations in reaching all farmers effectively. In this context, digital extension has emerged as a complementary approach to strengthen agricultural advisory services and support environmentally sustainable farming practices.

Environmental Sustainability and Digital Exten-

Environmental sustainability in agriculture refers to the efficient use of natural resources while minimizing negative impacts on soil, water, air and biodiversity. Lack of timely and reliable information often results in overuse of chemical fertilizers, pesticides and irrigation water. Such practices contribute to groundwater depletion, nutrient imbalance and environmental pollution. Digital extension helps bridge the information gap by providing practical and need-based advisories that support sustainable farm management. Digital extension refers to the use of information and communication technologies to deliver agricultural information and advisory services to farmers. Technologies such as mobile phones, SMS services, mobile applications, websites, social media platforms and online portals are widely used.

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Digital extension complements conventional extension systems by improving outreach, speed and effectiveness of communication. Farmers receive real-time information regarding crop management, weather forecasts, pest outbreaks and market trends directly on their mobile devices.

Role of Digital Extension in Promoting Environmentally Sustainable Agriculture

Digital extension contributes to environmental sustainability by supporting better decision-making at different stages of crop production. It helps farmers adopt practices that reduce resource wastage and environmental risks while maintaining productivity. The role of digital extension in strengthening environmentally sustainable agriculture through improved farmer decision-making is illustrated in Figure 1.

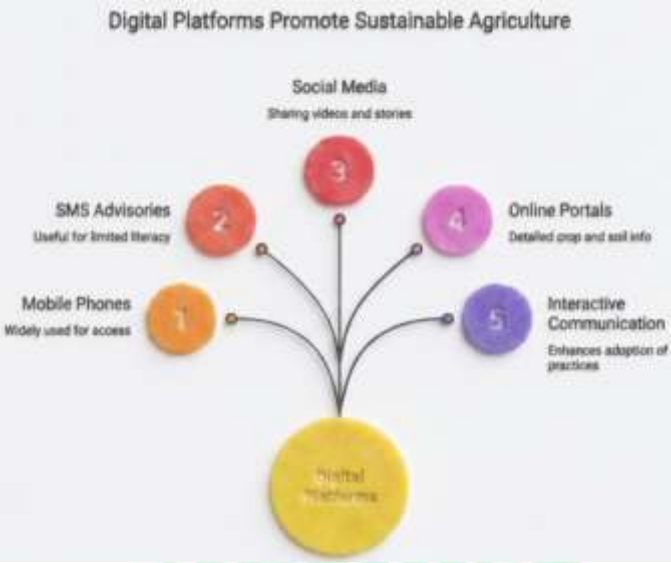
Figure 1: Digital extension-driven decision loop for sustainable agriculture

The figure is showing how digital extension supports environmental sustainability in agriculture. Digital advisory tools improve farmer decision-making related to input use, timing of operations and risk management. These informed decisions lead to adoption of sustainable on-farm practices such as balanced fertilization, efficient irrigation and integrated pest management. Improved practices result in positive environmental outcomes, including resource conservation, reduced pollution and enhanced climate resilience. Feedback from field outcomes further strengthens the quality and relevance of digital advisories, creating a continuous cycle of sustainability. Digital advisory systems also provides climate-related information such as weather forecasts, extreme event warnings and crop-specific recommendations. Such advisories help farmers adjust sowing dates, irrigation schedules and crop operations according to changing climatic conditions. Climate-informed decision-making reduces production risks and enhances resilience against climate variability.

Digital Extension Platforms Supporting Sustainable Agriculture

Several digital platforms and initiatives are being used to disseminate agricultural information in India. Mobile phones remain the most widely used tool due to their accessibility and ease of use. SMS and voice-based advisories are particularly useful for reaching farmers with limited literacy. Social media platforms such as WhatsApp and YouTube are increasingly used for sharing videos, images and success stories related to sustainable farming practices. Online portals and mobile applications provide access to detailed information on crop management, soil health and government schemes. These platforms enable interactive communication and peer learning, which enhances adoption of environmentally sustainable practices. The contribu-

tion of major digital extension tools to environmental sustainability is shown in Figure 2.



Benefits and challenges of digital extension for sustainability

Digital extension improves access to timely agricultural information, reduces dependency on physical visits and enhances the efficiency of extension services. Farmers can make informed decisions that improve input-use efficiency, lower production costs and reduce environmental impacts. Environmentally, digital extension promotes soil and water conservation, reduces pollution and supports adoption of climate-resilient agricultural practices. Despite its potential, digital extension faces several challenges including limited digital literacy, poor internet connectivity in rural areas and lack of localized content. Farmers may also hesitate to rely completely on digital advisories without support from extension personnel. Strengthening digital infrastructure, capacity building and integration of digital tools with conventional extension services are necessary for wider adoption.

Conclusion

Digital extension has emerged as an important tool for promoting environmentally sustainable agriculture in India. By improving access to timely and accurate information, it supports efficient resource use, climate-smart farming and environmentally safe agricultural practices. Although challenges related to digital literacy and infrastructure remain, strengthening digital extension systems through training, collaboration and policy support can significantly contribute to sustainable and resilient agricultural development.

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Seed Microbiome and Its Role

S. Nisha, S. Ambika and R. Vedhanayagi

Introduction

Seed microbiomes have emerged as a promising area in sustainable agriculture because of their potential to enhance crop productivity, efficiency, and environmental sustainability. Recent research has emphasized the crucial role of seed-associated beneficial microorganisms in promoting plant growth, development, and yield. These microorganisms include bacteria, fungi, and cyanobacteria (photosynthetic blue-green algae), which interact with seeds through methods such as biopriming, seed coating, and inoculation, offering eco-friendly alternatives to chemical fertilizers and pesticides.Beyond supporting plant growth, seed microbiomes contribute to improved plant health, enhanced disease resistance, and greater tolerance to biotic and abiotic stresses.

Seed Microbiome

The seed microbiome comprises a diverse assemblage of microorganisms, including bacteria, fungi, archaea, and other microscopic entities, that coexist with seeds, either as epiphytes on the exterior or as endophytes within internal tissues. These microbial communities are crucial for seed vitality, germination, seedling establishment, nutrient absorption and enhancement of plant growth. Through advantageous biological processes such as nitrogen fixation, phytohormone synthesis, and pathogen suppression. These bacterial groups are crucial for seed health, germination, seedling establishment, nutrient absorption, and enhancing plant development. The seed microbiome influences a plant's resilience to diseases and environmental stressors through beneficial biological processes such as nitrogen fixation, phytohormone synthesis, and pathogen suppression. It serves as a crucial pathway for the vertical transmission of advantageous microorganisms between successive generations of plants. Recent investigations into the seed microbiome have gained prominence in agriculture and horticulture due to their potential applications in sustainable crop production, biofertilizer innovation, and biological disease control.

Procedure of Seed Microbiome

The methodology for examining the seed microbiome includes the collection, isolation, identification, and characterisation of micro-organisms associated with seeds. Initially, healthy and representative seed samples are collected using sterile techniques to avert contamination. The seeds are next cleansed to remove dust and debris, and surface-sterilised with ethanol and sodium hypochlo-

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rite to eradicate external contaminants while safeguarding internal bacteria. Subsequent to sterilisation, seeds are rinsed with sterile distilled water and then either macerated or immersed in a sterile buffer solution to liberate the related bacteria. The resultant microbial solution is inoculated onto a suitable culture medium to isolate bacteria and fungi. The plates are incubated under controlled conditions, and the resulting microbial colonies are purified and identified using morphological and biochemical assays. DNA is extracted from microbial isolates and analysed using molecular techniques, such as PCR amplification and next-generation sequencing, to assess microbial diversity and composition. The obtained data are analysed to understand the role of seed-associated microorganisms in seed germination, plant development, nutrient absorption, and disease resistance.

Mechanism of Seed Microbiome

The seed microbiome consists of a diverse assemblage of microorganisms -including bacteria, fungi, archaea, and actinomycetes -that associate with seeds on the seed coat or within seed tissues. These microorganisms create intimate associations with the seed and are crucial for seed health, germination, seedling establishment, plant growth, and stress tolerance. Their processes include many biological, metabolic, and ecological interactions that affect plant growth and defence. Interest in seed microbiomes has increased in agriculture and horticulture due to their potential contributions to sustainable crop production and biological disease management. Key processes include seed colonisation and vertical transfer. Beneficial microorganisms inhabit the seed surface and interior tissues during seed development on the parent plant. They are transmitted vertically to the next generation via seeds, ensuring their presence throughout initial plant development. Upon germination, these bacteria rapidly colonise developing roots and shoots, facilitating robust seedling development. Some also migrate from the seed into the rhizosphere, where they persist in facilitating growth and nutrient absorption. Another significant role is encouraging plant growth. Numerous seed-associated microorganisms synthesise plant growth regulators, including auxins, gibberellins, and cytokinins, as well as enzymes that regulate ethylene. These chemicals promote germination, root extension, cellular division, and seedling vitality. Auxin-producing bacteria promote the growth of root hairs and the root system, hence enhancing water and nutrient absorption. Some bacteria synthesise vitamins and amino acids that enhance metabolic activities in seedlings. As a result, plants with advantageous seed microbiomes often exhibit enhanced growth and improved field establishment. The seed microbiome facilitates nutrient mobilisation and acquisition. Certain seed-associated microorganisms convert atmospheric nitrogen into forms that plants can use. Others solubilise insoluble phosphates and mobilise micronutrients such as zinc, iron and potassium from the soil. Phosphate-solubilising bacteria excrete organic acids and enzymes that

transform insoluble phosphorus into soluble forms, hence enhancing nutrient availability for germinating seeds and young plants. These practices reduce dependence on artificial fertilisers and promote sustainable agriculture. Biological control and disease suppression are also essential. Beneficial seed microorganisms protect seeds and seedlings against diseases via antagonistic mechanisms. They vie for space, nutrition, and opportunities for colonisation on and within plant tissues. Certain organisms synthesise antibiotics, lytic enzymes, siderophores, and antifungal agents that impede infections. Others elicit induced systemic resistance, activating the plant's inherent defences against fungus, bacteria, and viruses. The seed microbiome serves as a natural protective barrier during the first stages of plant development. Improving stress tolerance is another significant method. Abiotic stresses-drought, salt, temperature extremes and heavy metal toxicity-hinder germin-ation and growth. Beneficial seed microorganisms assist plants in coping by synthesising osmoprotect-ants, antioxidants, and stress-related enzymes. Certain entities modulate stress hormones, such as abscisic acid, and diminish ethylene levels via ACC deaminase activity, thereby preserving normal physiological functions under stress. Consequently, seed microbiomes enhance plant adaptability and resilience under challenging environments. Seed microbiomes also influence plant immune responses. Specific bacteria interact with plants through signalling molecules that activate defence-related genes. This prepares the immune system, facilitating rapid responses to pathogen invasion. The activation of induced systemic resistance and systemic acquired resistance is a crucial defence mechanism triggered by beneficial microorganisms, augmenting total plant resilience without damaging tissues. Preserving microbial equilibrium and ecological interactions constitutes an additional mechanism. Microbes linked with seeds participate in cooperation, competition, and communication, influencing community composition and stability. A healthy microbiome enhances seed quality and restricts disease colonisation. Microbial diversity enhances ecolog-ical stability and resilience within the plant ecosystem. The seed microbiome operates via interrelated pathways that improve seed health, germination, nutrient absorption, growth, disease resistance, and stress resilience. These seed-associated micro-organisms function as natural plant allies and are essential for sustainable agriculture and horticulture. Understanding their processes facilitates the development of environmentally sustainable products, such as biofertilizers, biopesticides, and microbial seed treatments, that enhance crop performance while reducing reliance on chemical inputs.

Advantages of the Seed Microbiome

- ✓ Enhances Seed Germination
- ✓ Stimulates Plant Growth
- ✓ Improves Nutrient Access
- ✓ Confers Disease Resistance.
- ✓ Boosts Stress Tolerance.

Disadvantages of the Seed Microbiome

Vegetable Crop	Seed Microbiome / Dominant Microbes	Effect on Crop	Author(s)
Tomato	*Pseudomonas*, *Bacillus*, *Sphingomonas*	Increased seed germination, disease suppression, seedling vigor	Eric B. Nelson (2018)
Cucumber	*Burkholderia* spp., phosphate-solubilizing bacteria	Higher nutrient mobilization and growth	Xiangning Qi *et al.* (2026)
Lettuce	Seed-associated beneficial bacteria	Better seedling establishment and vigour	Eric B. Nelson (2018)
Brinjal / Eggplant	Seed endophytes and fungal microbiota	More vertical transfer of beneficial microbes	Aadil Farooq War *et al.* (2023)
Onion	Seed-borne beneficial microbes	Protection against fungal pathogens	Eric B. Nelson (2018)
Carrot	Diverse bacterial and fungal microbiota	Early growth promotion and plant fitness	Marie Simonin *et al.* (2022)
Squash / Pumpkin	Proteobacteria and Actinobacteria	Drought adaptation and stress tolerance	Cristóbal Hernández-Álvarez *et al.* (2021)

- ✓ Carries Potential Pathogens.
- ✓ Inconsistent Microbial Profiles.
- ✓ Sensitive to Environmental.
- ✓ Challenging to Study and Identify.
- ✓ Unreliable Field Results.

Conclusion

There has been promising news on the potential of beneficial microbes for seed development to improve agricultural efficiency, resilience to stress, and stability. Supported by evidence of vertical transfer from parent plants to offspring, seed-related bacteria play an important role in germination, seedling establishment, and the health of continuing plant development. This proposes a heritable strategy for increasing agricultural qualities across generations. Improved germination rates, seedling viability, and overall yield have been shown using methods such as seed biopriming.

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Role of Vegetables in Human Nutrition and Disease Prevention

M. Vignesh, J. Dharani, K. Abirami, M. Karal Marks and J. Aneesha

Abstract

Vegetables are essential components of a healthy diet and play a major role in maintaining human health and preventing diseases. They are rich sources of vitamins, minerals, dietary fiber, antioxidants, and bioactive compounds that support normal body functions and improve overall well-being. Regular consumption of vegetables helps reduce the risk of chronic diseases such as obesity, diabetes, cardiovascular disorders, hypertension, cancer, and digestive problems. Important nutrients found in vegetables include vitamins A, C, K, folate, calcium, iron, potassium, and magnesium, which are necessary for growth, immunity, bone health, blood formation, and metabolic activities. In addition, vegetables contain phytochemicals such as flavonoids, carotenoids, polyphenols, glucosinolates, and anthocyanins that exhibit antioxidant, anti-inflammatory, antimicrobial, and anticancer properties. These compounds protect cells from oxidative stress and contribute to disease prevention. Different groups of vegetables, including leafy greens, cruciferous vegetables, root vegetables, and colorful vegetables, provide unique nutritional and therapeutic benefits. Modern scientific research recognizes vegetables as functional foods that promote long-term health and reduce healthcare burdens. However, inadequate vegetable consumption remains a global public health concern. This paper discusses the nutritional composition, health benefits, disease-preventive roles, therapeutic properties, challenges, and future prospects of vegetables in human nutrition and healthcare.

Introduction

Vegetables are among the most important foods in human diets because of their high nutritional value and protective health benefits. They are consumed worldwide in fresh, cooked, processed, and preserved forms. Vegetables provide essential nutrients required for growth, development, energy metabolism, and disease prevention. In recent years, the increasing prevalence of lifestyle-related diseases such as obesity, diabetes, cardiovascular disorders, and cancer has highlighted the importance of healthy dietary habits. Scientific studies consistently show that diets rich in vegetables improve overall health and lower the risk of chronic diseases.

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Vegetables are naturally low in calories and fats while being rich in vitamins, minerals, dietary fiber, and bioactive compounds. Different categories such as leafy vegetables, cruciferous vegetables, root crops, legumes, and salad vegetables offer unique nutritional benefits. Beyond basic nutrition, vegetables possess medicinal and therapeutic properties that support immune function, digestion, cardiovascular health, and metabolic balance. Therefore, vegetables are increasingly recognized as functional foods essential for healthy living and disease prevention.

Nutritional Composition of Vegetables

Vegetables contain a wide variety of nutrients essential for normal body functions and overall health. They provide vitamins such as vitamin A, vitamin C, vitamin K, vitamin E, and folate, which are important for immunity, vision, skin health, blood clotting, and cell growth. Vitamin C acts as a powerful antioxidant and improves iron absorption, while vitamin A supports eye health and immune defense. Vegetables also contain minerals including calcium, potassium, magnesium, phosphorus, iron, and zinc. Potassium helps regulate blood pressure and fluid balance, whereas calcium contributes to strong bones and teeth. Iron supports hemoglobin formation and oxygen transport in the body. Dietary fiber present in vegetables improves digestion, prevents constipation, and promotes gut health. In addition to nutrients, vegetables contain bioactive compounds such as flavonoids, carotenoids, glucosinolates, and phenolic acids that possess antioxidant and therapeutic properties. Due to their rich nutritional composition, vegetables are indispensable for maintaining health and preventing nutrient deficiencies.

Role of Vegetables in Disease Prevention

Vegetables play an important role in preventing chronic diseases and maintaining overall health. Their high antioxidant content protects the body from oxidative stress caused by free radicals, which can damage cells and contribute to aging and diseases. Colorful vegetables such as tomatoes, carrots, spinach, broccoli, beetroot, and bell peppers contain antioxidants like lycopene, beta-carotene, lutein, flavonoids, and anthocyanins that help protect DNA, proteins, and lipids from oxidative damage. Regular vegetable consumption is strongly associated with reduced risks of cardiovascular diseases. Potassium-rich vegetables help control blood pressure, while dietary fiber lowers cholesterol levels and improves lipid metabolism. Leafy vegetables also contain natural nitrates that improve blood vessel function and circulation. As a result, vegetables contribute to the prevention of hypertension, stroke, coronary artery disease, and heart failure. Vegetables are also beneficial in diabetes and obesity management because they are low in calories and high in dietary fiber. Fiber slows glucose absorption, improves insulin sensitivity, and helps regulate blood sugar levels. Non-starchy vegetables such as spinach, cucumber, cabbage, broccoli, and bitter gourd are especially beneficial for diabetic individuals. Their high water and fiber

content promote satiety and support healthy body weight. Many vegetables possess anticancer properties due to the presence of bioactive compounds. Cruciferous vegetables such as broccoli, cabbage, cauliflower and kale contain glucosinolates and sulfur compounds that support detoxification and reduce carcinogen activity. Tomatoes contain lycopene, which is associated with a lower risk of prostate and digestive cancers. Garlic and onions contain organosulfur compounds with antimicrobial and anticancer effects. Studies indicate that diets rich in vegetables lower the risk of colorectal, stomach, breast, lung, and oral cancers.

Immune-Boosting and Functional Properties

Vegetables strengthen the immune system by supplying nutrients necessary for immune cell production and function. Vitamin C-rich vegetables such as bell peppers, cabbage, spinach, and broccoli improve white blood cell activity and resistance to infections. Vitamin A supports mucosal immunity and tissue repair. Many vegetables also possess anti-inflammatory properties due to the presence of flavonoids, carotenoids, and phenolic compounds. Chronic inflammation is linked to diseases such as arthritis, obesity, cardiovascular disorders, and cancer. Bioactive compounds in vegetables help reduce inflammatory responses and improve immune regulation. Garlic, ginger, onion, turmeric, and leafy greens are especially recognized for their immune-enhancing effects. Because of these health-promoting properties, vegetables are increasingly used in functional foods and nutraceutical products. Vegetable extracts, juices, powders and supplements are widely used in preventive nutrition and therapeutic diets. Beetroot juice is known to improve blood circulation and athletic performance, while spinach extracts are commonly used in dietary supplements. The growing demand for plant-based and natural foods has increased the importance of vegetables in healthcare and wellness industries.

Challenges and Future Prospects

Despite their importance, vegetable consumption remains inadequate in many populations due to urbanization, changing dietary habits, and increased consumption of processed foods. Limited awareness regarding the health benefits of vegetables also contributes to poor intake. Other challenges include postharvest losses, seasonal availability, high prices, poor storage facilities, and concerns related to pesticide residues and contamination. Addressing these issues requires public awareness programs, improved agricultural practices, better storage technologies, and promotion of healthy eating habits. Increasing vegetable production and accessibility is essential for improving global nutrition and public health. The future of vegetables in human nutrition and healthcare is highly promising. Biofortification programs aim to increase nutrient levels in vegetables through breeding and biotechnology. Modern cultivation methods such as hydroponics, vertical farming, urban agriculture, and protected cultivation are improving year-round vegetable production and nutritional security. Research on personalized nutrition and therapeutic diets is also

expanding the role of vegetables in disease management. Government initiatives promoting healthy diets and sustainable food systems will further support vegetable consumption worldwide.

Conclusion

Vegetables are essential components of healthy diets and contribute significantly to human nutrition and disease prevention. Rich in vitamins, minerals, dietary fiber, antioxidants and phytochemicals, vegetables support growth, immunity, digestion, cardiovascular health, and metabolic regulation. Regular vegetable consumption reduces the risk of chronic diseases such as obesity, diabetes, hypertension, cardiovascular disorders, and cancer. Their antioxidant and anti-inflammatory properties further strengthen their therapeutic importance in modern healthcare systems. Although challenges related to accessibility, awareness, and food safety still exist, advancements in agriculture, food technology, and nutrition science are improving vegetable production and utilization. Promoting vegetable-rich diets is essential for achieving better public health, nutritional security, and sustainable food systems worldwide.

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Dr. Murthy's Triad Concept based Global Agricultural Universities and Institutions for Resilience under El Nino and Climate Change

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Abstract

Food is the foundation of civilization, human survival, and global stability. Agriculture, which is fundamentally the scientific exploitation of solar radiation through crops, livestock, water, soil, and weather resources, now faces unprecedented threats from climate change and recurrent El Niño events. Therefore, there is an urgent global necessity to redesign agricultural universities and institutions into climate-resilient systems capable of protecting farmers, strengthening food security, reducing cultivation costs, and sustaining humanity under increasingly uncertain environmental conditions.

Food, Solar Radiation and the Foundation of Agricultural Life

Food is not merely a commodity; it is the biological expression of solar radiation transformed through plants, animals, water, soil, and atmosphere into sustenance for humanity. Every grain of rice, wheat, maize, fruit, vegetable, milk, or livestock product is fundamentally a conversion of solar energy into edible biomass through photosynthesis and biological processes. Therefore, crop production may rightly be described as the scientific exploitation of solar radiation under favorable environmental conditions. In this process, weather elements such as solar radiation, wind, temperature, rainfall, and humidity, serve as vital non-monetary agricultural inputs supporting growth, development and productivity. Unlike costly chemical and industrial inputs, weather resources are natural assets available to all farming communities. However, their efficient utilization requires scientific understanding, timely advisories and institutional support systems. Modern agriculture must therefore recognize weather and climate as strategic production resources rather than uncertain external factors. Agricultural universities and research institutions have a historic responsibility to educate future generations in climate-responsive resource management. This perspective establishes the scientific and philosophical basis for resilient agricultural systems worldwide.

Climate Change, El Nino and the Global Agricultural Crisis

The twenty-first century agricultural landscape is increasingly threatened by steadily intensifying climate change and recurrent El Niño

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phenomena. Rising global temperatures, irregular rainfall, prolonged droughts, floods, heat waves, and cyclonic disturbances are destabilizing food production systems across continents. Simultaneously, El Niño events are disrupting monsoon circulation, seasonal weather behavior, livestock productivity, water availability, and crop yields in many vulnerable regions of the world. These climatic abnormalities are occurring alongside an alarming increase in cultivation costs, including fertilizers, pesticides, electricity for irrigation, machinery operations, labor wages, storage, transportation, and post-harvest management. For millions of small and marginal farmers, particularly in developing countries, agriculture is becoming economically unsustainable and socially distressing. The combined impacts of climatic uncertainty and rising production costs are now threatening global food security, nutritional stability, and rural livelihoods. In many regions, indebtedness, migration, and agrarian distress are increasing rapidly. Therefore, the future of agriculture depends not merely on increasing production, but on developing resilient systems capable of reducing risks, conserving resources, and protecting farmers under hostile climatic conditions. The need for climate-resilient institutional transformation has never been more urgent than at present.

Weather-Based Agriculture as a Scientific and Economic Solution

Scientific and judicious utilization of weather resources offers one of the most powerful solutions for reducing cultivation costs and enhancing agricultural resilience. Weather information, climate forecasts, agro-advisories, early warning systems, and agrometeorological services can significantly improve decision-making related to sowing, irrigation, fertilizer application, pest management, harvesting, livestock care, storage and transportation. Such weather-based agricultural management helps farmers avoid unnecessary expenditures while improving productivity and quality of produce. In this context, “weather health” becomes equally important as soil health, crop health, and animal health. Maintaining weather health means understanding atmospheric behavior, protecting ecological balance, conserving natural resources, and minimizing climate-induced agricultural vulnerabilities. The integration of agrometeorology into mainstream agricultural education and extension is therefore indispensable. Modern agricultural universities must train students not only in crop science and livestock production, but also in climate intelligence, weather interpretation, disaster preparedness, and risk communication. Need-based climate products and localized weather services should be developed for farmers, extension workers, livestock managers, and policymakers. Such institutional efforts can transform weather from a source of uncertainty into a strategic tool for climate-resilient agriculture. In the emerging era of climate volatility, weather-based farming will become the backbone of sustainable food systems.

Dr. Murthy’s Triad Concept: PCCC-MCCC-

CCAC for Global Resilience

To address the interconnected challenges of climate change, El Niño, food insecurity, and agricultural instability, Dr. Murthy's TRIAD Concept PCCC-MCCC-CCAC emerges as a visionary and globally relevant framework. The Policy Concept on Climate Change (PCCC) provides strategic policy direction for integrating climate resilience into agricultural governance, institutional planning and development programs. The Micrometeorological Concept on Climate Change (MCCC) emphasizes localized climate understanding, field-level weather interactions, and scientific utilization of weather elements for practical agriculture. The Climate Change and Agriculture Center (CCAC) serves as an institutional platform integrating education, research, extension, climate services, and farmer-centered innovation. Together, these three pillars create a comprehensive architecture for resilient agricultural transformation. The TRIAD Concept advocates converting agricultural universities into dynamic climate-resilient institutions capable of addressing real-time farmer problems under changing environmental conditions. It strengthens linkages between scientists, teachers, students, policymakers, extension agencies, and farming communities. Importantly, the concept combines global scientific standards with local agricultural realities, making it adaptable for every nation irrespective of geographical or economic differences. By integrating policy, micrometeorology and institutional action, the TRIAD Concept offers a practical roadmap for sustainable agriculture under climate uncertainty. It represents a transformative model for the future of global agricultural education and food security.

Transforming Global Agricultural Universities for the Future

The future of humanity depends greatly on the ability of agricultural universities and institutions to evolve into centers of climate resilience, innovation, and farmer welfare. Traditional agricultural education systems must now move beyond conventional teaching toward integrated climate-responsive learning frameworks. Universities should establish specialized climate resilience centers, agrometeorological advisory units, digital weather platforms, and farmer-oriented extension systems capable of delivering timely and practical solutions. Curricula must include climate science, El Niño dynamics, risk management, weather-based decision support systems, renewable energy applications, sustainable farming systems, and climate-smart livestock management. Agricultural education should become globally connected yet locally relevant, scientifically rigorous yet socially compassionate, technologically advanced yet farmer-centered. Institutions must strengthen partnerships with international organizations such as FAO, WMO, ICAR, CGIAR, and national meteorological agencies to improve climate services and educational quality. Above all, agricultural universities should function as humanitarian institutions committed to reducing cultivation costs, increasing productivity,

improving nutritional security, and protecting the dignity of farmers. Such transformation will empower rural youth as future climate leaders and agricultural innovators. In this direction, Dr. Murthy's TRIAD Concept offers one of the most comprehensive and practical institutional models for ensuring resilient agriculture, resilient education, and resilient humanity in the age of climate change and El Niño.

Conclusion

Climate change and El Niño are redefining the future of global agriculture, food security, and rural livelihoods. Under these challenging conditions, Dr. Murthy's TRIAD Concept PCCC-MCCC-CCAC provides a truly world-class, scientifically sound, farmer-centered, and globally adaptable framework for transforming agricultural universities and institutions into climate-resilient systems. By integrating weather science, policy innovation, agricultural education, and humanitarian commitment, this model has the potential to protect farmers, strengthen food production, reduce cultivation costs, and guide humanity toward a sustainable, resilient, and food-secure future.

Effect of Pesticides and their Residues on Biodiversity

C. G. Sawant and Sandip Sarkar

Introduction

Pesticides are chemical substances used in agriculture to protect crops from insects, weeds and plant disease so that they can grow better and produce higher yield. They are widely used by the farmers and are also applied in flower production to improve quality and productivity. However, when pesticides are used extensively or without proper care,they can harm the environment. After spraying, not all of the pesticide remains on the crops. Rainwater can wash these chemicals into nearby rivers, ponds, lakes, and integrated fish farms, creating serious problems due to runoff from agriculture field. Some pesticides also seep into the soil and reach groundwater, a process known as leaching. During spraying tiny droplets of pesticides can mix with water vapour in the atmosphere and later fall back to the ground with rain; this process is called atmospheric deposition. As a result, many aquatic ecosystem becomes contaminated. Pesticides residues can remain in water or settle at the bottom as sediments for a long time. Even small amounts of these chemicals can be harmful to aquatic life. They first affect tiny organisms such as phytoplankton and zooplankton, which from the base of the food chain. The impact then spreads to the larger organisms like fish, frogs and other aquatic animals. These chemicals can cause poisoning, reduce growth, disturbed reproduction and even lead to death. Over time, pesticides toxicity increase as it moves up the food chain (biomagnification), which can also affect human and terrestrial ecosystems. Ultimately, this leads to a decrease in biodiversity and distrubsthe natural balance of both aquatic and terrestrial ecosystems.

Sources of Pesticides Exposure

Surface Runoff: After spraying on agriculture fields, not all the pesticides are absorbed by the plants. During rainfall or irrigation, these chemicals are washed off from the soil surface and carried into nearby rivers, ponds, lakes, and other water bodies.

Leaching into groundwater: Some pesticides do not flow over the surface but instead dissolve in rainwater or irrigation water and move downward through the soil. They reach groundwater, which later connects to wells, springs, or rivers.

Spray Drift: During pesticides application, tiny droplets can be carried away by the wind. These droplets may later settle directly on the water bodies or nearby land.

Atmospheric Deposition: Some pesticides evapo-rate into the air after application. They later return to the earth through rain, fog, or dust, contaminating water bodies even far from the original source.

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Agriculture Drainage: Irrigation water containing pesticides residues drains into canals and streams, eventually reaching rivers and lakes.

Industrial effluents: Wastewater from pesticides manufacturing industries may be discharged directly into rivers without proper treatment, causing serious pollution.

Pesticides used in household (such as mosquito control and cleaning products) can mix with sewage water and entre river or other water bodies without proper treatment.

Effects of Pesticides on Terrestrial Ecosystems

Excessive or improper use of pesticides can negatively affect terrestrial ecosystems in many ways. The major effects are as follows:

- ✓ Excessive use of the pesticide leads to accumulate of toxic chemicals in the soil after repeated applications. Many pesticides remain in the soil for a long period and reduce soil quality. They kill beneficial soil microorganisms that help in nutrient cycling and decomposition. As a result, soil fertility and agriculture productivity decrease.
- ✓ Pesticides do not only kill harmful pests; they also affect beneficial and non target organisms. Pollinators such as bees and butterflies, natural predators, birds, reptiles and small mammals may die after exposure to toxic chemicals. This creates ecological imbalance in terrestrial ecosystems.
- ✓ Heavy use of recommended and non-recommended pesticides reduce the diversity of plants and animals in agricultural fields and nearby habitats. Sensitive species decline, leading to imbalances in food chains and ecosystem instability.
- ✓ Certain pesticides, especially organchlorines, remains in the environment for a long time. These chemicals accumulate in living organisms and become more concentrated at higher levels of the food chain, making them highly toxic to predators and wildlife.
- ✓ Continuous use of the same pesticides can lead to the development of pest Resistance over time. As pests become resistant, farmers needs to use stronger doses or new pesticides, which further increase environmental damage.
- ✓ Wild animals may consume contaminated food, water, or prey exposed to pesticides. This can cause poisoning, reproductive failure, hormonal imbalance, and even death in terrestrial wildlife.

Case study

- ✓ One of the most serious pesticide-related environmental disasters in India occurred in the Kasaragod district of Kerala. From the 1970s to the early 2000s, the pesticides Endosulfan was aerially sprayed over cashew plantation managed by the plantation corporation of Kerala.
- ✓ The continuous spraying contaminated soil, water bodies, vegetation and nearby habitats. Domestic animals, birds, frogs, insects and other beneficial organisms were severely affected leading to a significant decline in local biodiversity.

- ✓ Many residents reported serious health problems such as deformities, neurological disorders, cancer, reproductive problems, and development abnormalities. Children were among the most affected victims.
- ✓ Due to public protests and scientific evidence regarding its harmful effects, Kerala banned Endosulfan in 2005. Later, India also imposed restrictions and eventually banned it's use across the country. (National institute of occupational Health (NIOH) India).

Effects of Pesticides on Human Health

Major Effects on Human Health are the following:

- ✓ Some pesticides which are used in agriculture fields they show acute (short-term) effects like Headache, Nausea and vomiting, Dizziness, skin and eye irritation, breathing difficulty, and weakness and fatigue.
- ✓ Some pesticides show chronic (long-term) effects also like Cancer, Damage to the nervous system, Hormonal imbalance, liver and kidney damage, Reproductive disorders, Birth defects in children, Developmental and learning problems.
- ✓ Farmers and pesticides sprayers are at greater risk because they handle pesticides directly. Lack of protective equipment increase exposure and health hazards.

Indian case study

- ✓ A major pesticides poisoning incident occurred in Yavatmal during 2017 affecting hundreds of cotton farmers and farm workers.
- ✓ Farmers in Yavatmal district were spraying pesticides on cotton crops to control pests such as bollworms. Due to excessive use of highly toxic pesticides mixtures and lack of proper protective equipment, many farmers inhaled toxic chemicals during spraying. Because of inhaling they faces many health problems like headache, vomiting, blurred vision, breathing problems, etc. (The Hindu, 2017)

Effects of Pesticides on Aquatic Ecosystems

Water Pollution: Pesticides contaminate surface water and groundwater after rainfall or irrigation washes them from agricultural fields. Toxic chemicals dissolved in water and reduce its quality. Polluted water becomes unsafe for aquatic organisms as well as for human use. Some pesticides and their residues remain in water for a long period because they degrade slowly. Persistent chemicals accumulate in sediments and continue affecting aquatic life for many years.

Toxicity to Fish: Fish are highly sensitive to pesticides. Even a small concentration of toxic chemicals can affect their health. Pesticides enter fish bodies through gills, skin, and food.

Effects on fish include

- ✓ Damage to gills and the respiratory system
- ✓ Reduction in growth rate
- ✓ Abnormal swimming behavior
- ✓ Failure in reproduction
- ✓ Weak immune system
- ✓ Death in severe cases

Insecticides such as organophosphates and carbamates are particularly harmful to fish species.

Destruction of Aquatic Biodiversity

- ✓ Pesticides do not only kill target pests; they also harm non-target aquatic organisms. Zooplankton, phytoplankton, aquatic insects, mollusks, frogs, and beneficial microorganisms are affected.
- ✓ Reduction of these organisms disturbs the aquatic food chain. Loss of biodiversity weakens ecosystem stability and reduces natural productivity of water bodies.

Bioaccumulation and Biomagnification

- ✓ Certain pesticides such as organochlorines accumulate in the tissues of aquatic organisms. This process is called bioaccumulation.
- ✓ When small organisms contaminated with pesticides are eaten by larger organisms, the concentration of toxic substances increases at each trophic level. This process is known as biomagnification.

As a result:

- ✓ Predatory fish accumulate high pesticide levels
- ✓ Birds feeding on fish are affected
- ✓ Human health may also be threatened through fish consumption

Effect on Reproduction and Growth

Many pesticides interfere with hormones and reproductive systems of aquatic organisms.

Common effects includes:

- ✓ Reduction in egg production
- ✓ Delayed hatching
- ✓ Deformities in larvae
- ✓ Reduced fertility
- ✓ Slow growth and development

These effects decrease population size and threaten the survival of sensitive aquatic species.

Oxygen Depletion in Water: Pesticides can kill aquatic plants and microorganisms that maintain ecological balance. Decomposition of dead organisms increases biological oxygen demand in water.

Lower dissolved oxygen levels lead to

- ✓ Fish suffocation
- ✓ Death of aquatic organisms
- ✓ Poor water quality

This condition may create dead zones where aquatic life cannot survive.

Disruption of Food Chains: Aquatic ecosystems depend on balanced food chains. Pesticides reduce populations of plankton, insects, and small aquatic animals that serve as food for fish and birds.

When lower trophic organisms decline

- ✓ Fish populations decrease
- ✓ Bird populations are affected
- ✓ Ecological balance becomes unstable

Effects on Amphibians

Frogs and other amphibians are very sensitive to pesticide contamination because their skin easily absorbs chemicals from water.

Pesticides may cause

- ✓ Developmental abnormalities in fishes
- ✓ Weak immune response
- ✓ Reduction in reproductive success
- ✓ Increased mortality

Decline of amphibian populations is conside-

red an indicator of aquatic ecosystem degradation.

Prevention and Control Measures

To reduce pesticide pollution in aquatic ecosystems, the following measures should be adopted:

- ✓ Use pesticides only when necessary
- ✓ Follow recommended doses
- ✓ Promote organic farming and biopesticides
- ✓ Adopt Integrated Pest Management (IPM)
- ✓ Avoid spraying near rivers, ponds, and lakes
- ✓ Create buffer zones around water bodies
- ✓ Increase farmer awareness regarding safe pesticide use

Conclusion

Pesticides play an important role in modern agriculture by protecting crops from pests, diseases, and weeds, thereby improving agricultural productivity. However, excessive and improper use of these chemicals has created serious environmental and health concerns. Pesticides and their residues enter aquatic ecosystems through surface runoff, leaching, spray drift, atmospheric deposition, agricultural drainage, industrial effluents, and domestic sewage. Aquatic organisms such as phytoplankton, zooplankton, fish, amphibians and beneficial microorganisms are highly sensitive to pesticide contamination. These chemicals reduce water quality, damage aquatic food chains, interfere with growth and reproduction, and may even cause death of many species. Persistent pesticides also undergo bioaccumulation and biomagnification, increasing their toxicity at higher trophic levels and posing risks to wildlife and humans.

In addition to aquatic damage, pesticides also affect terrestrial ecosystems, soil health, biodiversity, and human health, as seen in several Indian case studies such as the Endosulfan tragedy in Kerala and pesticide poisoning incidents in Yavatmal. Therefore, there is an urgent need for safe and sustainable pesticide management practices. Farmers should be encouraged to use pesticides only when necessary and in recommended doses. Adoption of Integrated Pest Management (IPM), organic farming, biopest-icides and proper awareness programs can significantly reduce environmental contamination. Protecting aquatic ecosystems is essential for maintaining biodiversity, ecological stability, food security and human well-being. Sustainable agricultural practices are the key to balancing crop production with environmental conservation for future generations.

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Importance of Microorganisms in Protected Cultivation

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Abstract

In protected farming, sowing crops under crop residues with zero tillage increases yields and improves soil health. Using crop residues as mulching material increases the number of microorganisms and carbon. A higher number and diversity of microorganisms increases the availability of nutrients in the soil to plants, leading to healthier plants and higher production. Using various types of crop residues as mulching material prevents farmers from burning crop residues. Harmful gases such as carbon monoxide, carbon dioxide, sulfur dioxide, and other gases released from crop residue burning can adversely affect the atmosphere, thus protecting the environment. Thus, adopting fully protected farming prevents damage from atmospheric changes, soil damage, loss of biodiversity and adverse effects on human health.

Introduction

Through conservation agriculture, farmers experience a reduction in agricultural resource costs, while crop yields are found to be comparable to and in some instances, even higher than those achieved through traditional methods. Furthermore, agricultural operations are completed in a shorter timeframe. Globally, the area under conservation agriculture spans approximately 250-270 mha, whereas in India, this area covers roughly 1.5-2.0 mha. This acreage is continuously expanding, as the benefits of this approach are applicable across a diverse range of crops and environmental conditions. The key components of conservation agriculture include minimal tillage, covering the soil with crop residues, refraining from burning crop residues, adopting crop rotation and utilizing farmyard manure.

Today, conservation agriculture is being embraced as a pathway toward sustainable farming. Through this approach, natural resources are utilized judiciously and conserved, thereby enhancing their utility within crop production systems. The objective is to conserve rainwater improving its utilization efficiency and channel it for crop use, while simultaneously increasing the availability and efficiency of nutrients within the soil. By adopting various crop rotation cycles within the framework of conservation agriculture, the physical and biological properties of the soil are preserved and harnessed to support crop growth. Integrating appropriate crop intensification strategies with livestock rearing within the crop rotation cycle ensures that the requirements of both sectors are mutually fulfilled. A critical component of conservation agriculture involves the permanent retention of crop residues

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and the sowing of crops using zero-tillage techniques. Concurrently, the adoption of crop rotation is essential, as it helps preserve soil biodiversity and mitigates the depletion of soil fertility. The rice-wheat cropping system is widely adopted in India, covering an area of approximately 10 million hectares. In this cropping system, following the harvest of rice, farmers have a window of only 2-3 weeks to sow wheat a period that coincides with the optimal time for wheat sowing. During this critical period, farmers often face a severe time constraint in preparing their land and carrying out the sowing operations. Adopting conservation agriculture techniques for wheat sowing leads to reduced costs and, by ensuring timely sowing, results in higher yields; furthermore, it helps minimize adverse environmental impacts. Conservation agriculture comprises three key components:

- ✓ Zero tillage and reduced tillage practices.
- ✓ Complete retention and mulching of crop residues.
- ✓ Implementation of crop diversification.

Benefits of conservation agriculture

Benefits of reduced tillage: Reduced tillage of the land results in savings of cost, time and energy. Furthermore, the reduced use of machinery for tilling leads to a decrease in the emission of gases such as carbon dioxide and carbon monoxide into the atmosphere. Additionally beneficial microorganisms within the soil are preserved. Consequently, improvements are observed in both the physical condition and the fertility of the soil. The absence of tillage helps maintain soil biodiversity, while simultaneously keeping the lower soil layers soft, thereby facilitating the proper development of crop roots (Fig. 1).

Fig. 1: Wheat sowing in zero traction

Fig. 2: Sowing of wheat in crop residue

Fig. 3: Crop diversification Benefit

Benefits of crop residue mulching: Applying a mulch of crop residues over the soil surface (Fig. 2) yields various benefits, such as conserving soil moisture thereby ensuring moisture availability to crop roots reducing weed populations, minimizing the quantity of irrigation water required, and eliminating the need to burn crop residues through their proper utilization. Consequently, the availability of ample moisture facilitates proper seed germination and robust crop establishment, leading to increased yields. Over time, the crop residues decompose and integrate into the soil, thereby enriching its organic matter content. By refraining from burning residues, farmers can mitigate the negative environmental impacts on the atmosphere. Furthermore, burning crop residues adversely affects human health and releases a multitude of gases into the atmosphere, contributing to the problem of global warming.

Benefits of crop diversification: By adopting various types of crop rotation cycles through crop diversification, farmers can help maintain the fertility of their fields. Furthermore, this practice aids

in reducing weed infestation; for instance, within a rice-wheat cropping system, cultivating leguminous crops such as Moong (green gram) or Urd (black gram) during the *Zaid* season not only enriches the soil with nitrogen but also leads to a noticeable reduction in the weed population within the subsequent rice crop. By growing leguminous crops during the Zaid season (Fig. 3) and subsequently incorporating the crop residue into the soil as green manure after one or two pickings of the pods farmers also benefit from an enhancement in the soil's overall fertility. The various benefits of crop diversification are outlined below:

- ✓ Suppression of weeds.
- ✓ Enhancement of soil fertility.
- ✓ Improvement in the physical and chemical properties of the soil.
- ✓ Increase in crop productivity.

Need for protected cultivation

Given the current scenario, protected cultivation is absolutely essential due to its numerous benefits. Along with increasing crop yields, it also enhances the quality of natural resources such as soil, water, nutrients, and crop produce as well as the overall environment. This has become critically important for ensuring the long-term sustainability and health of agriculture.

Impact of traditional farming: Traditional farming practices exert an adverse effect on various natural resources, the details of which are outlined below.

- ✓ Decline in soil fertility and productive capacity.
- ✓ Deficiency of nutrients in the soil.
- ✓ Continuous depletion of groundwater levels.
- ✓ Increasing weed infestation in fields.
- ✓ Rise in soil salinity due to the use of nitrogen-based chemical fertilizers.
- ✓ Presence of toxic agrochemicals in food products.
- ✓ Deteriorating soil health.
- ✓ Climatic anomalies.
- ✓ Issues such as stagnation or decline in crop productivity.
- ✓ The unbalanced utilization of resources is leading to a continuous increase in air, soil, and water pollution.
- ✓ Rising agricultural input costs for farmers, coupled with declining incomes, remain a matter of concern.

The aforementioned factors are having an adverse impact on human health. The expansion of industrialization, modernization, and urbanization is resulting in a reduction in the total area of arable land. Consequently, the challenge lies in generating higher yields from this diminishing land area to sustain the growing population.

Factors responsible for problems: The improper utilization of resources by farmers is giving rise to various types of problems.

- ✓ Failure to properly implement crop rotation.
- ✓ Use of unbalanced and excessive chemical fertilizers.
- ✓ Failure to adopt proper irrigation practices.
- ✓ Over-exploitation of soil fertility.
- ✓ Excessive use of pesticides.

- ✓ Over-exploitation of groundwater resources.
- ✓ Deterioration of soil health.
- ✓ Reduced use of organic fertilizers.
- ✓ Reduced use of green manure and leguminous crops.

Importance of microorganisms

Microorganisms found in the soil enhance soil quality and boost the productivity of plants. To understand the health of the soil, it is crucial to study its microbial inhabitants. In the field of agriculture, we utilize various types of chemical fertilizers, which have a significant impact on the population, size, and metabolic activities of soil microorganisms. The decomposition of organic matter present in the soil is facilitated by cellular enzymes, which are produced by these microorganisms. These enzymes are secreted by microbes, enabling the extraction of limited nutrients from carbon-rich organic substrates. The activity of cellular enzymes is often closely linked to the chemical composition of soil organic matter, specifically its carbon and nitrogen content. When farming is undertaken in saline soils, the quality of organic matter deteriorates; this, in turn, negatively impacts microbial activity and creates drought-like conditions within the soil environment. It has also been observed that the use of heavy machinery often employed during conventional tillage practices frequently leads to a degradation of the soil's structural integrity. Furthermore, rising temperatures can adversely affect soil quality. Microorganisms serve as the living and active components of soil organic matter; by becoming metabolically active under diverse environmental conditions, they influence soil quality. Through the decomposition of plant and animal residues, they enrich the soil and actively participate in the nutrient cycling process, thereby playing a fundamental role in the formation and structuring of the soil itself. Thus, microorganisms play a pivotal role in this ecosystem; it is through their collective activities that soil fertility is enhanced and its overall productive capacity is augmented.

Impact of climate change

Much like other components of agriculture, soil is also being adversely affected by climate change. Due to the use of chemical fertilizers, the soil is already becoming depleted of organic carbon; now, rising temperatures further compromise its moisture content and functional capacity. Furthermore, this leads to a decline in soil salinity and a reduction in biodiversity. The continuous depletion of groundwater levels also negatively impacts the soil's fertility. While disasters such as floods accelerate soil erosion, droughts contribute to increased barrenness. The felling of trees and the failure to adopt crop diversification practices exacerbate the erosion of fertile soil, thereby contributing to the rendering of agricultural fields into barren land.

Benefits of reduced tillage

In reduced-tillage soils, the topsoil layer is more compact compared to that of conventionally tilled soils. The direct changes in physical and

chemical conditions resulting from tillage influence the growth and stability of the microorganisms present in the soil. Consequently, reduced tillage leads to shifts in the dynamics of microbial processes. Tillage also alters the microflora present within the soil; it is for this reason that changes in microbial processes occur. Thus, in contemporary practice, zero tillage exerts a significant influence on microbial populations, soil enzyme activities, and the organic constituents of the soil. The zero-tillage system impacts the abundance of microorganisms, as well as their activity and stability within the soil. Conservation tillage systems play a pivotal role in fostering crop development and enhancing soil fertility. Reduced tillage lowers operational costs and holds the potential to boost crop production. Different tillage practices induce substantial changes in the status of soil microorganisms. These practices influence crop production by affecting the soil's organic matter content, microbial activity, and the dynamic availability and depth-wise distribution of nutrients.

Fig. 4: Crop sown in zero traction

Fig. 5: Crop sown in mulching

Soil microorganisms: Microorganisms convert unavailable nutrients found in the soil into available forms that can be easily utilized by plants. By transforming essential chemical elements such as nitrogen, phosphorus, potash, sulfur, and iron into available forms, microorganisms significantly enhance the accessibility of these elements to plants; these processes are driven entirely by microbial activity. The most critical function of micro-organisms is their participation in elemental cycles, wherein they facilitate the transformation of oxygen, carbon, nitrogen, phosphorus, sulfur, and iron present within the soil matrix.

- ✓ Microorganisms break down organic matter in the soil, thereby releasing organic carbon into the soil matrix, which becomes available for plant uptake. This process enhances the overall fertility of the soil.
- ✓ Microorganisms decompose crop residues and animal remains, integrating them into the soil and consequently increasing the content of organic carbon. They play a pivotal role in improving both the structural composition and the fertility of the soil.
- ✓ The excessive use of pesticides and chemical inputs leads to a significant decline in the population of beneficial microorganisms.
- ✓ They suppress pathogenic microorganisms. Alth-ough pathogenic microorganisms are themselves members of the microbial community, they are effectively outcompeted and displaced by the beneficial microorganisms.

Impact of microorganisms on the environment

- ✓ Carbon dioxide emissions result from the microbial decomposition of organic matter in the soil, the respiratory activity of microorganisms present in the soil, and the burning of organic

materials.

- ✓ Nitrous oxide emissions from the soil occur through the transfer of nitrogen within biological microorganisms and via organic fertilizers, which serve as a primary source.

Conclusion

Based on the aforementioned facts, it can be concluded that fields prepared using conventional tillage (plowing prior to sowing) exhibit higher levels of organic carbon and microbial carbon compared to fields utilizing zero tillage. This increase was found to be even more pronounced when mulching was employed in conjunction with zero tillage; furthermore, this practice also resulted in higher crop yields.

Extension Strategies for Natural Farming and Organic Agriculture: A Pathway toward Sustainable Agricultural Development

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Abstract

Natural farming and organic agriculture are gaining importance as sustainable alternatives to chemical-intensive farming due to their positive impact on soil health, environmental conservation, food safety, and climate resilience. The successful adoption of these farming systems depends largely on effective agricultural extension services that promote awareness, knowledge, and skill development among farmers. This article discusses major extension strategies for promoting natural and organic farming, including farmer training, frontline demonstrations, participatory approaches, ICT-based advisory services, market-led extension, and strengthening farmer organizations. It also highlights the role of government schemes, research-extension-farmer linkages, and youth and women participation in accelerating sustainable agricultural development. The article concludes that strong extension systems integrating scientific knowledge with indigenous practices are essential for achieving environmentally sustainable and economically viable agriculture in India.

Introduction

Agriculture forms the backbone of the Indian economy and sustains the livelihoods of millions of rural households. However, the rapid intensification of agriculture during the Green Revolution era, although successful in increasing food grain production, also led to several ecological and socio-economic challenges. Excessive use of chemical fertilizers, pesticides, herbicides, and intensive irrigation practices has resulted in soil degradation, declining biodiversity, groundwater depletion, environmental pollution, and increasing production costs (Roling and Pretty, 1997). Simultaneously, concerns regarding food safety, climate change, and the sustainability of conventional farming systems have intensified across the globe.

In response to these challenges, natural farming and organic agriculture have emerged as sustainable alternatives capable of ensuring long-term agricultural productivity while protecting ecological balance and human health (IFOAM, 2005). These farming systems emphasize the use of locally available resources, ecological processes, biological nutrient cycling, and environmentally friendly production practices. However, the success of these sustainable farming approaches depends not only on scientific innovations but also on effective agricultural extension strategies that facilitate knowledge dissemination, behavioural change, skill development, and farmer empowerment (FAO, 2001). Agricultural extension acts as a bridge between research institutions and farming communi-

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ties. It plays a critical role in educating farmers, transferring technologies, strengthening local institutions, building confidence, and enabling farmers to adopt sustainable agricultural practices effectively. Therefore, extension strategies for natural farming and organic agriculture must be participatory, location-specific, knowledge-intensive and market-oriented (FAO, 2000; Roling and Pretty, 1997).

Understanding Natural Farming and Organic Agriculture

Concept of Natural Farming: Natural farming is a low-input, eco-friendly agricultural system based on the principle that nature itself can sustain agricultural production without dependence on synthetic chemicals. It promotes the use of indigenous knowledge, biological inputs, crop diversity, soil microorganisms, and ecological harmony (Palekar, 2006). In India, Subhash Palekar Natural Farming (SPNF), also known as Zero Budget Natural Farming (ZBNF), has gained considerable popularity. This approach emphasizes Jeevamrut for microbial activity enhancement, Beejamrut for seed treatment, mulching for moisture conservation, Waaphasa for maintaining soil aeration, mixed and intercropping systems, and indigenous cattle-based farming practices (FAO, 2018). Natural farming aims to reduce cultivation costs by minimizing external input dependence and restoring the natural fertility of the soil ecosystem.

Concept of Organic Agriculture: Organic agriculture is a production management system that avoids synthetic fertilizers, pesticides, hormones, antibiotics and genetically modified organisms. It relies on organic manures, composting, green manuring, crop rotation, biological pest management, vermi-composting, biofertilizers, and biopesticides. According to the Food and Agriculture Organization, organic agriculture is a holistic production management system that promotes agroecosystem health, biodiversity, biological cycles, and soil biological activity (FAO, 2002). Organic agriculture not only improves environmental sustainability but also enhances food quality, nutritional value, and export opportunities (Lampkin, 1994).

Importance of Extension in Sustainable Agriculture

Agricultural extension refers to an educational process aimed at improving farmers' knowledge, skills, attitudes, and decision-making capacities. In the context of natural and organic farming, extension becomes even more significant because these systems are knowledge-intensive rather than input-intensive. Farmers require continuous technical guidance regarding organic nutrient management, biological pest control, soil health restoration, crop diversification, certification procedures, market linkages, resource recycling, and climate-resilient farming practices (Swanson and Rajalahti, 2010). Extension systems help farmers understand the scientific rationale behind sustainable agricultural practices while encouraging practical adoption at the field level. The Indian Council of Agricultural Research (ICAR) has emphasized the

importance of farmer-centric extension approaches for promoting sustainable agriculture in India (ICAR, 2015). Participatory and demand-driven extension services are considered essential for strengthening sustainable farming systems and improving rural livelihoods (FAO, 2001)

Need for Extension Strategies in Natural Farming and Organic Agriculture

Despite growing awareness about sustainable agriculture, the adoption of natural and organic farming remains limited due to several constraints such as lack of scientific knowledge among farmers, fear of yield reduction during the transition period, non-availability of quality organic inputs, limited market access, certification complexities, inadequate extension support, poor awareness regarding government schemes, and weak research extension-farmer linkages (NCOF, 2021; FAO, 2017).

Therefore, systematic extension strategies are essential to accelerate adoption and ensure long-term sustainability. Effective extension approaches help farmers gain technical knowledge, improve confidence in sustainable farming systems, access markets and certification services, and strengthen linkages among researchers, extension personnel, and farming communities (Swanson and Rajalahti, 2010).

Major Extension Strategies for Promoting Natural Farming and Organic Agriculture

Farmer Training and Capacity Building: Training programmes are among the most effective extension tools for promoting sustainable agriculture. Farmers require practical knowledge regarding compost preparation, biofertilizers, biopesticides, vermicomposting, mulching, crop diversification, natural pest control, and soil health management (Swanson & Rajalahti, 2010). Krishi Vigyan Kendras (KVKs), State Agricultural Universities, NGOs, and extension agencies regularly organize hands-on training programmes, exposure visits, field demonstrations, and workshops. Recently, ICAR-KVK Howrah conducted capacity-building programmes focusing on organic inputs, nutrient cycling, and farmer-led innovations in natural farming. Capacity building should also include skill development in organic certification, value addition, branding, packaging, and direct marketing. Trained "Certified Farm Advisors" can further support farmers in adopting sustainable practices effectively (FAO, 2001).

Frontline Demonstrations and Model Farms: Demonstration is a powerful extension method because farmers believe more in "seeing than hearing." Establishing model organic and natural farms helps farmers observe the practical benefits of

sustainable farming systems. Frontline demonstrations conducted by KVKs and extension agencies can showcase improved soil health, reduced production costs, enhanced biodiversity, and better crop quality under organic systems (ICAR, 2015). Farmer Field Schools (FFS) and participatory technology demonstrations can also encourage experiential learning and peer-to-peer knowledge transfer. Successful farmers practicing natural farming should be identified as "farmer ambassadors" to motivate neighbouring farmers through local examples and community interactions (FAO, 2000).

Use of Information and Communication Technologies (ICTs): Digital extension services have become highly important in disseminating agricultural information quickly and effectively. Mobile applications, WhatsApp groups, community radio, YouTube channels, social media platforms, and online advisory portals can provide real-time guidance on organic and natural farming practices. ICT-enabled extension services improve farmers' access to weather forecasts, pest management advisories, market prices, and training materials (Aker, 2011). Indian Council of Agricultural Research (ICAR) has also initiated ICT-led information dissemination systems such as VISTAAR to promote agricultural technologies among farmers. Video-based learning in local languages can simplify complex concepts and increase adoption among small and marginal farmers (FAO, 2011).

Participatory and Farmer-Centred Extension Approaches: Traditional top-down extension approaches are gradually being replaced by participatory models that involve farmers in planning, experimentation, and decision-making. Participatory Rural Appraisal (PRA), Farmer Interest Groups (FIGs), Self-Help Groups (SHGs), and Farmer Producer Organizations (FPOs) can strengthen collective learning and community participation (Chambers, 1994). Farmers possess valuable indigenous technical knowledge regarding seed conservation, botanical pesticides, mixed cropping, and soil fertility management. Extension personnel should integrate scientific recommendations with local knowledge systems for location-specific solutions. ICAR emphasizes participatory and eco-friendly research approaches that respect farmers' traditional wisdom and grassroots innovations (ICAR, 2015).

Strengthening Farmer Organizations and Cooperatives: Farmer Producer Organizations (FPOs), cooperatives, and organic farming clusters can improve collective input procurement, certification, processing, and marketing. Group approaches reduce certification costs and improve bargaining power in the market. Extension agencies should facilitate the formation and strengthening of organic farmer groups and cooperatives. Cooperative -based organic marketing systems can enhance farmers' income and ensure better market access (Trebbin, 2014). Mobilization and organization of farmers are considered crucial strategies for sustain-

able agricultural development (FAO, 2000).

Market-Led Extension and Value Chain Development: One of the major challenges in organic agriculture is marketing organic produce at remunerative prices. Extension services should therefore move beyond production-oriented advisories and focus on market-led extension approaches. Farmers need training on grading, packaging, branding, certification, traceability, and export opportunities (Trebbin, 2014). Establishing organic markets, farmer markets, e-commerce platforms, and direct farmer-consumer linkages can increase profitability. Strengthening value chains through aggregation, processing, and branding is equally important. Market intelligence and consumer awareness campaigns can encourage demand for organic products and improve economic sustainability for farmers (FAO, 2017).

Promotion of Government Schemes and Policy Support

Government support plays a vital role in scaling up natural and organic farming. Extension personnel must create awareness regarding various government schemes such as:

- ✓ National Mission on Natural Farming (NMNF)
- ✓ Paramparagat Krishi Vikas Yojana (PKVY)
- ✓ Mission Organic Value Chain Development for North Eastern Region (MOVCDNER)
- ✓ Rashtriya Krishi Vikas Yojana (RKVY)

Indian Council of Agricultural Research (ICAR) and the Ministry of Agriculture & Farmers Welfare are actively promoting natural farming in hundreds of districts through coordinated extension programmes and training initiatives (Government of India, 2022). Extension workers should assist farmers in availing subsidies, certifications, training opportunities, and financial support under these schemes.

Research-Extension-Farmer Linkages

Strong coordination among research institutions, extension agencies, NGOs, private organizations and farmers is necessary for effective technology dissemination. Agricultural universities and ICAR institutes should develop location-specific organic farming technologies and disseminate them through extension networks. Regular feedback from farmers can help researchers identify field-level problems and refine technologies accordingly. The integration of research, extension and entrepreneurship development has been strongly emphasized for sustainable agricultural transformation (Swanson and Rajalahti, 2010).

Youth and Women Involvement: Rural youth and women can become important agents of change in promoting sustainable agriculture. Extension programmes should encourage agri-entrepreneurship among youth through training on organic input production, mushroom cultivation, beekeeping, vermicomposting, and value addition (FAO, 2014). Women Self-Help Groups (SHGs) can also play an important role in organic vegetable production, seed preservation, processing, and direct marketing activities. Their participation strengthens household nutrition, livelihood security, and rural empowerme-

nt (Agarwal, 2018).

Climate-Resilient and Integrated Farming Approaches

Extension strategies should promote integrated farming systems that combine crops, livestock, fisheries, agroforestry, and organic recycling. Such systems enhance resource-use efficiency and reduce climate-related risks (FAO, 2013). Indian Council of Agricultural Research (ICAR) has developed agro-climatic zone-specific integrated and organic farming models suitable for different regions of India. These models improve sustainability, reduce dependence on external inputs, and increase farm profitability (ICAR, 2019).

Challenges in Extension of Natural and Organic Farming

Although considerable progress has been made, several challenges still hinder the expansion of sustainable agriculture:

- ✓ Lack of trained extension personnel
- ✓ Inadequate organic input availability
- ✓ Limited market infrastructure
- ✓ Certification complexities
- ✓ Transition period yield reduction
- ✓ Poor awareness among farmers
- ✓ Weak institutional coordination
- ✓ Insufficient research on location-specific technologies

Addressing these challenges requires coordinated efforts among government agencies, research institutions, NGOs, cooperatives, and private stakeholders.

Future Strategies for Strengthening Extension Systems

To improve the effectiveness of extension strategies, the following measures are essential:

- ✓ Strengthening public extension infrastructure
- ✓ Increasing investment in sustainable agriculture research
- ✓ Promoting digital extension systems
- ✓ Developing village-level resource persons
- ✓ Encouraging participatory research
- ✓ Enhancing farmer-to-farmer extension
- ✓ Strengthening organic markets and certification systems
- ✓ Integrating traditional and scientific knowledge
- ✓ Promoting climate-smart agriculture

Public-private partnerships and NGO participation can also strengthen extension outreach.

Conclusion

Natural farming and organic agriculture offer sustainable solutions for ensuring food security, environmental conservation, and farmers' livelihood improvement. However, their widespread adoption largely depends on effective agricultural extension systems. Extension strategies such as farmer training, participatory approaches, ICT-based advisories, market-led extension, demonstrations, institutional support, and farmer organization development are essential for promoting eco-friendly agriculture. The future of sustainable agriculture in India lies in integrating scientific innovations with indigenous knowledge, strengthening research-extension-farmer linkages, and empowering farming communities

through continuous capacity building. With appropriate extension interventions and policy support, natural farming and organic agriculture can contribute significantly toward climate-resilient, profitable, and sustainable agricultural development in India.

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Microgreen: A Nutritional Powerhouse for Health

Nikita Bisht and Ajay Hemdan

Abstract

Microgreens are tiny crop species seedlings that are harvested at the cotyledon stage, typically within 7 to 20 days after germination. Recently microgreens have gained global popularity due to functional food are nutrient dense profile. They are packed with essential vitamins, minerals and bioactive compounds. Furthermore, they possess antioxidants, anti-inflammatory and immune boosting properties, however, also provide various mental health benefits through horticulture therapy. Cultivation of microgreens requires minimal space making them ideal for urban agriculture, home gardening and even remote military operation. Microgreens represent ready solutions to fulfill global nutritional demand in the future.

Introduction

An adequate supply of dietary is essential for proper growth and sound health; however mineral malnutrition remains a persistent global but mineral malnutrition has remained a global challenge for human nutrition. Micronutrient deficiency in the diet has been described as “hidden hunger”. Microgreens are seedlings of vegetables, herbs, or even wild species that are grown to the stage of fully opened cotyledons and vary in flavor, color, and texture. Microgreens belong to a special group of vegetables that are considered to be functional food possessing health-promoting and disease-prevention benefits in addition to their nutritional, vitamin, mineral, and antioxidant-rich value. They are the tender, immature greens harvested at the cotyledonary stage or shortly after the first true leaves appear, generally within 7 to 21 days after germination. They have three basic parts a central stem, two cotyledon leaves and first pair of very young true leaves. Microgreens are slightly older, generally harvested when the seedlings reach about 2 inches in height and have developed their first true leaves. Microgreens have gained popularity due to their higher concentrations of bioactive compounds and mineral nutrients in comparison to mature plants. While there are roughly 100 plant species suitable for microgreen cultivation, the mustard family including arugula, broccoli, cabbage, kale, and mustard, are the most commonly chosen due to their easy germination, short growing time, and diverse array of flavors and colors. Mustard family (Brassicaceae) microgreens play a significant role in promoting health due to their high concent-rations of bioactive compounds such as ascorbic

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acid, carotenoids, tocopherols and phenolic compounds, in addition to glucosinolates and mineral nutrients.

Microgreen faming can be done by anyone with very little time and less space. Eating green vegetables helps to a lower risk of many diseases because they contain a high concentration of vitamins, minerals and beneficial plant-based compounds. Additionally, microgreens are blessed with essential nutrients that shield us from different ailments. In order to improve the availability of extra essential nutrients in Soldier's diet, the Defense Institute of High-altitude research, developed technology for the production of vegetable microgreens in 2011-2012 for Indian troops based in remote areas. In recent years, growing interest in organic and natural foods has brought microgreens into the spotlight, owing to their ease of cultivation, rich nutritional profile, and wide-ranging culinary applications. Requiring minimal space and time, microgreens can be grown at home or in resource-limited settings, including vertical farms and hydroponic systems. Rich in vitamins, minerals, and antioxidants, they help lower the risk of various diseases and are considered a healthier alternative to sprouts. Their appeal extends to gourmet cooking as toppings in salads, soups, and sandwiches, owing to their vibrant color, texture, and flavor.

Techniques for production of microgreens

Sowing time: Dry the media properly by exposing it to sunlight and then fill the trays/container. Any living place like rooms or any type of mini-greenhouse can be used to keep your greens to maintain optimum temperature, humidity and light intensity. Microgreens grown in an environment with high light condition, low humidity and good air circulation will result in a better harvest.

Temperature and Humidity control: Microgreens growth is influenced by temperature and humidity. During germination microgreens requires an average temperature range between 20-30°C and a Relative Humidity of 50-80% depending upon the crop species used. Microgreens need a dark environment during the first 3 days of their germination. The ideal temperature ranges between 25-30°C and Relative humidity of 60-70% should be used for successful production of microgreens. For production of microgreen an adequate light exposure of 12-16 hrs. per day for encouraging growth is to be required.

Harvesting: Microgreens have very short life cycle. Depending on the crop and other environmental factors, microgreens can be harvested 7-14 days after germination in a tropical climate and a little later (14-28 days) in a temperate climate. With the help of scissor, microgreens, their stem and any attached seed leaves can be cut. Broccoli microgreens mature in 7-9 days and its nutrient content is 1.73 times higher than its mature counterpart.

Post harvest management: The shelf life of microgreens is limited and there is a need of better transportation and storage methods. It requires specific conditions to stay fresh and safe. Commercial microgreens are usually kept at 2.5 to 3.5°C for a maximum of seven days in plastic clamshell boxes.

Fig. 1: Home grown 7-year old Cauliflower (*Brassica oleracea var. botrytis*) Microgreens

Health benefit

Microgreens are an important part of horticulture therapy it provides a green space to overcome stress and fatigue. Growing microgreens could help reduce laziness among people in remote areas who suffer from a monotonous state of mind that leads to fatigue and social sickness. It's time to replace sprouts with microgreens because of their vibrant color, crunchy texture, flavor, health benefits, Phyto-composition, disease preventing properties that plays a major role in human health. By snacking on microgreens or adding them to meal it naturally boosts immunity. Microgreens are 4 to 40 folds more nutrient concentrated than their mature counterparts. The potential of microgreens as functional foods arises from their nutrient dense profile, rich phytochemicals and diverse health-promoting effects. Microgreens have antioxidant, anti-inflammatory, cardioprotective and anti-diabetic properties. For example, red cabbage microgreen had 40 times more vitamin E and six times more vitamin C than mature red cabbage. Cilantro microgreens had three times more beta-carotene than mature cilantro. Microgreens from the Brassica family, which include broccoli, contain high level of vitamin E, a phenolic antioxidant. Asteraceae microgreens, such as chicory and lettuce, appear to be high in vitamin A, carotenoid anti-oxidants.

Challenges

Despite the number of benefits of micro-greens, it also faces challenges such as during Production, improving storage techniques, consumption, optimizing growth rate and yield of microgreens. Microgreens are more susceptible to bacterial infiltration than their mature parts. Mature plants have Casparian strip barrier, but young plants lack this strip and that allows the bacterial penetration into the xylem. There is a limited awareness of microgreens in India it is due to lack of interest of people trying to accept new things mainly among those who follow traditional and cultural beliefs. It is necessary to raise the awareness of microgreens among people. Microgreens have very short shelf-life even very low temperature; micro-greens young shoot cause the higher respiration rate than their mature parts that causes the deterioration of quality after harvest. Some practices can help in extend microgreens shelf life by applying calcium before harvest and after storage as well as prepacking, washing and dewatering. There is a need of optimizing the growth rate and yield of microgreens. Microgreen farming has been changed by automation which allow precise control over growing condition and gives consistent yield and quality.

Conclusion

Microgreens are best alternate in today's world as a supplement which fulfils the nutritional

demand and helps in prevention from many diseases, and it also makes the food aesthetic. Surely, it is good for healthy and wealthy well-being. It is easy to grow in today's fast paced world, where we neglect our health. By adopting these tiny soft texture greens in our diet, we can change lot in our diet. Different microgreens have different flavor which gives a unique impact to dishes. So, changes are small, but the outcome is big and healthy. It helps with increasing immunity and can also provide a sustainable business model. Everyone is aware about their health that's why everyone want to give every penny for their health. Nowadays, many young entrepreneurs and startups are looking on microgreen farming business as a sustainable and successful venture. In a less time, people can get a nutritious diet. And it is a good alternate for employment because it elevates the status of food.

Nano-Fertilizer in Transplanted Rice

Prakhar Singh Raghuvanshi, Susibna Subhadarsini and Abhisar Singh

Introduction

Rice (*Oryza sativa* L.), family- Gramineae or Poaceae, sub-family Bamboosoideae, Tribe- oryzeae and Genus- Oryza, is the most important food crop around the world, followed by wheat. About 90% of the world's rice production is produced and consumed in Asia. It is a staple food for more the 60% of the world's population and 50% of India's population. The 3rd most important cereal crop in the world is rice after wheat and maize. Rice is the crop of tropical climate. However, it is grown successfully in humid region of sub-tropical and temperate climate. Since independence, area of the rice increased 1.5 times, productivity 3 times and production more than 4 times. China is the leading country in the production of rice followed by India, and area wise India is the leading country in the world. In India, rice ranks first among cereals in term of both area and production. Rice contain 70% carbohydrates, 6-7% protein in white and 7.8% in brown rice, 2-2.5% fat, and low amount of calcium. Rice grain relatively rich in lysine which is 4% of the total protein fraction. The main protein in rice is Oryzenin. The rice bran which is a thin brown, nutrient-rich aleurone layer tightly attached to the endosperm, beneath the husk. It contain the average 20% oil and 12-15% protein.

History: Rice breeding program which was started in early 1911. The imperial council of agriculture research established the central rice research institute (CRRI) at Cuttack, Odisha in 1946 for developing high yield rice varieties and technology for different part of the countries (Ramaiah, 1953). In 1965 the all India coordinate right improvement project was established for rapid generation and identification of varieties and management technician appropriate to different agro ecological situation to accelerate and coordinate rice research at National level, partner with state Agriculture University and department of agriculture and Central agriculture institute. A major breakthrough was made by (IRRI) by releasing the IR8 variety in 1966. A number of special high ending varieties have released from different purpose such as earliness, deep water, flood resistance, lodging resistance, drought resistant, non-shading of grains, disease resistance, and high response to heavy manuring.

Nano-Technology: The concept behind this principle originated in a talk entitled, "There's Plenty of Room at the Bottom" by Richard Feynman a noble laureate in physics in 1959,in which he described the possibility of synthesis via direct manipulation of atoms. The term "Nanotechnology" was coined by Professor *Norio Taniguchi*. A nanoparticle or ultrafine particle is usually defined as a particle of matter that is between 1 and 100 nanometres (nm) in

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diameter In the modern agriculture, conventional agriculture demands the regular use of fertilizer which boost up the crop growth resulting in higher yield, which increase the income of the farmer. These practice have been boosted after the green revolution where chemical fertilizer along with HYV seed were tremendously used in agriculture.

In context with the sustainable agriculture nanotechnology emerge with the promising approach to significantly increase the crop production and feed world's rapidly growing population. As we know the conventional fertilizer has 30-40 % N.U.E. (Nutrient Use Efficiency) whereas nano-fertilizer has 51-80% N.U.E through which it fulfill the nutrient demand by the crop and reduces the environmental impact.

They can be classified based on their mode of action, nutrient composition and consistency. These categories include controlled-release nano-fertilizer, nano-fertilizer for target delivery, plant growth nano-fertilizer, nutrient loaded nano-fertilizer such as surface coated, biological product coated and nano carrier based nano-fertilizer. The toxicity and availability of nanoparticles depends on various biological and geochemical changes that occur within the soil matrix. Following interaction with the root system, nanoparticles migrate to the higher regions of the plant and become lodged in cells and sub-cellular organelles (Shirsat *et al.,* 2024). The nano fertilizer usually has a great targeted area and contains size 1-100 nm (nano meter) and when applied through foliar spray the particle penetrate through microscopic opening, particles size less than 50 nm navigate through stomatal the stomatal pores while the less than 2 nm particles diffuses through lipophilic cuticle layer.

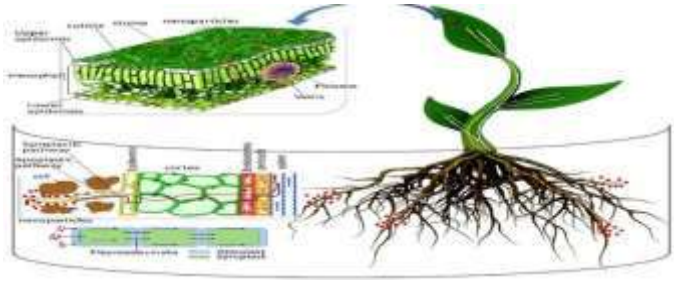

Fig. 1: Absorption of Nano fertilizer in leaf

Nanotechnology in transplanted rice

In a transplanted ecosystem, nutrient loss is accelerated in the anaerobic waterlogged soil condition. Conventional fertilizer *viz.*, urea, DAP etc. Dissolves rapidly leading to ammonia volatilization and nitrate leaching or get fixed in the soil making the nutrient unavailable to the plant. Nano fertilizers feature a high surface-area-to volume ratio and particles size under 100 nm (Abdel-Hakimm *et al.*, 2023). Through this it allows the nano fertilizer for slow release mechanism, and make the plant nutrient fulfill the demand throughout its critical stage as well as reproductive stage.

Method of application

Seed Root Dipping (SRD): Before transplanting the seedlings the seedlings should be dipped in a nano-nutrient suspension *viz.*, Nano-DAP. This directly influence the early root formation, enhance seedling vigor, and establishes strong root zone bio-fortification before the plant get field stress.

Foliar spraying: Rice through conventional agriculture basal dose of chemical fertilizer as well as top dressing in the flooded fields is very common

instead of that foliar spray of the nano-fertilizer at the critical and reproductive stage *viz.,* Active tilllering and Panicle Initiation maximizes the plant growth, no. of panicle bearing tillers and boost up the grain filling, because of their smaller size these nano particles penetrates into the plant through the microscopic opening effortlessly.

Mechanism in N.U.E.: Transplanted rice faces severe challenges like nutrient loss, economic loss, environmental impact. In the flooded paddy fields 50-60% of the broadcasted nitrogen is lost through leaching, denitrification and ammonia volatilization, whereas nano-fertilizer has a unique physiochemical properties that change the nutrient interaction with paddy ecosystem. Rather than providing chemical fertilizer in the standing water, nano-fertilizer contain biodegradable polymers like chitosan, which releases core nutrients in a slow and steadily manner to match vegetative and panicle initiation stage of rice. After the penetration from the cell wall, nano-particles such as zinc or nitrogen are used as metabolic catalysts. They activate enzymes involved in the synthesis of nitrate reductase and glutamine synthetize, the enzymes are responsible for the nitrogen into bio-available protein and amino acid.

Advantages

Higher Absorption: Sub-cellular particle provide nano particles to easily penetrate through leaf stomata and root membrane which increases the absorption rate.

Controlled Nutrient Release: Nano-fertilizer are coated with porous polymers (e.g. chitosan, zeolites, or hydroxyapatite)

Environmental Impact: Sloe release mechanism decreases the groundwater leaching and greenhouse gas emissions.

Reduces logistic cost: Compared to granular fertilizer *viz.,* bulky bags the liquid volume fertilizer reduces the transport, storage and field handling.

Conclusion

Nano-fertilizers can be referred to as revolutionary innovations that have made great contributions towards the improvement of transplanted rice farming by overcoming the challenges encountered with traditional fertilization methods. This is possible owing to their high Nutrient Use Efficiency (51-80%), slow release, and cell-level targeting, which guarantees the continued supply of nutrients throughout various physiological stages of plant growth. Additionally, nano-fertilizers play a crucial role in the production of nitrogen assimilation enzymes like nitrate reductase and glutamine synthetize, hence contributing towards increased agronomic efficiency while reducing nitrogen losses. In summary, the use of nano-fertilizer technology in the cultivation of transplanted rice is environmentally friendly, economical, and scientifically practical.

Resource Conservation Technologies for Millet Crops

Susibna Subhadarshini, Prakhar Singh Raghuvanshi and Abhisar Singh

Abstract

Resource Conservation Technologies (RCTs) are a suite of farm management strategies that focus on improving the efficient use of natural resources including land, water, nutrients, labor, and capital, without affecting crop productivity. In the case of millets, the applicability of RCTs becomes highly relevant towards sustainable agriculture development. The millets are robust crops and have a significant contribution in providing food and nutrition security in adverse climatic conditions. In this study, various RCTs related to millets are discussed, including minimum and zero tillage, Site-Specific Nutrient Management (SSNM), LCC-based Nitrogen Management, Nano Fertilizer, Micro Irrigation Technology, Laser Land Leveling, Mulching, Nutriseed Pack Technology, and Crop Residue Management System. Overall, these practices are intended to increase input resource use efficiency, minimize cost of cultivation, save water for irrigation, improve soil properties, and minimize environmental pollution. It is known from practice that SSNM, application of nano-fertilizers, and laser leveling of fields gradually increase the crop yields and efficiency of use of nutrients and irrigation water. Similarly, proper utilization of crop residues can decrease the amount of greenhouse gas emissions, as well as increase soil organic carbon content and fertility. Despite the proven benefits of RCTs for agronomic and environmental performance, the spread of these technologies in India is not uniform across regions.

Introduction

Millets are the small seeded annual cereal crops belong to family poaceae. Research shows the earliest known consumption of millet was around 8000 BC in China after which cultivation gradually extended across Asia, Europe and Africa. The Food and Agriculture Organization (FAO) classifies millets as small seeded annual cereal crops cultivated for food and fodder, primarily in regions characterized by low and erratic rainfall. They grow across a wide range of climatic and soil conditions, particularly on marginal and degraded lands, exhibiting remarkable resilience to various environ-mental stresses. Today, agriculture is facing a convergence of unprecedented factors: rapid population growth, dwindling arable land, depleting water tables, and the increasing pressures of climate change. Resource conservation technologies (RCTs) are indispensable for long term sustainability of agriculture in the face of declining per capita availability of land, water and other natural resources as a result of climate change and growing world population. Against this background, RCTs have emerged as a critical suite of practices and tools to optimize input use, reduce

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environmental degradation and sustain agricultural productivity in diverse agro-ecological settings. Resource conservation technologies include a wide range of agronomic innovations. Important RCTs include laser land leveling, zero tillage, bed planting, direct seeded rice, leaf color charts, green seekers and crop diversification. In essence, resource conservation technologies represent a paradigm shift in the dynamic interaction of agriculture with natural systems. RCTs are essential in millet-based systems since the crop is adapted to marginal environments. Conservation tillage such as minimum and zero tillage reduces soil disturbance and conserves residual moisture which is vital for short duration millets. SSNM and LCC based nitrogen application ensures accurate nutrient supply. Foliar application of nano fertilizers at critical growth stages increase nutrient uptake and yield attributes. Micro-irrigation systems, such as drip and sprinkler irrigation, help make the most of scarce water resources and improve water productivity. By way of laser land leveling, it helps in uniform irrigation and saving of water. The use of mulch and residue contributes to moisture conservation, regulation of temperatures and addition of organic matter, which increase soil fertility and reduce GHG emissions. Use of Nutriseed pack technology leads to vigorous growth of the millet plants.

Importance of Millets in Resource Conservation Technology

Water conservation: Water saving mechanisms in millets include C_4 photosynthesis, deep fibrous roots and a short duration crop life. C_4 photosynthesis, allows the CO_2 fixing through slightly closed stomata, minimizes transpirational loss of water and results in better water use efficiency. Deep roots with a wide spread are capable of drawing water from deeper soil strata as the surface layers get dry. Life cycle of 60-90 days facilitates "drought escape" where grain filling phase is completed even before the available moisture is exhausted. Narrow, waxy and rolled leaves reduce the area from which water evaporates and osmotic adjustments help to maintain turgidity in the cells under water deficit conditions.

Soil conservation and Land management: Millets are valuable for land and soil conservation, particularly on degraded, marginal, and sloped lands. Their highly developed, fibrous roots hold soil aggregates, increase structural integrity, and promote infiltration, thus reducing surface runoff and soil erosion during periods of intense rainfall. This large root biomass is responsible for increasing porosity and organic matter after decomposition, enhancing water holding capacity and preventing crust formation. The low input and drought tolerant nature of millets requires minimum tillage thus conserving the soil profile from disturbance and loss of organic carbon. Their shorter crop duration and capacity to grow on marginal and infertile lands reduces the need to clear forests or farm on marginal lands. The post-harvest crop residues from millets are excellent mulch protecting topsoil from impact of rain drops, moderating temperature and reducing evaporation.

Nutrient Balance: Millets efficiently absorb and

recycle nutrients and have low nutritional demand, therefore maintaining nutrient balance. Their thick, fibrous root structure scavenges nutrients from lower soil layers, enhancing the utilisation of residual and native soil fertility. Millets are evolved to low-input systems and so require 30-40% less NPK compared to rice or wheat, thus decreasing nutrient mining. Residues left in the field decay slowly giving back organic matter, N, P, K and micronutrients such as Zn and Fe to the soil. In rotations or intercropping with legumes, millets benefit from biological nitrogen fixing which enhances the overall fertility of the system. They may grow on marginal soils and hence save unnecessary fertiliser input and reduce losses from leaching and runoff. Hence, millet-based systems help in maintaining the nutrient status of the soil, improving nutrient usage efficiency and ensuring long-term agro-ecological balance.

Crop Rotation and Diversification: Millets are known to enhance soil health, break pest and disease cycles and improve system resilience under climate stress, therefore contributing considerably to crop rotation and diversification. Their extensive fibrous root systems improve soil structure and organic matter content and their low fertiliser and water requirements prevent resource depletion in cereal intensive rotations. Millets are short duration, drought- and heat tolerant crops that offer temporal and spatial diversity, and can be integrated with pulses, oilseeds and vegetables to optimise land usage and labour. It reduces dangers of mono-cropping, smoothens yields and enhances nutritional and economic security of farming households.

Habitat Creation: Millets contribute to habitat development by increasing agro-biodiversity in the dryland and marginal agro-ecosystems. They provide ground cover through their compact canopy and short duration of growth thus minimizing exposure of soil to solar radiation and providing adequate micro-climate to conserve moisture and moderating temperature. These conditions encourage soil micro-flora, earthworms and pollinators. Birds, insects and small animals are attracted to millet fields which have little chemical application and can improve on-farm biodiversity. Animal husbandry, wild birds and natural enemies of pests are also provided with feed and shelter by crop residues and standing stubble. Their interaction with legume or oilseed crops in intercropping systems can enhance structural diversity to enhance habitat for many species and different ecological niches can be provided.

Major Resource Conservation Technologies for Millet Crops

Minimum Tillage and Zero Tillage: Minimum tillage practice requires minimal cultivation or minimum mechanical disturbance of soil, mostly through shallow loosening or direct drilling. Resource conservation is encouraged as it maintains the soil structure, reducing wind and water erosion of organic matter. Cheaper costs for fuel and labor due to less tillage means less energy expenditure is used. Soil moisture is conserved in rainfed areas due to enhanced infiltration and retention capacity.

This method was originally introduced in USA in 1974. Zero tillage is a method of resource conservation technology where the crop dry seeding is followed in soya and maize directly by drilling without fresh or old tillage. The tillage or plowing is also avoided in the residual crop stubble lands, as it results in preservation of soil structure, prevents erosion, loss of organic carbon and high evaporation losses. The surface retained crop or pasture residues are used as mulch for conservation of moisture, moderating soil temperature and suppression of weeds. It results in decreased usage of water for irrigation, fuels and energies, thus optimum reduction in input costs and energy use. It was pioneered by Edward H. Faulkner in 1940.

Nutri Seed Pack Technology: A tubule, biodegradable system known as 'Nutri seed Pack' has been designed to serve as the precision seed cum nutrient delivery system. A pack measuring approximately 1.25.0cm would be placed once on soil either on sowing or at the time of planting. The pack from top to bottom would consist of a bioinoculant treated seed at top, a enriched manure pellet at the center and encapsulated NPK fertilizer at bottom. The pack is wrapped with polyester coated paper, having nano-pores for entry of water to be able to release nutrients at near root zone through slow process. This will save broadcast losses and ammonia volatalization losses and may reduce 50% of the fertilizer application and increase 10-30% of yield. The technology has been developed by Department of Soil Science and Agricultural Chemistry of TNAU, Coimbatore. For commercializing the technology into an industrial entreprene-urship model, DST, New Delhi along with TNSCST, Chennai has funded Rs. 30.91 lacs during 2011-14.

Site Specific Nutrient Management: Site Specific Nutrient Management is a precision-based fertiliser technique that matches the application of nutrients to the crop, field and season specific demands. Unlike blanket recommendations, SSNM links the supply of nutrients to the need of crops at each growth stage, based on the indigenous nutrient supply of the field. The available N, P, K and micronutrients are first evaluated using soil tests, crop residue data or diagnostic instruments like Leaf Colour Chart, Nutrient Expert and sensors. Then the nutrient requirement is calculated as: crop nutrient uptake for goal yield soil supply fertilizers are administered in 3-4 splits during important stages of growth, generally at the root zone or via fertigation, drip or drones. SSNM enhances Nutrient Use Efficiency by minimizing losses due to leaching, volatilisation and runoff. It reduces input costs, prevents over/under fertilisation and increases yields by 10-30%. Environmentally, it reduces greenhouse gas emiss-ions and protects groundwater. SSNM is presently being extensively used for rice, wheat, maize, sugarcane and vegetables to achieve economical, sustainable and climate-smart fertilisation.

Leaf Color Chart: Leaf Color Chart (LCC) is a simple low-cost method for in-season management of nitrogen on crops, particularly rice, wheat, and maize, enables application of fertilizer in response to

crop demand. It is a plastic strip with 4-6 green shaded standards (from 2 to 5). During the critical growth stage (14-21 days after transplanting in rice and at 7-10 days interval after that for all crops), the farmers match the color of the topmost fully expanded leaf with the shaded standards. If the color is lighter than the shaded standards, fertilizer is applied. For rice, generally shaded standards 4 is the threshold, and for wheat and maize it is shade 3. Only when the crop appears to have deficiency of N, apply fertilizer at very small dose, that too split applied. No over application, and no broad application.

Nano Fertilizers: Nano fertilizers are nutrient formulation developed at nano scale (typically between 1 and 100 nm). The particle size of the nutrients is reduced and these nano-nutrients are encapsulated inside the nano-carriers, thereby enhancing the solubility, surface area and crop's nutrient uptake. The nutrients like N, P, K, Zn or Fe are either coated by polymers, zeolites or chitosan or synthesized as nano-particles and it enables the slow and regulated release of these nano-nutrients near the roots or via foliar spray. Due to improved root and leaf uptake of nano-fertilizers, loss of nutrient by leaching, volatalization and fixation in the soil is minimized. Some examples are nano Urea, nano zinc and nano DAP developed by IFFCO and other research institutes. For example, nano Urea can be used as foliar spray for crops of cereals can replace up to 50% of conventional urea.

Micro Irrigation: Micro irrigation refers to the type of water-saving irrigation where the water is applied to the root zone of the crop in small and frequent intervals and it includes drip irrigation, sprinkler, micro sprinkler and bubbler irrigation systems. Drip irrigation is a micro-irrigation method in which the water is directly applied at the root zone of the crops in small volumes in a fixed interval, through the application network which includes filters, pipes, valves and drippers or emitters which works under low pressure so that the minimum water losses occur. The water is conveyed by drops or fine streams to the soil at base of the plants and hence optimum soil moisture is maintained without wetting the entire field thereby the evaporation, runoff and deep percolation are minimized. The application efficiency of drip system is 90-95 %and it results in saving of 30-60% of water and 25-35 % of time. Sprinkler irrigation is the type of micro-irrigation where water is distributed to the crops in the form of fine spray under high pressure through a network of pipes, pumps, valves and sprinklers like rotary or fixed which resembles natural rainfall. The water is delivered to the required area with uniform coverage over the soil surface and crop canopy thus the surface flow and deep percolation is minimized and only required water is applied which saves water (30-50%) in comparison to surface irrigation (40-50%) while, there is less requirement of labor, leveling, and reduced soil erosion.

Laser Land Levelling: Laser land leveling is a precision land-forming practice, where a laser transmitter is installed on one side and a sensor guided scraper is attached on a tractor that maintains

a uniform land gradient of 0.1-0.2%. It reduces the high spots and fills the low spots in the field. As the tractor moves on the field the laser receiver attached to it senses the elevation differences and automatically adjusts the height of the scraper so that the whole field becomes leveled and uniformly sloped. Because of the leveling with the help of laser there is about 20-30% water saving by having even distribution of water and hence reducing run off, water logging, deep percolation, by about 25-35%. Better moisture distribution result in even germination, crop stand and hence 5-15% yield increase in rice, wheat, maize, sugarcane, cotton, and vegetables. Input cost like fertilizers, herbicides are saved due to decreased loss of nutrients and chemicals. Soil erosion is reduced, and salt accumulation in low lying areas is minimized.

Mulching: Mulching is a water-saving technique where the soil surface is covered by organic material like straw, crop residues, leaves, coco peat, etc. and inorganic material like plastic film, gravel, pebbles etc. To protect the soil surface and promote crop growth. Mulch layer decreases evaporation from the soil surface by 30-50% which conserves the soil moisture and regulates soil temperature by keeping the soil cool during summer and warm during winter; prevents wind and water erosion; checks weed germination by blocking sunlight. Organic mulches improve soil structure, porosity, increase organic matter and activity of microorganisms, slowly releases N, P, K and micronutrients into the soil, thus preventing their losses by leaching and minimizing their application.

Conclusion: Millet crops are of critical importance in the context of global food security, not only as a subsistence crop for many communities but as a nutritionally rich source of vital carbohydrates, high quality proteins and dietary fibre. Thus, millet crops address both the issue of caloric sufficiency and the micronutrient adequacy challenge in an age of demographic growth and dietary change. Millets are getting awareness as climate-smart cereals that can stabilise yields in marginal and rainfed agro-ecologies where traditional cereals often fail due to their inherent sensitivity to abiotic stresses such as drought, heat and poor soil fertility. But the sustainability and nutritional benefits of these crops are closely tied to the prudent management of natural resources during their production. Therefore, the need to conserve and optimise inputs like water, nutrients, energy and soil organic matter has become a prerequisite for sustainable intensification in agriculture. The use of resource conservation technologies in millet-based farming systems has been found to be very effective in achieving the dual objective of productivity along with ecological sustainability by reducing external dependence and boosting system efficiency. The set of transformative practices includes micro-irrigation and solar-powered irrigation systems that allow for targeted, demand-driven water supply to the root zone, thereby reducing evaporative losses, mitigating the depletion of groundwater and increasing the water-use efficiency per unit of output.

Soil Microorganisms for Drought and Salinity Stress Management

Harish V., Priya Paghdar, Priyanka Jat and Kavan Patel

Abstract

Drought and salinity are major abiotic stresses that severely affect crop growth, productivity and food security under changing climatic conditions. Beneficial soil microorganisms such as plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), cyanobacteria, and endophytes help plants tolerate these stresses through improved nutrient uptake, water absorption, phytohormone production, osmotic adjustment, and antioxidant defense mechanisms. Microbial inoculants also enhance soil fertility and reduce dependence on chemical fertilizers, supporting sustainable agriculture. However, challenges such as inconsistent field performance and poor microbial survival limit their application. Integrating microbial technologies with sustainable farming practices can improve climate resilience and agricultural productivity.

Introduction

Abiotic stresses such as drought and salinity are major constraints on crop productivity and threaten food security under changing climate conditions. Plant responses to these stresses are complex, involving physiological, metabolic, and molecular adjustments. When combined, drought and salinity create more severe effects due to both water deficit and salt toxicity, disrupting nutrient balance and plant growth. Although developing stress-tolerant crops is essential, it is time-consuming. Therefore, integrating improved crop varieties with sustainable agronomic practices and beneficial microbes is crucial for managing stress and ensuring stable agricultural production.

Drought and Salinity stress: Drought is a condition of insufficient water availability that adversely affects ecosystems, agriculture, and overall plant growth. It disrupts essential physiological processes such as photosynthesis, respiration, and nutrient uptake, leading to reduced growth and yield. In addition, drought induces the accumulation of reactive oxygen species, which cause cellular damage and may result in plant death. To cope with such stress, plants develop adaptive mechanisms including maintenance of water balance, protection of cellular structures, and synthesis of protective compounds. Similarly, salinity stress further aggravates these effects by limiting water uptake through osmotic stress and causing ion toxicity due to excessive salt accumulation in plant tissues. This leads to nutrient imbalance, impaired cellular functions and reduced plant productivity. Consequently, key processes such as germination, photosynthesis, and yield are negatively affected, and under severe conditions, salinity stress can ultimately

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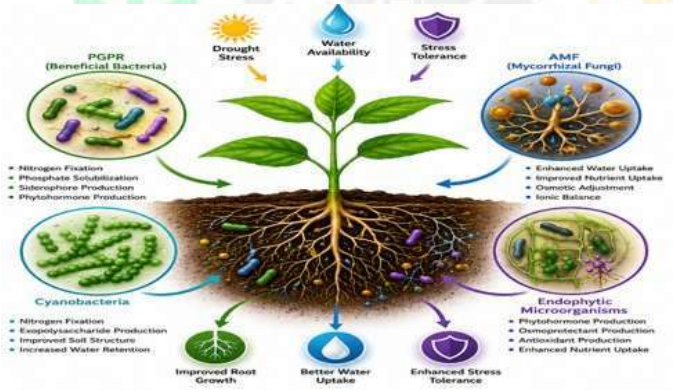
lead to plant death (Parihar *et al*., 2015).

Role of Soil Microorganisms in Stress Mitigation

Beneficial soil microorganisms play a crucial role in helping plants survive under unfavourable environmental conditions such as drought and salinity stress. These microorganisms inhabit the rhizosphere region or live within plant tissues, where they establish beneficial associations with plants. Through several physiological and biochemical processes, they improve plant growth, nutrient availability, water uptake and overall stress tolerance. Soil microbes also contribute to maintaining soil fertility and biological activity, making them important components of sustainable agriculture under changing climatic conditions (Vurukonda *et al.*, 2016).



Plant Growth-Promoting Rhizobacteria (PGPR): Plant growth-promoting rhizobacteria (PGP R) such as Bacillus, Pseudomonas, Azospirillum and Rhizobium enhance plant growth through nitrogen fixation, phosphorus solubilization and phytohormone production. Under drought stress, PGPR improve root growth, water uptake, and soil moisture retention through exopolysaccharide production and ACC deaminase activity. During salinity stress, they maintain ionic balance by reducing sodium toxicity and increasing potassium uptake. PGPR also stimulate antioxidant enzymes and osmolyte accumulation, protecting plants from oxidative and osmotic damage. Consequently, PGPR-treated plants exhibit better growth, higher chlorophyll content, and improved tolerance to drought and salinity stress.

Arbuscular Mycorrhizal Fungi (AMF): Arbuscular mycorrhizal fungi (AMF) form beneficial associations with plant roots and enhance water and nutrient uptake, particularly phosphorus. Their hyphae extend beyond the root zone, increasing nutrient absorption under stress conditions. During drought, AMF improve water relations, photosynthesis, antioxidant activity and osmotic adjustment, helping plants tolerate water deficiency. Under saline conditions, AMF reduce sodium accumulation and enhance potassium, calcium, and phosphorus uptake, thereby maintaining ionic balance and reducing salt toxicity. Consequently, mycorrhizal plants show better growth, higher chlorophyll content, and improved tolerance to drought and salinity stress.

Cyanobacteria and Entophytic Microorganisms: Cyanobacteria are photosynthetic microorganisms that contribute to soil fertility through nitrogen fixation and organic matter production. They release extracellular polysaccharides that improve soil aggregation, increase water-holding capacity, and enhance soil stability. In saline environments, cyanobacteria help reduce salt stress by improving soil structure and nutrient availability, thereby creat-

ing a more favourable environment for plant growth. Endophytic microorganisms live within plant tissues without causing any harmful effects to the host plant. These microbes improve plant stress tolerance by producing phytohormones, osmoprotectants, and antioxidant compounds. Entophytes also enhance nutrient uptake and stimulate various defence responses that help plants adapt to drought and salinity stress. Their ability to induce systemic tolerance makes them highly valuable for developing climate-resilient agricultural systems.

Mechanisms of Microbial Stress Tolerance

Beneficial soil microorganisms help plants survive under drought and salinity stress through several important physiological and biochemical mechanisms. These microbes improve plant growth, protect cellular structures, and enhance the ability of plants to adapt to unfavourable environmental conditions (Yang, Kloepper and Ryu, 2009).

Production of Phytohormones: Many beneficial microorganisms produce plant growth hormones such as auxins, gibberellins, cytokinins, and abscisic acid, which play a major role in regulating plant growth and stress responses. These phytohormones stimulate root elongation, improve nutrient uptake, and promote better plant establishment under stressful conditions. Enhanced root growth allows plants to absorb more water and nutrients from deeper soil layers, thereby improving tolerance to drought and salinity stress.

ACC Deaminase Activity: Under stress conditions, plants produce higher levels of ethylene, a stress hormone that can inhibit root growth and overall plant development. Certain beneficial micro-organisms produce the enzyme ACC deaminase, which breaks down ACC, the precursor molecule of ethylene. By lowering ethylene levels, these microbes help maintain normal root growth and improve plant performance under drought and saline environments.

Osmotic Adjustment: Beneficial microbes also support osmotic balance in plants by stimulating the accumulation of osmoprotective compounds such as proline, glycine betaine, trehalose, and soluble sugars. These compounds help maintain cell turgor pressure, stabilize proteins and membranes, and protect plant cells from dehydration and osmotic stress caused by water deficiency or excess salts.

Antioxidant Defense System: Drought and salinity stress often lead to the excessive production of reactive oxygen species, which can damage cellular components. Beneficial microorganisms enhance the activity of antioxidant enzymes including superoxide dismutase, catalase, and peroxidase. These enzymes neutralize harmful reactive oxygen species and reduce oxidative damage, thereby protecting plant tissues and improving stress tolerance.

Improved Nutrient and Water Uptake: Microbial inoculation improves nutrient availability and water absorption by promoting root growth, soil aggreg-ation and nutrient solubilisation. Beneficial microbes increase the availability of essential nutrients such as phosphorus, nitrogen, and micronutrients in the rhizosphere. Arbuscular mycorrhizal fungi, in partic-

ular, extend fungal hyphae into the soil and significantly enhance phosphorus and water uptake under stress conditions, leading to improved plant growth and productivity.

Applications in Sustainable Agriculture

- ✓ Microbial inoculants are widely used in sustainable agriculture to improve crop growth under drought and salinity stress.
- ✓ Bio fertilizers containing beneficial microbes such as PGPR and AMF help enhance plant growth and productivity naturally.
- ✓ These microbial products are eco-friendly and reduce the excessive use of chemical fertilizers and soil amendments.
- ✓ Microbial consortia, which contain different beneficial microorganisms, are more effective because each microbe performs specific functions that support plant growth.
- ✓ Combining microbial inoculants with organic farming, mulching, conservation agriculture, and proper irrigation practices improves soil fertility and crop resilience.

Challenges of Microbial Interventions in Sustainable Agriculture

- ✓ The performance of microbial inoculants is often inconsistent under different field and environmental conditions.
- ✓ Soil characteristics such as pH, salinity, temperature, and moisture levels influence microbial survival and activity.
- ✓ Different crop varieties respond differently to microbial inoculation, which affects overall efficiency.
- ✓ Beneficial microorganisms may not survive for long periods during storage and transportation.
- ✓ Competition with native soil microorganisms can reduce the establishment of introduced microbial strains.
- ✓ Lack of awareness among farmers regarding the benefits and proper application of bio fertilizers limits their adoption.

Conclusion

Soil microbial interventions offer an eco-friendly and sustainable approach for managing drought and salinity stress in agriculture. Beneficial microorganisms such as PGPR, arbuscular mycorrhizal fungi, cyanobacteria, and endophytes improve plant growth, nutrient uptake, water-use efficiency, and stress tolerance through various physiological and biochemical mechanisms. These microbes also enhance soil fertility and reduce dependence on chemical fertilizers. Although challenges such as environmental variability and poor microbial survival remain, advances in microbial technology and increased farmer awareness can promote their wider adoption. Integrating microbial inoculants with sustainable farming practices can play a vital role in achieving climate-resilient and productive agriculture.

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Reviving a Forgotten Super Crop: Bambara Groundnut as a Climate-Smart Solution for Food and Nutritional Security

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Bambara groundnut (*Vigna subterranea*) is an underutilized legume crop with immense potential to address global challenges of food and nutritional security under changing climatic conditions. Despite being indigenous to Africa and traditionally cultivated in marginal environments, it has gained recognition as a climate-resilient crop due to its drought tolerance, adaptability to poor soils, and balanced nutritional composition. This paper reviews the agronomic, nutritional, economic, and ecological significance of Bambara groundnut, emphasizing its role as a "complete food" rich in protein, carbohydrates, and essential micronutrients. The crop's ability to fix atmospheric nitrogen and thrive under low-input conditions makes it suitable for sustainable farming systems. Additionally, its importance in supporting smallholder farmers, particularly women, and its potential in value-added food processing industries are highlighted. However, constraints such as low productivity, limited research attention, and poor market integration hinder its widespread adoption. The study concludes that strategic interventions in research, breeding, processing, and market development can unlock the full potential of Bambara groundnut as a climate-smart crop for future food systems.

Bambara groundnut (*Vigna subterranea*) is a lesser-known legume belonging to the family Fabaceae. It is predominantly cultivated in sub-Saharan Africa and is increasingly recognized for its resilience under adverse climatic conditions. In the context of climate change, population growth, and food insecurity, there is a growing need to promote underutilized crops that can thrive in marginal environments. Bambara groundnut stands out due to its ability to produce reasonable yields under drought conditions and poor soils, making it an ideal crop for sustainable agriculture. It also plays a significant role in ensuring food and nutritional security for smallholder farmers.

Nutritional Value

Bambara groundnut is often referred to as a "complete food" due to its balanced nutrient profile:

- ✓ Protein: 18-24%
- ✓ Carbohydrates: 50-65%
- ✓ Fats: 6-8%
- ✓ Rich in essential amino acids such as methionine and lysine
- ✓ High in minerals like calcium, iron, and potassium
- ✓ Gluten-free, suitable for specialized diets

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Botanical Description

Bambara groundnut is an annual, self-pollinated, geocarpic legume. Similar to groundnut (*Arachis hypogaea*), it produces flowers above ground, while pods develop underground after fertilization. The pods typically contain 1-2 seeds, which vary in color from cream and red to brown and black, indicating genetic diversity within the crop.

Ecological Requirements

The crop is highly drought-tolerant and suitable for arid and semi-arid regions. It grows well in sandy loam soils with good drainage and can perform in marginal soils where other crops fail. Optimal rainfall requirement ranges from 600-800 mm, though it can survive under lower rainfall conditions.

Agronomic Practices

Land Preparation: Requires a fine seedbed similar to groundnut cultivation.

Sowing: Seeds are sown at a spacing of 50 cm × 25 cm with a depth of 3-5 cm.

Seed Rate: 20-25 kg ha^{-1}.

Weed Management: Early weeding is crucial.

Fertilization: Minimal fertilizer requirement due to nitrogen fixation; phosphorus application enhances yield.

Crop Duration: 90-150 days depending on variety and environment.

Yield and Production

Under traditional farming systems, yields range from 800-1,200 kg ha^{-1}. With improved agronomic practices, yields can reach up to 2,500 Kg ha^{-1}. Harvesting involves uprooting plants, followed by drying and threshing.

Uses

Food Uses: Consumed as boiled seeds, roasted snacks, flour, porridges, and soups.

Beverages: Used in preparation of traditional and fermented drinks.

Livestock Feed: Crop residues serve as protein-rich fodder.

Industrial Uses: Potential applications include protein isolates, plant-based milk, and bakery products.

Economic and Social Importance

Bambara groundnut is primarily cultivated by smallholder farmers and plays a vital role in household food security. It is often referred to as a "women's crop" due to its importance in women-led farming systems. Its resilience makes it a reliable crop during drought and famine, acting as a safety net for vulnerable communities.

Challenges

- ✓ Low yields due to unimproved varieties
- ✓ Limited research and breeding efforts
- ✓ Long cooking time requiring more fuel
- ✓ Poor market awareness and commercialization

Future Prospects

Bambara groundnut is categorized as a neglected and underutilized species (NUS) with significant potential to:

- ✓ Enhance food and nutritional security
- ✓ Promote climate-resilient agriculture
- ✓ Support sustainable farming systems through

nitrogen fixation

- ✓ Generate income through value addition

Advancements in breeding, processing technologies, and value chain development are expected to promote its mainstream adoption.

Conclusion

Bambara groundnut is a highly promising yet underutilized crop with the potential to contribute significantly to global food systems. Its adaptability to harsh climates, nutritional richness, and socio-economic importance make it a valuable resource for sustainable agriculture. Strategic efforts in research, awareness, and commercialization can transform it into a major crop for future food and nutritional security.

Genetic Modification Crops in India: Modern Biotechnology for Sustainable Agriculture and Food Security

Dinesh Kumar Meena, Sanjay Kumar, Diksha Sangh Mitra, Sunil Kumar Rawat and Ratan Kumar Pal

Introduction

Genetic modification (GM) in crops is one of the most significant scientific advancements in modern agriculture. It involves the introduction, deletion, or modification of genes in plants to develop improved crop varieties with desirable traits such as insect resistance, disease tolerance, drought resistance, enhanced nutritional quality and higher productivity. In India where agriculture supports millions of farmers and contributes significantly to the national economy, biotechnology has emerged as an important tool for ensuring food security and sustainable agricultural development. The infographic highlights various genetically modified crops, biotechnology tools, benefits, challenges and future prospects associated with GM crops in India. Technologies such as CRISPR-Cas9, tissue culture, molecular breeding, RNA interference (RNAi), nanotechnology and marker-assisted selection are transforming Indian agriculture by developing climate-smart and nutritionally improved crops.

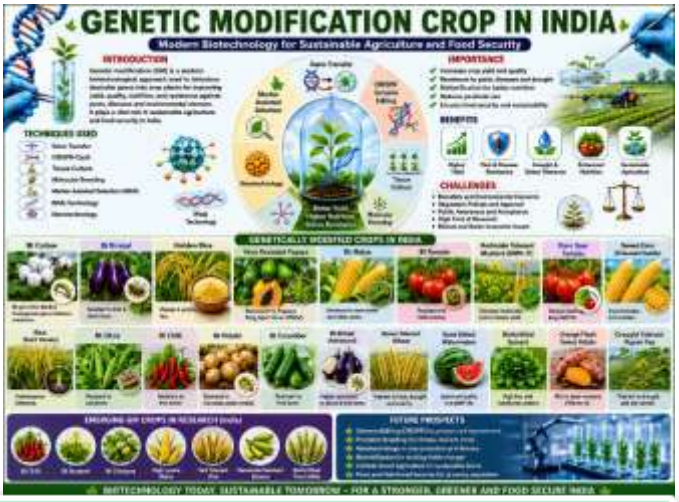
Biotechnology Tools Used in Genetic Modification

Modern biotechnology utilizes several advanced techniques for crop improvement:

Gene Transfer Technology: Gene transfer involves introducing beneficial genes from one organism into another to express desirable traits. This technology has been widely used in *Bt* crops to provide resistance against insect pests.

CRISPR-Cas9 Genome Editing: CRISPR-Cas9 is a revolutionary genome-editing tool that allows precise modification of genes. It helps scientists develop crops with improved stress tolerance, enhanced nutritional quality, and resistance to pests and diseases.

Tissue Culture: Plant tissue culture enables rapid multiplication of disease-free and genetically uniform plants under controlled laboratory conditions. It plays an important role in vegetable and horticultural crop improvement.



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Marker-Assisted Selection (MAS): MAS uses molecular markers linked to desirable genes for rapid and accurate crop breeding. This technology accelerates the development of superior crop varieties.

RNA Interference (RNAi): RNAi technology helps silence harmful genes in pests and pathogens, reducing crop damage and improving plant resistance.

Nanotechnology: Nanotechnology enhances nutrient delivery, pesticide efficiency and disease management while reducing environmental pollution.

Major Genetically Modified Crops in India

The infographic presents several important GM crops developed or researched in India:

***Bt* Cotton:** *B*t Cotton is the first commercially approved GM crop in India. It contains the *Bt* gene from *Bacillus thuringiensis*, which provides resistance against bollworm pests. *Bt* Cotton significantly reduced pesticide usage and improved cotton productivity.

***Bt* Brinjal:** *B*t Brinjal was developed to resist fruit and shoot borer insects. Although approved in some countries, its commercialization in India remains under regulatory consideration.

Golden Rice: Golden Rice is enriched with beta-carotene (Vitamin A precursor) to combat vitamin A deficiency and malnutrition.

Virus Resistant Papaya: This genetically modified papaya variety provides resistance against Papaya Ring Spot Virus (PRSV), reducing crop losses.

Herbicide Tolerant Mustard (DMH-11): DMH-11 mustard was developed to improve hybrid seed production and increase crop yield.

Biofortified Crops: Biofortified spinach, sweet potato and rice are being developed to improve nutritional quality and reduce micronutrient deficiencies.

Benefits of GM Crops

Increased Crop Productivity: GM crops help improve agricultural productivity by reducing crop losses due to pests, diseases and environmental stresses.

Reduced Pesticide Usage: Insect-resistant crops such as *B*t Cotton reduce the need for chemical pesticides, lowering production costs and environmental pollution.

Improved Nutritional Quality: Biofortified crops enriched with vitamins, minerals and antioxidants help address malnutrition and hidden hunger.

Climate Resilience: Genetically modified crops with drought, salinity and heat tolerance support agriculture under changing climatic conditions.

Sustainable Agriculture: Biotechnology promotes sustainable farming by increasing efficiency, reducing resource wastage and improving environmental safety.

Future Prospects of Genetic Modification in India

The future of GM crops in India is highly promising. Emerging technologies such as genome editing, precision breeding, artificial intelligence and nanobiotechnology will further strengthen crop improvement programs. Scientists are focusing on developing climate-resilient crops capable of tolerating drought, heat, salinity and emerging pests under changing climate conditions. Genome editing technologies like CRISPR-Cas9 offer faster, more

accurate and cost-effective crop improvement approaches compared to traditional breeding. Biofortification programs are expected to improve nutritional security by enhancing vitamin and mineral content in staple crops. The integration of biotechnology with sustainable agricultural practices can help India achieve long-term food security, higher farmer income, and environmental sustainability.

Conclusion

Genetic modification in crops represents a transformative approach toward modernizing Indian agriculture. Advanced biotechnological tools are helping scientists develop crops with improved yield, better nutritional quality, enhanced resistance to pests and diseases and tolerance to environmental stresses. GM crops such as Bt Cotton, Golden Rice and virus-resistant Papaya demonstrate the potential of biotechnology in addressing food security and agricultural sustainability. Although challenges related to biosafety, regulation and public acceptance remain important, responsible research, transparent policies and scientific awareness can support the safe and effective adoption of GM technology. With continued innovation and interdisciplinary research, genetic modification will play a critical role in building a sustainable, climate-resilient and nutritionally secure agricultural future for India.

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Entomopathogenic Nematodes as Biological Control Agents in Sustainable Agriculture

Priyanka K.

Introduction

The global agricultural system faces a paradox. Feeding nearly 8 billion people requires intensive crop production, yet the chemical pesticides that enabled the Green Revolution now threaten the ecological foundations of farming itself. Pollinator collapse, contaminated groundwater, pesticide-resistant superbugs, and residues in food have prompted scientists and farmers alike to search for alternatives that kill pests without poisoning everything else. Among the most promising solutions are organisms so small they're invisible to the naked eye: entomopathogenic nematodes, or EPNs. These microscopic worms, typically measuring less than a millimeter in length, have evolved a remarkably sophisticated hunting strategy. They carry lethal bacteria inside their bodies, infiltrate insect hosts, and deploy their bacterial partners to kill from within usually within 48 hours. The result is a biological weapon system refined over millions of years of evolution, now being harnessed for crop protection.

The Biology of a Microscopic Predator

EPNs belong to the phylum Nematoda, one of the most abundant animal groups on Earth. While most nematodes are harmless, two families *Steinernematidae* and *Heterorhabditidae* have evolved as insect killers. Their success lies in a mutually dependent relationship with bacteria. *Steinernema* species carry *Xenorhabdus*, while *Heterorhabditis* harbor *Photorhabdus*. The nematodes act as vectors, delivering bacteria into insect hosts, while the bacteria produce toxins that ensure rapid death. The infective juvenile (IJ) stage is central to their life cycle. These non-feeding, stress-resistant forms survive in soil, locating hosts through cues like carbon dioxide, chemical signals, and even vibrations. Despite having only 302 neurons, they display surprisingly complex behaviors, including the ability to avoid already-infected hosts suggesting efficient resource management.

Anatomy of an Infection: Once a host is located, EPNs enter through natural openings or, in some species, directly through the insect cuticle. Inside the haemocoel, they release their symbiotic bacteria, initiating a lethal cascade.

The bacteria produce toxins and enzymes that:

- ✓ Destroy host tissues
- ✓ Suppress immune defenses
- ✓ Convert the insect body into a nutrient-rich environment

Death occurs quickly due to septicemia. The cadaver is preserved by antimicrobial compounds, preventing decay and allowing nematodes to reprod-

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uce. A single host can yield tens of thousands of new infective juveniles within two weeks. An unusual feature of *Photorhabdus* bacteria is bioluminescence infected insects can glow in the dark. The purpose of this remains unclear but may relate to ecological signaling or microbial compet-ition.

Ecological Distribution and Target Pests

EPNs are found worldwide in diverse soil environments. They infect a wide range of insects, particularly those in soil or protected habitats. Key targets include:

- ✓ White grubs (affecting turf and crops)
- ✓ Caterpillars like cutworms
- ✓ Fungus gnats in greenhouses
- ✓ Weevils in root crops
- ✓ Borers in trees and stems

Their effectiveness depends on ecological compatibility. "Ambusher" species wait for mobile hosts near the surface, while "cruisers" actively search soil for sedentary pests. Matching nematode behavior to pest biology is critical for success.

Commercial Development and Application

EPNs became commercially viable in the 1980s with advances in mass production. Today, they are used in over 40 countries.

Production Methods

In vivo: Grown inside insect hosts; high quality but labor-intensive

In vitro: Produced in liquid fermentation; scalable but technically complex

Formulation Challenges

As living organisms, EPNs require careful handling. Formulations include:

- ✓ Water-dispersible granules
- ✓ Moisture-retaining gels
- ✓ Protective capsules

Shelf life is limited (weeks to months), often requiring refrigeration.

Application Methods

EPNs can be applied through:

- ✓ Soil drenching
- ✓ Irrigation systems
- ✓ Foliar sprays (with protection)
- ✓ Trunk injections

Success depends on environmental condit-ions adequate moisture, moderate temperatures, and protection from UV light.

Role in Integrated Pest Management (IPM)

EPNs are most effective when integrated with other pest control strategies.

Compatibility: They work well with:

- ✓ Beneficial fungi
- ✓ Botanical pesticides
- ✓ Selective synthetic chemicals
- ✓ Good agricultural practices

Resistance Advantage: Unlike chemical pesticides, EPNs use complex biological mechanisms, making resistance development unlikely. Despite decades of use, no field resistance has been documented.

Economic Considerations: Although initially more expensive, EPNs offer long-term benefits:

- ✓ Reduced health risks
- ✓ No residue issues
- ✓ Protection of beneficial insects

- ✓ Improved soil health
- ✓ Access to premium markets

Current Research Frontiers: Advances in science are expanding EPN potential:

Genomics: Genome sequencing enables:

- ✓ Selection of more resilient strains
- ✓ Better understanding of nematode-bacteria interactions
- ✓ Discovery of new bioactive compounds

Stress Tolerance: Research focuses on improving:

- ✓ Heat and drought resistance
- ✓ Storage survival
- ✓ Field persistence

Application Technologies: Innovations include:

- ✓ Precision agriculture targeting pest hotspots
- ✓ Smart delivery systems responsive to soil conditions
- ✓ Microbiome-based enhancements

Limitations and Challenges: Despite their promise, EPNs are not a universal solution.

Environmental sensitivity: Require moisture and moderate temperatures

Higher costs: Compared to conventional pesticides

Variable field performance: Influenced by environmental factors

Limited foliar effectiveness: Best suited for soil pests

Quality variability: Affects reliability of commercial products

These constraints mean EPNs are best used as part of integrated systems rather than standalone replacements.

Conclusion

Entomopathogenic nematodes demonstrate how natural systems can inform sustainable agriculture. Their partnership with bacteria creates a highly efficient biological weapon against insect pests one that avoids many drawbacks of chemical pesticides. They are not a complete replacement for conventional methods, but within integrated pest management systems, they provide a powerful and environmentally responsible tool. Continued research, improved formulations, and better application strategies will further enhance their role. Ultimately, EPNs highlight a broader truth: the future of agriculture may depend less on synthetic inputs and more on understanding and working with the biological systems that have existed all along.

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Plant-Rhizosphere Microbial Interactions for Enhanced Organic Pollutant Remediation

Suman Maurya and Narendra Kumar Bharati

Abstract

Phytoremediation is a promising method of cleaning up contaminated environments. There is growing interest in extending the method's applications to include the removal or degradation of organic pollutants in the environment, even though it has only been used to remove dangerous heavy metals from contaminated soil. Both plants and soil bacteria have a hard time getting rid of or breaking down organic substances. Many of the restrictions may be overcome by plants that remove and/or break down hydrophobic substances and rhizosphere bacteria that make them more accessible, providing a useful foundation for enhancing clean-up of contaminated environments.

Introduction

The extensive use of synthetic organic compounds over the past several decades has created serious and long-lasting environmental challenges. Excessive application of pesticides in agriculture and public health programs has resulted in widespread contamination of food products, agricultural soils, and surface and groundwater resources. Persistent pesticide residues, particularly organochlorines, continue to remain in the environment even decades after their restriction or ban. In addition to pesticides, contaminants such as polychlorinated biphenyls (PCBs), petroleum-derived compounds including BTEX (benzene, toluene, ethyl benzene, and xylenes) and polycyclic aromatic hydrocarbons (PAHs), explosives, detergents, dyes, pigments, and toxic heavy metals have significantly contributed to environmental pollution and ecological degradation (Chaudhry *et al.*, 2001). Growing environmental concerns and stricter regulatory frameworks have encouraged many countries to adopt rigorous soil and environmental protection policies. However, the high cost and technical limitations of conventional remediation technologies have restricted their large-scale application. Consequently, modern remediation strategies are increasingly focused on sustainable and risk-based approaches, aiming to minimize contaminant mobility and environmental hazards while preserving soil health and ecosystem functionality (Sheehan 1997).

Key Factors Affecting Organic Pollutant Biodegradation

Interactions between Bioavailability and Pollutant Toxicity: Biological remediation has great pote-

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ntial, yet it frequently has several drawbacks. The absorption of several soil-bound and soluble chemicals by remediating microorganisms and plants presents a unique challenge. When it comes to organic contaminants, this lack of availability is even more noticeable, which can occasionally severely limit plants' capacity to remediate. In many higher plants, the uptake and translocation of organic molecules through the transpiration stream may be severely limited for soil-bound and very hydrophobic chemicals, while it is ideal for mildly hydrophobic compounds (Bromilow and Chamberlain, 1995). In fact, the most crucial element influencing a remediation process's overall performance is the bioavailability of organic substances. For example, phytoremediation appeared to be a viable solution for a PAH-contaminated soil near Maarn, the Netherlands. However, this did not lead to any discernible removal or degradation of PAHs. A quick PAH-availability test (Cuypers *et al.*, 2000) revealed that bound forms of PAHs were present in the soil. Since it was thought to be a stable-end situation where contamination appeared to pose little environmental impact, the authorities allowed the area's development into a park.

Microbial Dynamics in the Rhizosphere: There is strong evidence that plants can control rhizospheric bacteria' metabolic processes by releasing root exudates, creating a mutually advantageous plant-microbe relationship. In contaminated soils, these complimentary interactions are thought to be a crucial adaptive response of plants to chemical stress. The substantially increased microbial population in the rhizosphere when compared to non-vegetated soils which frequently reaches several orders of magnitude greater near the soil-root interface is a clear sign of this interaction. The degree of these interactions, however, may differ based on the physicochemical characteristics of pollutants, especially hydrophobic organic substances, whose restricted soil diffusion limits microbial activity to a small rhizospheric zone. Rhizosphere-mediated biodegradation processes are also influenced by soil texture, organic matter concentration and contaminant bioavailability (Corgié *et al.*, 2003).

Strategies for Enhancing Pollutant Degradation

Genetic modification: There have been successful instances of genetically engineering plants and rhizospheric bacteria with pollutant-degrading enzymes, despite the fact that the primary focus of plant biotechnology in recent years has been to increase agricultural yields and quality. For instance, microorganisms and plants with the ability to break down pesticides have been created using genes for insecticide detoxification enzymes in resistant insects, such as esterases and cytochromes P450 (Roe, 1998). Tobacco plants have also been shown to have a Malian cytochrome P450, which is known to oxidize a variety of halogenated hydrocarbons. According to reports, this causes the transgenic plants to metabolize TCE up to 640 times faster, increasing the absorption and debromination of ethylene dibromide (Doty, 2000).

Rhizosphere-Mediated Enhancement of Microbi-

al Activity: In general, enhanced microbial activity within the rhizosphere is expected to accelerate the degradation of soil contaminants through co-metabolic processes and diauxic growth mechanisms. Therefore, the availability of suitable nutrients and favorable growth conditions plays a critical role in regulating rhizospheric microbial populations and improving the bioremediation efficiency of contaminated soils. Previous studies have demonstrated that the application of fertilizers, maintenance of adequate soil moisture, and incorpo-ration of organic manures significantly increase microbial abundance and activity in the rhizosphere. However, the microbial community composition differs considerably between soils amended with organic and inorganic fertilizers, which may sub-sequently influence contaminant degradation dynamics and soil ecological functions (Deavin *et al.,* 1981).

Root-Based Technologies for Environmental Remediation: The efficiency of contaminant uptake and remediation by plants largely depends on root length, root biomass, and spatial root architecture, which determine the plant's ability to access pollutants present in deeper soil layers and groundwater. Generally, phytoremediation is considered most effective for contaminants located within 0.5-1.0 m of soil depth; however, deep-rooted tree species such as poplar and certain perennial plants can extract contaminants from depths exceeding 10 m. Therefore, enhancing root growth and optimizing root system architecture represent important strategies for improving phytoextraction and phytodegradation efficiency in contaminated soils. In this context, the use of beneficial strains of *Agrobacterium tumefaciens*, a naturally occurring soil bacterium known for its plant-microbe interactions, has emerged as a promising approach for stimulating root development and enhancing phytoremediation potential (Cunningham *et al.,* 1996).

Conclusions

Plant-microbial interactions in the rhizosphere offer an effective and sustainable approach for the remediation of environments contaminated with persistent organic pollutants

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Sandalwood (*Santalum album*): Its Cultivation Practices and as a Component in Agroforestry System

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Abstract

Santalum album, commonly known as sandalwood, is one of the most valuable forest tree species. To meet the continuously increasing demand, itis essential for sandalwood cultivation to rapidly transition from an over-regulated "forest crop" to a commercially viable species grown under plantation forestry and agroforestry systems. Although the economic potential of sandalwood for farmers is still constrained by existing policies and marketing regulations, it remains a highly profitable tree species. With proper plantation management practices, sandalwood can become a significant income-generating or "dollar-earning" crop in agroforestry systems due to the high value of its heartwood and essential oil in domestic and international markets.

Introduction

Santalum album is commonly known as Indian sandalwood or white sandalwood. In different regions of India, it is also referred to by traditional names such as Chandan in Hindi. This aromatic evergreen tree is highly valued for its fragrant heartwood and essential oil, which are widely used in perfumery, cosmetics, traditional medicine, handicrafts, and religious rituals.

Zone: Eastern Himalayan

Region Area of Adoption: Assam

Agroforestry Model: Agri-silviculture

Tree Component: *Santalum album* L.

Common Name: Sandan

Family: Santalaceae

Habit and Habitat: *Santalum album* is a thornless, small-sized and evergreen tree growing up to 6-8 m height. It is a hemi-parasitic plant and parasitizes the roots of other tree species. *Santalum album* grows upto700 m elevation. It is adapted to wide range of soil; normally grows in sandy or well drained soils. It grows in locations having the temperature range from 0 to 38°C and the annual rainfall of 500 mm to 3000 mm. *Santalum album* should be planted in the areas with bright sunshine; stagnated areas are not at all suitable for the tree.

Distribution: *Santalum album* is native to semi-arid areas of the Indian subcontinent. It is also planted in China, Sri Lanka, Indonesia, Malaysia, the Philippines and Northern Australia. It is parasitic in nature during growing stage. The principal sandal tracts are most parts of Karnataka and adjoining districts of Maharashtra, Tamil Nadu and Andhra Pradesh. In Assam, rainshadow belt is the most suitable area for growing of *Santalum album*. Besides, this species grows luxuriantly in some

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pockets of Darrang, Sonitpur, Biswanath and Lakhimpur districts.

Phenology: Leaves are opposite, simple, light green-coloured above and paler beneath, thick, glabrous on both sides and have a 1 cm long petiole, leaf, blade is elliptic, apex is acute (sometimes obtuse), base is attenuate and the marginsare entire. The venation of the leaf is reticulate with a prominent midrib. Flowers axillary or terminal paniculatecymes, perianth-tubecup-shaped, 2 mm long and 2.5 mm wide, perianth-lobes are composed of 4 petals 2 mm long and 1.5 mm wide and roeciumis composed of 4 stamens with short filament and ovoid anthers, style is stout, about 1-1.5 mm long with a 3-lobedstigmaat the tip, ovaryis globose, 1 mm across and 1-loculed. Fruit is a subglobose or ovoid drupe, 1-1.5 cm long and 1 cm wide and contains 1 stone.

Parasitism: Sandal wood is an obligate parasite. It draws part of its nutrition (mainly Ca and K) from the soil and part of its nutrition (mainly N and P) from host plants through haustoria developed with secondary host plant. For Assam conditions plants like Bhatgila, Amlakhi, Karach, Coconut, Agarwood and Neem may be used as secondary host plants.

Nursery: Seeds are sown on raised and well prepared bed in line. Sandal wood seed show about 30-40 % germination. Fresh seeds take about 20 days to germinate and continued another 25-30 days to complete. Healthy seedlings at 2-4 leaf stage are transferred to previously fill up black polybag of size 30 cm x 14 cm. Arhar or *Ocium* species seeds sown to serve primary host for better growth of sandal-wood seedling. Polybag should contains oil mixture of ratio 2:1:1 (Sand: Garden soil: FYM). Poly bags are placed in rectangular beds with proper shade and irrigation.

Cultural Operations

Preparation of land: Land should be completely cleared of all vegetations followed by ploughing and harrowing.

Spacing: 4 m x 4 m

Pit size: 45 cm x 45 cm x 45 cm. Pits are dug for both sandalwood and secondary host plant and left for 15-20 days exposing to sunlight.

Fertilizer application: Well rotten FYM @ 5 kg pit^{-1} should be applied before planting. After 4 month of planting when the seedlings are well established, organic manures like compost or FYM @ 2 kg plant^{-1} is applied and mixed with the soil around crown of the plant. Application of FYM @ 3-4 kg plant^{-1} at 8-9 month of planting is beneficial. Second year onwards, manuring of FYM @ 4-5 kg plant^{-1} twice in a year, before and after monsoon followed by light earthing up, may be done.

Planting: Planting should be done during March to June with onset of pre monsoon shower. However, planting may be carried out throughout the year if proper irrigation facility is available. Pits are filled up in such a way that water does not accumulate in pit. After filling up the pits a well grown perennial

species as host plant like agar tree or any other suitable host tree seedlings should be planted. With high profitability, growing demand and lucrative market supported by favourable policies, sandalwood cultivation in farm land and agroforestry systems is attracting farmers. Sandalwood (*Santalum album*) is highly profitable in agroforestry. Because it is a hemi-parasite, it cannot grow alone. Sandalwood doesn't have root hairs, it receives water and nutrients from its host plant's roots through bell-shaped haustoria with well-developed vessels. It requires a primary (short-term) and secondary (long-term) host planted alongside it to extract water and nutrients. Nevertheless, host plant selection carries an important function in terms of supporting enhanced growth and resilience of *Santalum album* (sandalwood) (Chavan *et al.*, 2025). It is advisable to establish the host plant prior to plantation of sandal tree. After two months sandalwood seedlings are planted in the pit.

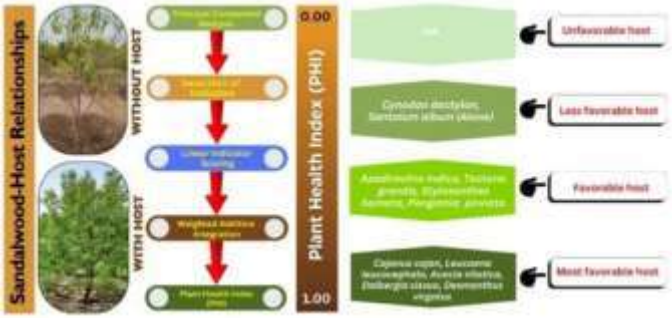

Fig. 1: Graphical representation of host species required for *Santanum album* (Chavan *et al.*, 2025)

Irrigation: For quick initial growth, irrigation may be done at 15-20 days interval during drought period in winter.

Tending Operation

Aftercare: The host plant is lopped to provide enough light to sandalwood seedling. Fencing is required to protect the seedling against browsing by animals. Soil working is done to a radius of 50 cm once in six month.

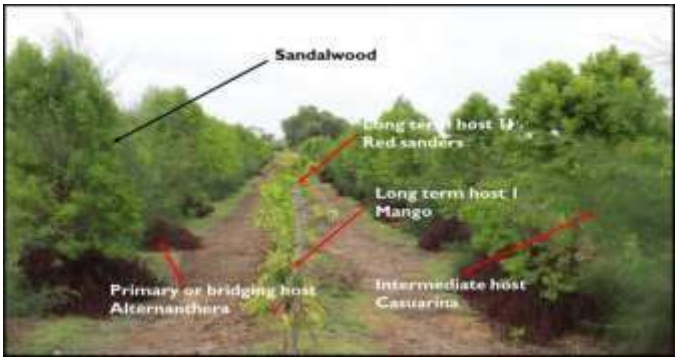

Fig. 2: Spatial arrangement of host and sandalwood (Chavan *et al.*, 2023)

Tree Protection: Common Insect-pest and diseases of Sandalwood and their control measures are mentioned below:

Table 1: Insect-pest in Sandalwood and its control measure

Insect-pest	Control measure
Insect defoliator	
Sympiezomias cretaceus	Spraying 0.2-0.3% Chlorpyriphos or Quinalphos or any contact insecticide
Holochlora albida	
Teratodes monticollis	
Letana inflata	
Cryptothelea cramerii	
Acanthopsyche moorei	
Pteroma plagiophleps	
Sucking Insect	
Ceroplastes ceriferus	Spraying of Monocrotophos (0.02-0.05%)
Saissetia sp.	Spraying 0.5% Quinalphos
Inglisia bivalvata	Spraying 0.2-0.3% Chlorpyriphos or Quinalphos
Tachardina lacca	Spraying 0.5% Quinalphos

Table 2: Disease of Sandalwood

Disease	Control measure
Pre-emergence rot	Selection of seeds, which are free of fungi, seed- Dressing with organo mercuric compound; good drainage
Damping off *Fusarium or Phytophthoraor rhizopus* spp.	
Fusarium wilt *Fusariu or Phytophthora* species followed by nematodes	Drench the potting medium with copper fungicide and nematicide (Bordeaux mixture and Quinalphosor Phorate);good drainage

Orientation: Boundary/in field/on bunds/homestead

Suitable intercrops: Oilseed and pulse crops can be grown as intercrop upto 3rd year of plantation. Thereafter, some shade tolerant crops such as Patchouli, Sarpagandha, Satmool, Ginger, Turmeric, pineapple etc. can be cultivated as intercrop.

Yield/Annual Return including Tree Productivity : Average tree yield of heartwood of *Santalum album* in Assam is in the range of 20-30 kg after 20 years of plantation. On steam distillation, the essential oil production is about 1.5 kg. Additionally after completion of crop cycle of *Santalum album*, a sizeable production of host plant is obtained depending on the species selected.

Economics: In foot hill area of Hojai district of Assam it is observed that heartwood formation take place 9th year onwards. After 15 years of planting the heartwood production of *Santalum album* is about 3097 kg ha^{-1} which fetches a net return of Rs. 42.80 lakh ha^{-1}. Income will be more if product is sold after value addition. Further delay in harvesting will increase the yield and income.

Environmental Benefits: Intervention of Agri-silviculture system helps in recycling of nutrients and improving soil health. Moreover, the tree along with the host plant has immense potentialities of carbon fixation. It is sometimes grown as an ornamental and as a low-branching wind-break.

Utilization: The wood is heavy, hard, durable, strong, resistant to termites attack and strongly aromatic as it seasons. Heartwood is much used for ornamental and carving work. Formerly, in China the most expensive coffins were made of sandalwood, while in India it was the preferred wood for funeral pyres. The dust of sandalwood is utilized for Agarbatti manufacturing. Oilis used as flavouring agentina range of foods including chewing gum, ice creamand bakery products. It is a basic component of countless perfumes, cosmetics and toiletries. The oil has been widely used in folk medicine for treatment of common colds, bronchitis, skin disorders, heart ailments, general weakness, fever, infection of the urinary tract, inflammation of the mouth and pharynx, liver and gallbladder maladies. It possesses antimicrobial and antioxidant properties. Leaves of *Santalum album* provide green manure.

Way Forward: Sandalwood based Agri-silviculture agroforestry system has tremendous scope especially in the foot hill region of rain shadow areas of Assam.

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Organic Crop Production System: Principles, Practices and Technology Advancements

Khushi Saroha

Abstract

When I first started learning about organic farming, I honestly thought it was just about avoiding chemicals. But the more I studied it, the more I realized it is something much deeper a complete and thoughtful system that works with nature rather than fighting against it. Organic crop production is built on the idea that healthy soil grows healthy food, and healthy food creates healthy people. This article explores the core principles that guide organic agriculture, the practical methods farmers use every day like composting, crop rotation, and biological pest control and the exciting new technologies that are making organic farming smarter and more efficient than ever before. Through this study, I also want to be honest about the real challenges organic farmers face, from lower initial yields to the complex certification process. But what I found in my research is that the long-term benefits for the soil, for the farmer, and for the environment make organic production one of the most promising pathways toward truly sustainable agriculture.

Introduction

We live in a time when the food on our plate matters more than ever. As a student of agriculture, I have seen first hand how the conversation around farming has shifted people are no longer just asking how much food we can grow, but also how we are growing it, and at what cost to the land and to our health. This is exactly where organic crop production steps in as a powerful and meaningful answer. Organic farming is not a new idea. Its roots go back to the early 20th century, when visionaries like Sir Albert Howard, who spent years studying farming in India, and Lady Eve Balfour in England began questioning whether chemical-heavy agriculture was truly sustainable. Their work showed that farms managed with respect for natural processes nurturing soil life, encouraging biodiversity, and closing nutrient cycles could produce healthy food season after season without depleting the land. Today, certified organic farmland covers more than 76 million hectares across over 180 countries, and the global organic food market has crossed USD 220 billion annually. These numbers tell us something important this is not just a trend among niche consumers. It is a global movement driven by real concern for human health, environmental protection, and the future of farming itself. What excites me most about studying this topic is how rapidly technology is now entering organic agriculture. Drones mapping soil health, robots pulling weeds, and AI-powered disease forecasting tools are proving that organic farming can be both ecologically sound

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and technologically advanced. This article attempts to bring all of these dimensions together the philosophy, the practice, and the future of organic crop production.

Core Principles of Organic Crop Production

One of the first things I learned about organic agriculture is that it is not simply defined by what you do not use no synthetic pesticides, no artificial fertilizers. It is defined by what you believe and how you think about the farm as a living system. The International Federation of Organic Agriculture Movements (IFOAM) has beautifully captured this through four core principles that I think every student of agriculture should understand deeply.

Principle of Health: This principle says something quite profound that the health of soil, plants, animals, humans, and the planet are all one and the same. You cannot separate them. When I think about this, it makes complete sense. A farmer who poisons the soil to grow a bigger crop is ultimately harming the food, the consumer, and eventually the land itself. Organic farming recognizes this connection and guides every decision from what to add to the soil to what to spray on a crop with the health of the whole system in mind.

Principle of Ecology: Nature has been running incredibly complex systems for millions of years nutrient cycles, predator-prey relationships, seasonal rhythms. The principle of ecology asks organic farmers to study these natural systems and design their farms to work with them, not against them. Instead of fighting pests with chemicals, encourage their natural enemies. Instead of forcing nutrients into the soil artificially, build biological processes that release nutrients naturally. This approach may take more knowledge and patience, but it builds something chemicals never can genuine long-term resilience.

Principle of Fairness: Farming is not just about soil and seeds it involves real people, communities, and livelihoods. The principle of fairness reminds us that organic agriculture should benefit everyone in the supply chain fairly, from the farmer who works the land to the consumer who buys the produce. It also asks us to be fair to the environment to take only what we need and return what we can, so that the land remains productive and healthy for those who come after us.

Principle of Care: Perhaps the most important principle of all is care acting with responsibility and caution, especially when we are uncertain. Organic farming does not rush to adopt every new technology or input without first asking whether it truly aligns with ecological values. This careful, thoughtful approach is what makes organic agriculture genuinely different from simply swapping one input for another.

Soil Health Management

If there is one lesson that organic agriculture teaches above all others, it is this: take care of the soil, and the soil will take care of your crops. This sounds simple, but it represents a completely different way of thinking compared to conventional farming, wher the focus is largely on delivering nutr-

ients directly to the plant through soluble fertilizers.

Composting and Organic Matter Inputs: Compost is often called the foundation of organic farming, and after studying it I completely agree. When plant residues, animal manures, and kitchen wastes are composted properly through aerobic decomposition, they transform into a rich, dark material teeming with beneficial microbes and slowly available nutrients. Unlike synthetic fertilizers that flood the soil with instantly soluble nutrients most of which leach away compost feeds the soil ecosystem gradually and sustainably. Research shows that consistent compost application over many years increases soil organic matter by 0.5-1.5% per decade and can improve the soil's water-holding capacity by which is especially valuable in rain-dependent farming systems.

Green Manures and Cover Crops: One of the most elegant practices in organic farming is the use of cover crops plants grown not for harvest but for what they give back to the soil. Legumes like clover, vetch, and cowpea have a remarkable ability to pull nitrogen directly from the air and fix it in the soil through their partnership with Rhizobium bacteria. Depending on the species and conditions, they can contribute 50 to 200 kg N ha^{-1} in a single season entirely for free, with no factory, no energy input and no chemical residue. Non-legume cover crops like cereal rye and oats play a different but equally valuable role, suppressing weeds and building organic matter when incorporated into the soil.

Reduced Tillage and Soil Structure: One thing that surprised me in my research was the growing movement toward reduced tillage in organic systems. Traditionally, organic farmers relied heavily on ploughing and tillage for weed control, but this disrupts the delicate networks of fungi, earthworms, and microbial communities that make soil truly productive. Strip-till and zone-till methods disturb only the narrow strips where seeds will be planted, preserving the rest of the soil structure. The Rodale Institute in the USA has pioneered a remarkable technique using roller-crimpers to fatten cover crops and create a weed-suppressing mulch layer allowing crops to be planted with minimal soil disturbance.

Crop Rotation and Diversity: Growing the same crop in the same field year after year is one of the quickest ways to exhaust the soil, build up pest populations, and invite disease. Organic farmers avoid this trap through carefully planned crop rotations sequencing different crops across seasons so that each one benefits from what the previous crop left behind. A good organic rotation typically moves through at least four phases: a nitrogen-fixing legume that enriches the soil; a cereal or grain crop that uses that nitrogen efficiently; a deep-rooted crop like sunflower or root vegetables that breaks up compacted layers and accesses different nutrient pools; and a fertility-building phase of cover crops or temporary pasture. Studies consistently show that rotations of three or more years reduce soil-borne diseases, harmful nematodes, and weed seedbanks by 40 to 70 percent compared to monocultures results that no pesticide can match in the long term. Even more interesting is intercropping growing two or

more crops side by side at the same time. When cereals and legumes are grown together, they share space, light, and nutrients in complementary ways that often produce more total food than either crop grown alone.

Scientists measure this with something called the Land Equivalent Ratio (LER), and when it is above 1.0, it means the intercrop is genuinely more productive than growing the crops separately.

Pest, Disease and Weed Management

This is the area where most people assume organic farming simply cannot compete how do you control pests without pesticides? But what I discovered in my research is that organic Integrated Pest Management (IPM) is not about doing nothing. It is about being smarter, more observant and more strategic than conventional farming.

Biological Control: Nature has its own pest control army predatory beetles, parasitic wasps, hoverflies, and countless microbial pathogens that attack harmful insects. The key insight of biological control is that these natural enemies already exist in and around the farm; they just need the right habitat to thrive. Flower strips along field edges, hedgerows, and beetle banks provide shelter and food sources that dramatically increase populations of these beneficial organisms. When natural populations are not enough during peak pest pressure, farmers can also release commercially raised beneficial insects like *Trichogramma wasps* or apply *Bacillus thuringiensis* (Bt), a naturally occurring soil bacteria that is toxic to certain caterpillars but completely safe for humans and other animals.

Approved Natural Inputs: When biological methods need support, organic farmers can turn to a carefully regulated list of natural-origin substances. Copper-based fungicides help control late blight and downy mildew in crops like potatoes and grapes. Sulfur is effective against powdery mildew. Neem extract (azadirachtin), derived from the neem tree which is so familiar across India, disrupts the molting cycle of many harmful insects without leaving toxic residues. These inputs are used as a last resort, not as a routine spray schedule a fundamental difference from conventional farming.

Weed Management: Honestly, weeds are the hardest challenge in organic farming, and I think it is important to say that clearly. Without herbicides, controlling weeds requires a combination of cultural tactics dense planting to shade out weeds, strategic timing of operations, flame weeding, mechanical cultivation between rows, and organic mulches. Modern camera-guided mechanical weeders can now distinguish crop plants from weeds with over 95% accuracy, reducing hand weeding labor by as much as 50 to 80 percent on vegetable farms a genuinely exciting development.

Nutrient Management in Organic Systems

In organic farming, the guiding philosophy of nutrient management is beautifully different from conventional agriculture. Instead of asking 'how do I feed this plant?' the organic farmer asks 'how do I feed the soil so the soil can feed the plant?' This shift in thinking changes everything about how nutrients

are managed.

Nitrogen Cycling: Nitrogen is the nutrient crops need most, and in organic systems it comes primarily through biological nitrogen fixation the remarkable process by which legume plants, working in partnership witl Rhizobium bacteria in their root nodules, pull nitrogen gas from the atmosphere and convert it into a form plants can use. Free-living bacteria like Azotobacter and Azospirillum also contribute to this process. Getting the best results from BNF requires attention to soil pH (ideally between 6.0 and 7.0), adequate trace minerals like molybdenum and cobalt, and using good quality bacterial inoculants when planting legumes. Composted manure provides supplemental nitrogen that is released slowly, matching crop uptake patterns and greatly reducing the risk of nitrate leaching into groundwater.

Phosphorus and Potassium Management: Phosphorus management in organic systems fascinated me because it relies so heavily on biological relationships. Mycorrhizal fungi microscopic fungal networks that colonize plant roots dramatically extend the root's reach into the soil, accessing phosphorus from zones the root itself could never reach. Phosphate-solubilizing bacteria release phosphorus from mineral forms that would otherwise be locked away and unavailable. Rock phosphate, an approved organic input provides a slow but steady phosphorus reserve. Potassium is returned to the system through crop residue incorporation, composted manure, and natural mineral sources.

Challenges and Limitations

I believe it is important in any honest article to discuss not just the successes but also the difficulties. Organic farming is genuinely better in many ways, but it is not easy, and pretending otherwise would not be fair to the farmers who face these challenges every day.

Yield Gap: The most commonly cited criticism of organic farming is that it produces lower yields. A large meta-analysis of 316 studies confirmed that organic yields average 19 to 25 percent below conventional equivalents. This gap is real, and it matters in a world where food security is a serious concern. However, the gap narrows significantly for legumes, mixed farming systems, and crops grown in rain-fed conditions in developing countries, It also shrinks considerably as farmers become more experienced and as organically adapted varieties become available. This is a problem that research and innovation are actively working to solve.

Certification Complexity: To legally sell produce as organic, farmers must go through a formal certification process that involves inspections, documentation, and strict compliance with standards. What makes this especially difficult is the mandatory two to three year conversion period during which farmers must follow all organic rules but cannot yet receive premium organic prices. For small farrners with limited savings, this financial gap can be genuinely dangerous. Simplifying and subsidizing certification for small and marginal farmers should be a policy priority.

Nutrient Management Risks: Managing nutrients without synthetic fertilizers requires significant knowledge and careful planning. Without the right rotation design and organic inputs, crops can suffer nitrogen deficiency at critical growth stages, reducing both yield and quality. On the other hand, excessive application of manure especially fresh manure can cause nutrient surpluses and nitrate leaching that is just as harmful as that from conventional farms.

Weed Pressure: I mentioned weeds earlier as a challenge, and it deserves repeating here as a limitation. Weed management is consistently the biggest operational headache for organic farmers, especially those transitioning from conventional systems where herbicides kept weed seedbanks suppressed for decades. Those weed seeds do not disappear when you go organic they just wait for their chance. Building effective weed management systems takes years of careful rotation planning, timing, and increasingly, investment in mechanical weeding technology.

Knowledge and Extension Gaps: Finally, and perhaps most importantly, organic farming is simply more complex and knowledge-intensive than conventional farming. It demands a deep understanding of soil biology, ecological relationships, and adaptive management. Unfortunately, most agricultural extension services were built around conventional inputs and are poorly equipped to guide farmers through organic transition. Strengthening organic-focused education and extension services is one of the most important investments governments can make in sustainable agriculture.

Conclusion

Writing this article has deepened my appreciation for organic crop production in ways I did not expect. What began as a study topic has become something I genuinely believe in. The principles of health, ecology. fairness, and care are not just good farming philosophy they are a responsible way of thinking about our relationship with the natural world. The practices of composting, cover cropping, crop rotation, and biological pest management are not outdated or inefficient they are increasingly supported by modern science and being enhanced by cutting-edge technology. The challenges are real, but so is the progress being made in addressing them. Farmers who choose the organic path are not choosing the easy path, but they are choosing one that builds something lasting healthier soil, safer food, stronger ecosystems, and more resilient farming communities.

Agricultural Drones and their Practical Applications

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Introduction

Agriculture has always been one of the most important sectors for human survival and economic development. With the rapid growth of population and increasing demand for food, farmers are facing major challenges such as shortage of labour, unpredictable climate conditions, water scarcity, pest attacks, and the need for higher productivity. Traditional farming methods are often time-consuming, labour-intensive, and less efficient in managing large agricultural fields. To overcome these challenges, modern technology is being introduced into farming practices. One of the most advanced and effective technologies used in modern agriculture is the agricultural drone. Agricultural drones are transforming traditional farming into smart farming by improving efficiency, reducing costs, and increasing crop productivity. Agricultural drones are unmanned aerial vehicles (UAVs) specially designed for farming and agricultural activities. These drones are equipped with advanced technologies such as GPS systems, cameras, sensors, artificial intelligence, and spraying mechanisms. They can fly over agricultural fields and collect valuable information about crops, soil conditions, irrigation requirements and pest infestations. Farmers can monitor their fields in real-time and make better decisions based on accurate data collected by drones. Agricultural drones help farmers save time, reduce manual effort, and increase the overall effectiveness of farming operations.

Key Practical Applications

Crop Monitoring and Scouting: Drones capture high-resolution multispectral imagery to assess crop health, identify pest attacks, monitor water stress, and check for nutrient deficiencies.

Precision Spraying: Drones are used for targeted application of fertilizers, pesticides, and herbicides. This method uses far fewer chemicals and water compared to traditional spraying while improving, uniformity and eliminating worker exposure.

Soil and Field Analysis: They provide accurate 3D field mapping, which helps in soil analysis, identifying irrigation needs, and monitoring field elevation to determine drainage patterns.

Planting and Seeding: Specialized drones are used to shoot seed pods, mixed with nutrients, into the soil, which is particularly effective in difficult-to-access terrain and helps in reforestation.

Livestock Monitoring: Drones can assist in tracking, counting, and checking the health of livestock, particularly on large-scale grazing farms.

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Table 1: Drone Used in Agriculture and their Possible Practical Applications

Drone Type	Features	Practical Application
Fixed-wing	✓ Long flight time ✓ High- speed coverage ✓ Energy efficient ✓ Suitable for large farms	✓ Large- scale crop monitoring ✓ Soil and topographic mapping ✓ Irrigation analysis ✓ Farm boundary surveying ✓ Yield estimation
Rotary-wing	✓ Stable flight ✓ Better control ✓ Suitable for precision operations ✓ Easy manoeuvrability	✓ Crop spraying ✓ Field inspection ✓ Precision agricultural tasks
Multi-rotor	✓ Precision spraying ✓ Crop monitoring ✓ Pest detection ✓ Orchard inspection	✓ Pesticide spraying ✓ Fertilizer application ✓ Disease detection ✓ Plant health monitoring ✓ Livestock monitoring

Table 2: Drone Used in Agriculture and their Possible Practical Applications

Feature	Fixed-wing	Rotary-wing	Multi-rotor
Flight time	Long	Medium	Short
Area coverage	Very large	Medium	Small to medium
Hovering ability	No	Yes	Yes
Speed	High	Medium	Low
Precision spraying	Low	High	High
Ease of operation	Difficult	Moderate	Easy
Best use	Mapping & survey	spraying	Monitoring & spraying

Table 3: Challenges in agricultural drone usage

Technical challenges	Economic challenges	Legal challenges
✓ Limited battery life ✓ Weather dependency ✓ Signal interference ✓ Payload limitations	✓ High initial cost ✓ Maintenance expenses ✓ Training requirements	✓ Government regulations

Yield Estimation: By analyzing crop health data throughout the season, drones help farmers predict and estimate crop yields, aiding in better harvest planning.

Conclusion

Agricultural drones are revolutionizing farm management, offering a sustainable, data-driven approach to food production. They effectively address labour shortages, rising chemical costs, and environmental concerns, resulting in higher efficiency and improved crop yields. While challenges such as regulatory frameworks and technology costs exist, the rapid evolution of this technology suggests that drones will become an indispensable asset in achieving global food security and promoting sustainable agricultural practices.

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Rise of Agricultural Drones: Transforming Modern Farming

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Abstract

The rise of agricultural drones is transforming modern farming by introducing advanced technologies that improve productivity, efficiency, and sustainability. Agricultural drones, also known as unmanned aerial vehicles (UAVs), are equipped with cameras, sensors, GPS, and imaging systems that help farmers monitor crops, assess soil conditions, and manage resources effectively. These drones provide real-time data that supports precision farming, reducing the excessive use of water, fertilizers, and pesticides. They also help in crop health analysis, irrigation planning, field mapping, and spraying operations, saving both time and labour costs. The use of drones enhances decision-making and increases crop yield while minimizing environmental impact. In addition, agricultural drones are useful in detecting diseases, pest attacks, and nutrient deficiencies at an early stage. As technology continues to advance, drones are becoming an essential tool in smart farming practices, contributing significantly to the development of sustainable and modern agriculture across the world.

Introduction

Agriculture has always been the backbone of human civilization. From traditional farming methods using manual labour and animal power to the adoption of tractors, irrigation systems, and modern machinery, farming practices have continuously evolved with technological advancements. In recent years, one of the most revolutionary innovations in agriculture has been the use of agricultural drones. These unmanned aerial vehicles (UAVs) are transforming modern farming by increasing productivity, improving crop monitoring, reducing labour costs, and promoting sustainable agricultural practices.

Agricultural drones are specially designed flying devices equipped with advanced technologies such as GPS, cameras, sensors, artificial intelligence (AI), and data analytics systems. These drones can collect accurate field data, spray fertilizers and pesticides, monitor crop health, and even assist in planting seeds. By providing farmers with real-time information about their fields, drones enable precision farming, where resources are used efficiently and crop yields are maximized. Modern drones are equipped with multispectral and thermal imaging cameras that help farmers detect plant diseases, pest infestations, and nutrient deficiencies at an early stage. Early detection allows farmers to take immediate corrective actions, preventing crop damage and increasing productivity. Drones can also generate detailed maps of agricultural fields, helping farmers analyse soil conditions, irrigation patterns,

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and crop growth. The adoption of agricultural drones has increased significantly in countries such as the United States, China, India, and Japan. Governments and agricultural organizations are encouraging drone usage through training programs, subsidies, and supportive regulations. In India, agricultural drones are becoming popular among farmers due to government initiatives promoting "Digital Agriculture" and "Smart Farming". Drones are especially useful in large farms where manual monitoring and spraying are time-consuming and labour-intensive. Another major advantage of agricultural drones is their ability to save time and labour. Traditional crop spraying methods require workers to carry heavy equipment across fields, exposing them to harmful chemicals. Drone spraying systems can cover large areas quickly and safely, reducing human effort and health risks. In addition, drones can operate in difficult terrains and inaccessible areas where tractors or manual workers may face challenges.

Agricultural drones also play an important role in precision agriculture, a modern farming approach that relies on accurate data and advanced technologies. Precision agriculture helps farmers make informed decisions regarding planting, irrigation, fertilization, and harvesting. Drones collect valuable information that can be analysed using software systems to improve farm management and increase profitability. The integration of artificial intelligence (AI), machine learning, and Internet of Things (IoT) technologies with drones has further enhanced their capabilities. Smart drones can automatically identify unhealthy crops, calculate fertilizer requirements, and generate field reports. Some advanced drones can even work autonomously without direct human control. These technological advancements are making agriculture more intelligent, efficient, and sustainable.

The future of agricultural drones is highly promising. Experts believe that drones will become an essential part of modern farming systems in the coming years. As technology continues to improve, drones will become more affordable, efficient, and capable of performing complex agricultural tasks. Their role in improving food security, conserving resources, and supporting sustainable agriculture will become increasingly important. Despite their numerous benefits, agricultural drones also face certain challenges. High initial investment costs, lack of technical knowledge among farmers, limited battery life, and government regulations can affect drone adoption. However, continuous technological development and decreasing drone prices are making them more accessible to farmers worldwide.

Fig.1: Traditional Farming Vs Farming with Drones

History of Agricultural Drones

- ✓ Drones were first developed in the early 20th century mainly for military purposes such as surveillance and reconnaissance.
- ✓ During World War I and World War II, unmanned aerial vehicles (UAVs) were used for target practice and gathering information.
- ✓ In the 1980s, drones started being introduced in agriculture, especially in Japan for crop spraying.
- ✓ The Yamaha Motor R-50 agricultural drone, introduced in 1987, became one of the first successful farming drones.
- ✓ Early agricultural drones helped farmers spray pesticides and fertilizers more efficiently in difficult farming areas.
- ✓ In the 1990s and 2000s, improvements in GPS, sensors, cameras, and batteries increased drone capabilities.
- ✓ Farmers began using drones for crop monitoring, soil analysis, irrigation management, and field mapping.
- ✓ The growth of precision agriculture increased the importance of drones in modern farming.
- ✓ After 2010, drones became more affordable and commercially available worldwide.
- ✓ Companies like DJI and Parrot developed advanced agricultural drones with smart technologies.
- ✓ Modern agricultural drones use AI, multispectral imaging, and automation for better farming decisions.
- ✓ Today, drones are widely used to improve crop yield, reduce labor costs, save time, and support sustainable agriculture practices.

Conclusion

The rise of agricultural drones has significantly transformed modern farming by improving efficiency, accuracy, and productivity. These advanced technologies help farmers monitor crop health, assess soil conditions, spray fertilizers and pesticides, and manage irrigation with greater precision. By using real-time aerial data and imaging systems, drones reduce labour costs, save time, and minimize the excessive use of chemicals and water resources. This supports sustainable farming practices and helps increase crop yield and quality. Agricultural drones are especially beneficial in precision farming, where accurate decision-making is essential for better farm management. They also help farmers quickly identify diseases, pest attacks, and nutrient deficiencies, preventing major crop losses. As technology continues to advance, drones are becoming more affordable and accessible to farmers across the world. Despite challenges such as high initial investment, technical knowledge requirements, and regulatory issues, the future of agricultural drones remains highly promising. Overall, agricultural drones are revolutionizing the agriculture sector and playing a vital role in meeting the growing global demand for food through smarter and more sustainable farming methods.

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Pest and Disease Monitoring Using Drones: A Smart Farming Approach

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Abstract

Pest and disease monitoring using drones has emerged as a revolutionary approach in modern smart agriculture. The use of Unmanned Aerial Vehicles (UAVs) equipped with advanced technologies such as RGB cameras, multispectral sensors, thermal imaging, GPS navigation, Artificial Intelligence (AI), Machine Learning (ML), and IoT systems enables rapid and accurate crop monitoring. Drone technology helps farmers identify pest infestations, plant diseases, nutrient deficiencies, and water stress at early stages, thereby reducing crop losses and improving agricultural productivity. Drone monitoring also supports sustainable agriculture by reducing excessive chemical usage, lowering environmental pollution, and promoting efficient resource management. Despite challenges such as high initial investment, limited battery life, weather dependency, and technical training requirements, drone technology offers immense potential for transforming traditional agriculture into an intelligent and sustainable farming system. Future developments integrating AI, cloud computing, automation, and real-time analytics are expected to make agricultural drones more efficient, affordable, and widely accessible for farmers.

Introduction

Agriculture is one of the most important sectors for human survival and economic development. It provides food, raw materials, and employment opportunities for millions of people around the world. However, modern agriculture faces several serious challenges such as increasing pest attacks, plant diseases, climate change, water scarcity, labour shortages, and rising production costs. Among these challenges, pests and diseases are considered major causes of crop loss and reduced agricultural productivity. Farmers often suffer significant economic losses because crop diseases and insect infestations are not detected at the proper time. Traditionally, farmers inspect agricultural fields manually to identify unhealthy crops, pest infestations, and disease symptoms. This method requires large amounts of labour, time, and physical effort. Manual crop monitoring is also less accurate because farmers may not easily identify early-stage infections spread across large agricultural fields. In many cases, diseases and pests spread rapidly before proper action can be taken, resulting in severe crop damage and lower yield production. To overcome these limitations, modern agriculture is increasingly adopting advanced technologies such as drones, Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), remote sensing, and precision farming systems. Among these technologies, drones or Unmanned Aerial Vehicles (UAVs) have

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become one of the most effective tools for smart farming and agricultural monitoring.

Drones are aerial vehicles equipped with advanced systems such as high-resolution RGB cameras, multispectral sensors, thermal imaging cameras, GPS navigation systems, and intelligent software. These drones can fly over agricultural fields and capture real-time aerial images and crop data with high accuracy. The collected data is analyzed using AI and image-processing techniques to identify unhealthy crops, pest-infected areas, nutrient deficiencies, water stress, and disease symptoms. Drone-based monitoring systems provide several advantages compared to traditional farming methods. They help farmers monitor large agricultural areas quickly and efficiently while reducing the need for manual labour. Drones can identify crop problems at an early stage, allowing farmers to take preventive actions before the disease or pest spreads widely. Early detection helps reduce crop losses, improve productivity and increase farm profitability.

Another major advantage of drones is their support for precision agriculture. Instead of spraying pesticides or fertilizers across the entire field, drones help farmers apply chemicals only to affected areas. This targeted approach reduces chemical wastage, lowers production costs, and minimizes environmental pollution. Drone technology also improves farmer safety by reducing direct exposure to harmful pesticides and chemicals. In recent years, the integration of Artificial Intelligence, Machine Learning, and IoT with drone systems has significantly improved agricultural monitoring capabilities. AI algorithms can analyze crop images automatically and detect diseases with high accuracy. IoT systems enable real-time data sharing and remote monitoring of farm conditions. Thermal and multispectral imaging technologies further enhance the detection of crop stress and hidden plant diseases that may not be visible to the human eye.

The rapid growth of the global agricultural drone market reflects the increasing importance of drone technology in modern farming. Governments, researchers, and agricultural industries are investing heavily in smart farming technologies to improve food production and support sustainable agriculture. As agricultural challenges continue to increase due to population growth and climate change, drone-based pest and disease monitoring is expected to play a major role in the future of intelligent and sustainable farming systems. Therefore, the use of drones in pest and disease monitoring represents a significant advancement in agricultural technology. It provides farmers with faster, smarter, and more efficient methods of crop management while supporting precision farming, environmental sustainability, and improved agricultural productivity.

Working Principle of Drone Monitoring System

The operation of drone-based agricultural monitoring systems involves several steps:

- ✓ Drone flies over the agricultural field
- ✓ Cameras and sensors capture crop images
- ✓ GPS records field location data
- ✓ AI and image-processing systems analyze crop

conditions

- ✓ Pest and disease affected areas are identified
- ✓ Farmers receive monitoring reports and recommendations
- ✓ Precision pesticide spraying is performed if required

Table 1: Efficiency Comparison: Manual Monitoring vs Drone Monitoring

Parameter	Manual Monitoring	Drone Monitoring
Speed	Slow	Fast
Labor Requirement	High	Low
Monitoring Area	Limited	Large-scale coverage
Accuracy	Moderate	High
Data Collection	Manual observation	Real-time aerial data
Pest Detection	Delayed	Early detection
Operational Cost	Higher labor cost	Reduced operational cost
Chemical Usage	Higher	Precision-based usage
Safety	Higher chemical exposure	Minimal exposure
Environmental Impact	More pollution	Reduced environmental impact

Conclusion

Pest and disease monitoring using drones is transforming traditional agriculture into a modern smart farming system. Drones provide rapid, accurate, and efficient crop analysis that helps farmers detect diseases and pest infestations at early stages. This technology reduces crop losses, minimizes labour requirements, improves crop productivity, and supports precision agriculture. The integration of AI, Machine Learning, GPS, thermal imaging, and IoT technologies has significantly improved the effectiveness of drone-based agricultural systems. Drone monitoring also reduces excessive pesticide usage and environmental pollution by enabling targeted treatment applications. Although challenges such as high initial costs, battery limitations, and technical skill requirements still exist, the future of agricultural drones remains highly promising. Continuous advancements in automation, AI, and cloud computing will further enhance the efficiency and affordability of drone technology. Drone-based pest and disease monitoring will play a major role in sustainable agriculture, intelligent farm management, and improved global food production in the future.

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Medicinal Mushrooms: Ancient Remedy or Modern Superfood?

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Introduction

Medicinal mushrooms have been used since ancient times in traditional medicines, especially in Asian countries such as China and Japan (Wasser, 2011). They had been traditionally believed to promote health, enhance immunity and improve overall well-being (Lindequist *et al.,* 2005). In recent years, medicinal mushrooms such as Reishi, Lion's mane and Cordyceps have gained increasing global attention due to their potential health benefits and their use as functional foods and natural health supplements. Recent scientific investigations have significantly enhanced interest in medicinal mushrooms due to the presence of various bioactive compounds, including polysaccharides, β-glucans, antioxidants and triterpenes, which are known to possess health-promoting properties (Valverde *et al.,* 2015). These bioactive constituents contribute to the growing importance of medicinal mushrooms in the fields of nutrition, functional foods and complementary medicines.

Historical Background of Medicinal Mushrooms

The utilization of medicinal mushrooms dates back more than 2,000 years ago and form an important component of Traditional Chinese Medicine (TCM) (Bishop *et al.,* 2015). Ancient Chinese literature described Reishi mushrooms as the "Mushroom of Immortality" owing to their perceived role in promoting longevity and overall well-being (Bishop *et al.,* 2015). Similarly, Cordyceps was traditionally employed in Tibetan medicine for enhancing physical strength, stamina and endurance (Holliday and Cleaver, 2008). Due to their rarity and high economic value, medicinal mushrooms were historically considered to be having valuable therapeutic resources and were predominantly accessible to emperors and affluent families (Wasser, 2011). In addition, Lion's mane mushroom was traditionally consumed by Buddhist monks to improve concentration and support meditation practices (Friedman, 2015).

Nutritional and Medicinal Components

Medicinal mushrooms are considered rich sources of nutrients and biologically active compounds with significant health-promoting potential (Valverde *et al.,* 2015). They contain essential vitamins including B-complex vitamins and vitamin D, minerals such as selenium and potassium, dietary fiber, antioxidants and various polysaccharides (Valverde *et al.,* 2015). Among these bioactive constituents, β-glucans are regarded as one of the most important compounds due to their potential role in modulating immune system responses (Lindequist *et al.,* 2005). In addition, antioxidants present in medicinal mushrooms help protect cells against oxidative damage induced by free radicals (Patel and

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Goyal, 2012). Owing to the presence of these beneficial compounds, medicinal mushrooms are widely recognized as functional foods, as they provide physiological and health benefits beyond basic nutritional values (Valverde *et al.*, 2015).

Reishi Mushroom: The Mushroom of Immortality

Reishi (*Ganoderma lucidum*) is one of the most widely recognized medicinal mushrooms and has been used in traditional Chinese medicine for centuries (Bishop *et al.*, 2015). It contains important bioactive compounds such as triterpenes and polysaccharides that are associated with anti-inflammatory and immune-modulating properties (Bishop *et al.*, 2015). Studies suggest that Reishi mushrooms have proved to be helpful to improve immunity, to mitigate stress as well as fatigue. These mushrooms also useful for the betterment of sleep quality and support the healthy cardiovascular system, including the potential balancing of blood pressure and cholesterol levels (Wasser, 2011). It is commonly consumed in the form of tea, capsules, powders or extracts so that the same is absorbed by the human beings to help them cope with physiological stress and fatigue (Lindequist *et al*., 2005).

Lion's Mane Mushroom and Brain Health

Lion's mane (*Hericium erinaceus*) has gained considerable attention due to its potential effects on brain health and cognitive functions (Friedman, 2015). It contains bioactive compounds such as hericenones and erinacines, which stimulate the production of nerve growth factor (NGF), a protein involved in the growth, maintenance and repair of neuron cells (Friedman, 2015). Lion's mane mushrooms boost memory functions, enhance concentration, support nerve regeneration, slow down the symptoms of anxiety and depression, and potentially protect against age-related factors (Friedman, 2015). Some small-scale human studies have reported improvements in cognitive performance following regular intake of supplements with lion's mane extracts (Friedman, 2015). It has also been found useful for its potential role in the risk management of neuro degenerative disorders such as Alzheimer's disease.

Cordyceps and Boosting of Energy

Cordyceps is a distinctive medicinal fungus that naturally occurs on insect larvae in high-altitude and mountainous regions (Holliday and Cleaver, 2008). Due to its rarity and high cost in nature, most commercial cordyceps products are now produced through controlled laboratory cultivations. It has gained international recognition for its potential to enhance physical performance and stamina (Holliday qand Cleaver, 2008). It has been found that cordyceps help to support the production of adenosine triphosphate (ATP), the primary energy carrier in muscle cells, thereby improving energy metabolism (Patel and Goyal, 2012). Reported benefits of cordyceps include increased energy levels, improved oxygen utilization, enhanced endurance, reduced fatigue and support for the healthy respiratory system (Holliday and Cleaver, 2008). Because of these properties, it is commonly used by athletes and

fitness enthusiasts to support recovery from any injury and also improve upon physical performance. In addition, some studies have found that it contains potential antioxidant and anti-aging properties (Patel and Goyal, 2012).

Modern Scientific Research

Modern scientific research on medicinal mushrooms has expanded considerably in recent years (Wasser, 2011). Recent studies have focused on understanding how bioactive compounds in the mushrooms influence immune system, brain function, inflammatory processes and disease prevention mechanisms. A number of findings have shown promising outcomes, particularly in relation to immune enhancement and antioxidant activity (Lindequist *et al.*, 2005). Most studies are conducted under laboratory or animal models, while well-controlled human clinical trials remain relatively restricted. However, the quality and standardization of commercial mushroom supplements may vary less or more among various manufacturers. It is also emphasized that medicinal mushrooms must be considered as complementary agents and not as substitutes for the conventional medical treatments (Patel and Goyal, 2012).

Medicinal Mushrooms in Modern Wellness System

Medicinal mushrooms have become an important trend within the global health and wellness industry. They are now widely incorporated into various commercial products such as mushroom coffee, herbal teas, dietary supplements, protein powders and functional beverages like energy drinks. Growing consumer interest in natural health products has contributed to increased demand for ingredients that may support immunity, improve mental health and stress as well as fatigue management (Valverde *et al.*, 2015). In addition, social media platforms and wellness influencers have significantly contributed to the popularization and marketing of mushroom-based products. One popular example is mushroom coffee, which combines conventional coffee with extracts of mushrooms such as Lion's mane or Reishi mushroom. It is often promoted as a practical beverage that may enhance energy and cognitive performance while potentially reducing some of the undesirable effects associated with caffeine consumption.

Safety and Precautions

Medicinal mushrooms are generally regarded as safe for most individuals when consumed appropriately and in moderate amounts (Lindequist *et al.*, 2005). However, in some cases, they may cause mild adverse effects such as allergic reactions, gastrointestinal discomfort or interactions with certain medications. To ensure safe use, healthcare professionals typically advise sourcing products from reputable manufacturers, adhering strictly to recommended dosage guidelines and seeking medical consultation before initiating mushroom supplementation. It is also strongly recommended to avoid the collection and consumption of unidentified mushrooms grown in the wild ares, as several species may posess highly toxic and poisonous elements that

may lead to serious health risks (Wasser, 2011).

Conclusion

To conculde, it can be said in a nutshell, a medicinal mushrooms represent a unique integration of traditional healing practices and modern scientific interest. Mushroom such as Reishi, Lion's mane and Cordyceps have been traditionally valued for their potential health benefits and emerging research is beginning to bestow scientific support for some of their uses. Although further clinical studies are required, they are believed to contribute to immune support, cognitive function, energy metabolism and stress management (Patel and Goyal, 2012). Their increasing global popularity highlights their growing significance in nutrition, functional foods and complementary medicine.

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Utilizing *Trichoderma* and *Pseudomonas* for Sustainable Disease Management

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Abstract

Widespread reliance on synthetic agrochemicals has caused severe environmental degradation, soil fertility loss, and health hazards. Consequently, sustainable agriculture increasingly depends on eco-friendly biocontrol agents to manage plant diseases and optimize crop yields. This article highlights *Trichoderma* and *Pseudomonas* species as highly effective rhizosphere-colonizing organisms that suppress plant pathogens and promote growth. *Trichoderma* limits disease through antibiosis, resource competition, and direct mycoparasitism of host hyphae. Similarly, *Pseudomonas* utilizes multiple antagonistic mechanisms, including the production of powerful antibiotics like 2,4-diacetylphloroglucinol, competitive root colonization, hydrogen cyanide synthesis, and iron-chelating siderophores. Furthermore, these beneficial microbes trigger induced systemic resistance, enhancing the plant's immune response against pathogen attacks. Embracing these biological agents provides a sustainable barrier against soil-borne diseases, reduces chemical dependencies, lowers pest resistance risks, and ensures long-term global food security.

Introduction

In an effort to maximize the production of an adequate supply of safe, nourishing, and high-quality food worldwide, agricultural systems have been continuously enhanced over the past few decades. Unquestionably, the widespread use of agrochemicals such synthetic pesticides and fertilizers contributes significantly to preserving adequate food supply and boosting crop output in the shortest amount of time (Hanapi *et al*., 2012). However, a number of problems have emerged that link the use of these agrochemicals to environmental problems. Numerous negative consequences, including the emergence of resistant plant diseases, air pollution, groundwater pollution, soil degradation, decreased fertility, health risks, and environmental hazards, have resulted from the overuse of synthetic pesticides and fertilizers (Tomer *et al*., 2016). These issues have made it necessary to find safe, affordable, and sustainable substitutes. As a result, environmentally acceptable substitutes such biocontrol agents were taken into consideration as a modern replacement for the usage of synthetic chemicals. According to Panpatte *et al*. (2016), biocontrol agents are natural, effective strains of any microorganism or modified organism that assist lessen the severity of diseases caused by plant pathogens or toxicities produced by pesticides and fertilizers. Biocontrol agents come in a variety of forms, including *Bacillus* species, *Pseudomonas*

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species, *Trichoderma* species, and *Beuveria* species. *Pseudomonas fluorescens* and *Trichoderma* sp. are the most successful biocontrol agents of all. They have the ability to colonize the rhizosphere and are persistence throughout the growing season. They also help to enhance plant growth and control plant pathogenic microbial population.

Biocontrol mechanisms of *Trichoderma* against different plant pathogens

Trichoderma a genus of filamentous fungi has gained significant attention for its potential as a bio control agent against various plant pathogens. Its effectiveness can be attributed to several bio control mechanisms such as:

Antibiosis Production: The majority of fungal species have the ability to secrete one or more substances that have antibiotic qualities. Numerous *Trichoderma* species are capable of producing low molecular weight secondary metabolites with antibiotic qualities, which can impede the growth of different microorganisms (Rincón *et al*., 2009). Antibiosis is the term for this inhibitory activity. It is one of the main ways that *Trichoderma* uses biocontrol. The synthesis of volatile, low molecular weight, non-polar chemicals raises the concentration of antibiotics in the soil environment, which affect the microbial community across a comparatively long distance. 6-pentyl apyrone and the majority of isocyanide derivatives are examples of volatile antibiotics. Substances that dissolve in water, such as koningic acid or heptelidie acid. Peptaibols, which are linear oligopeptides of 12-22 amino acids rich in a-amino sobutyric acid, N- acetylated at the N-terminus and containing an amino alcohol at the C-terminus (Mukherjee *et al*., 2010).

Competition: According to certain research, there may be a struggle between diseases and fungi as an additional biocontrol strategy. *Trichoderma* may restrict the growth of infections and compete for vital resources (Gosling *et al*., 2006). *Trichoderma* can compete with other diseases for space, including infection sites on plant roots, in addition to nutrients (Rincón *et al*., 2009). *Trichoderma* can significantly alter plant metabolism and readily infiltrate the rhizosphere of a variety of settings (Mayo *et al*., 2015). In *Trichoderma,* the processes that facilitate colonization of the many ecological niches are highly evolved and diversified (Vinale *et al*., 2008). Additionally, *Trichoderma* is resistant to harmful metabolites that plants create in response to infection, including flavonoids, terpenoids, phenols, and phytoalexins. *Trichoderma* can defend plants against pathogens through a physical interaction between *Trichoderma* and the plants up to the outer layer of the epidermis and the root bark (Mayo *et al*., 2015).

Mycoparasitism: According to numerous research, *Trichoderma* can prevent certain plant diseases by inhibiting plant pathogens that are primarily located in the rhizosphere through mycoparasitism or hyperparasitism (Ng *et al*., 2015). *Trichoderma* directly targets and parasitizes other fungi, especially plant diseases, via a unique method. Other harmful fungi, like *Trichoderma* hyphae, are parasitized by

antagonist fungi, which either grow along or coil around the host hyphae. Mycoparasitism greatly reduces disease and is highly effective against soil-borne pathogens (Mukhopadhyay and Kumar 2020).

Biocontrol mechanisms of *Pseudomonas fluorescens* against plant pathogens

A wide variety of rhizosphere micro-organisms have been identified, described, and frequently evaluated for their potential as biocontrol agents against soil-borne plant infections in recent years. Antagonists must be able to efficiently colonize the root system (Weller, 1988; Parke, 1990) and generate specific antagonistic secondary metabolites (Defago and Hass, 1990) in order to achieve biological control. The major mechanisms by which *Pseudomonas* exerts its biocontrol effects are:

Antibiotic Production: Antibiotics are a diverse class of chemical substances with low molecular weight that inhibit the growth of other bacteria. According to Glick *et al*. (2007), the production of antibiotics is a crucial mechanism that aids rhizobiacteria that promote plant growth in their antagonistic activity against phytopathogens. Phloroglucinal, phenazines, pyrrolnitrin, pyolute-orin, cyclic lipopeptides, and hydrogencyanide are the six groups of antibiotics that are linked to the biocontrol of plant diseases (Hass and Defago 2005). *Pseudomonas* produces 2,4 diacetylphlroglucinol (DAPG), the most significant antibiotic. It aids in preventing diseases of the roots and young seedlings of a variety of crops, such as fusarium wilt, tomato crown rot, and root rot (Duffy and Defago, 1997; Tamietti *et al.*, 1993).

Competition of Root Niches and Nutrients: The rhizosphere's intense microbial diversity and competition are putting biological buffering to the test (Keel *et al.*, 1996). In order for Pseudomonas to colonize the roots and offer defense against all soil-borne diseases, its introduction is crucial. In order to limit the availability of nutrients in root exudates and make them suitable for colonization niches, biocontrol chemicals are used in soils to compete with diseases and hazardous microbes. Fungal infections are eliminated from soil by boosting competition for minerals like iron (Sahu *et al.*, 2018).

Induced Systemic Resistance: The spectrum plant immune response that is triggered by helpful plant bacteria that coexist with plant roots is known as ISR. Plant growth promotion, physiological tolerance induction of all wall reinforcement, increased synthesis of phytoalexins, defense enzymes, and lignin deposition are just a few of the numerous mechanisms of ISR (Jain *et al.*, 2015. Following a pathogen attack, these immunized plants exhibit greater and quicker responses, increasing the degree of protection (Van Peer *et al.*, 1991).

HCN Production: *Rhizobacteria* that promote plant growth create chemical compounds that have various advantages for the plants. One of *Pseudomonas fluorescence*'s most significant processes is the formation of HCN, which has been shown to be effective against *Thielaviopsis basicola* on tobacco (Laville *et al*., 1992). The generation of HCN and the

biological regulation of luminous *Pseudomonas* are strongly correlated, according to Ellis *et al*. (2000). In vitro HCN formation and plant protection were found to be positively associated in the tomato/ *Fusarium oxysporum* f. sp. *radicis-lycopersici* and cucumber/*Pythium ultimum* pathosystems (Ramette *et al*., 2003).

Siderophore Production: Iron is a vital and abundant element, but microbes struggle to acquire it because it exists as insoluble ferric hydroxide, which is not easily absorbed by cells. Metal-chelating compounds such as siderophores, produced by *Pseudomonas*, play a key role in iron metabolism. Siderophores aid in promoting plant growth, managing phytopathogens, and reducing the toxic effects of heavy metals in soil (Panpatte *et al*., 2016).

Conclusion

The heavy reliance on chemical pesticides threatens crops and human health, driving a global shift toward sustainable alternatives. Biocontrol agents like *Pseudomonas* and *Trichoderma* offer an eco-friendly solution for plant disease management by reducing chemical dependency and restoring ecosystem balance. Beyond suppressing pathogens, these beneficial organisms actively promote plant growth, optimize nutrient uptake, and increase crop yields. Driven by public concern over toxicity, global research centres are intensively studying these biological agents to replace chemical pesticides. Furthermore, these microorganisms colonize plant roots, creating a defensive barrier against soil-borne pathogens and inducing systemic resistance throughout the plant. This natural mechanism lowers pest resistance risks, making biocontrol crucial for securing future global food supplies.

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Biofuel from Chinar (*Platanus orientalis* L.) Leaflitter: An Incredible Solution to the Severe Cold in Kashmir

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Abstract

Converting fallen *Chinar* leaflitter into biofuel offers a highly practical, eco-friendly way to generate renewable heat during harsh winters. *Chinar* biofuel is produced from dried *Chinar* leaflitter by controlled burning using indigenous technology and skills inherited through generations. *Chinar* leaflitter is rich in lignocellulosic fibres, ignites easily, burns longer and hotter, and offers a reliable, steady heat output. A huge quantity of leaflitter is generated every year from *Chinar* plantations, providing an essentially free, renewable energy source in Kashmir. *Chinar* biofuel produces less smoke and ash than raw leaf burning, replacing traditional firewood. *Chinar* biofuel, made from locally sourced *Chinar* tree leaflitter is a primary heat source used in traditional *kangris* (fire pots) to survive harsh winters in Kashmir. *Chinar* biofuel making plays a significant role in local entrepreneurship and livelihood generation.

Leaf Biofuel

Energy sources that are safe, secure, and reliable are essential next to food to every society's socioeconomic growth and well-being (Ycaza and Barre, 2018). Leaflitter biofuel is one of the renewable energy sources that is crucial to averting energy problems. When used sustainably and effectively, leaf biofuel, a renewable and CO_2-neutral energy source, can help create a cleaner world. Leaf biofuel is still widely utilized in many developing nations for domestic heating, cooking, rural industry, household rituals and functions, cattle protection, and other purposes. In addition, the leaf biofuels have economic advantages, particularly in rural areas where they create jobs and revenue.

The *Chinar* Tree: A Blessing for Kashmir

The Chinar (*Platanus orientalis* L.) tree, called "*Booune*" in Kashmir, is an enormous, deciduous, long-living tree belonging to the Platanaceae family and is an essential component of indigenous culture and tradition (Khuroo *et al*., 2010). The tree produces "lace wood," a hard, costly, tough wood that is used in the delicate furniture industry. The tree's roots are utilized for dye making, and greyish bark are utilized as medicine. The large leaves are borne alternately on the stem; they are palmate or maple-like, with a long stalk, deeply 5-7 lobed, and 12-20 cm in length. During the harsh winter months,

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the dried leaflitter is burned to create light biofuel, which is then used in fire pots (*kangri*). Biofuel made from *Chinar* leaflitter gathered from departmental plantations, trees outside forests (TOF), farm woodlots, and private places provides the energy needed for body warming in rural Kashmir. *Chinar* biofuel is the primary source of energy for millions of households in rural Kashmir, and nearly all of the *Chinar* leaflitter is consumed annually (Islam *et al*., 2018).

Chinar Leaflitter- A Source of Biofuel

The primary raw material used to make biofuel, a renewable energy source, is dried *Chinar* leaflitter. Making *Chinar* biofuel also contributes to the management of solid waste and protects the environment because all leaflitter is collected for biofuel. The rural people employ primitive methods to convert dried Chinar leaflitter into biofuel, ensuring home energy security. These indigenous traditional knowledges (ITKs) have been derived from management experiences through trial-and-error methods and have been transmitted from the previous generation to the present generation. These ITKs could be used and combined with scientific technology to investigate more human and sustainable biofuel-making processes.

Collection of *Chinar* Leaflitters

Indigenous women typically gather leaflitters, make biofuel, light *kangri*, and even sell biofuel (Figure 1). The larger, higher-quality leaflitters are gathered by hand from the ground in plantations, village commons, and woodlots. Using the broom, the women gather the dry leaflitters from the *Chinar* tree into a heap. They gather 20 kg of leaflitters from the tree stands for a headload, which takes them four to five hours to compile into a heap. They visit *Chinar* stands early in the morning or late in the afternoon to gather fallen leaflitter; this is a three-month-long ritual that takes place from October to December.

Fig. 1: Collection of *Chinar* leaflitter

Fig. 2: Packing and transportation

Packing and Transport of *Chinar* Leaflitters

Using rags or ropes, the dried leaflitters are loosely packed into the bags or baskets. Usually, the bags or baskets containing 5-10 kg of dried leaflitters are generally transported as head loads by the women to their homes (Fig. 2). Head-loading women habitually have a carrying capacity of about 10 kg. In the family backyard, the women usually burn the dried *Chinar* leaflitters to biofuel, but occasionally they store the leaflitters in specially designed stockrooms.

Chinar Biofuel Making

Chinar leaf biofuel, often referred to as "*Punn Tsenei*" in the local dialect and typically used in *kangris* is produced from dried *Chinar* leaflitters using important indigenous technology (Figure 3). The skill of this craft is passed down through folklore, song, and poetry, as well as by learning by doing. To make biofuel, a stick, a long-handled

broom, handy water buckets, and a technique to douse flames are needed. First, they create a heap of the *Chinar* dry leaflitters, which are carefully lighted with matchsticks from the bottom. The backyard glows magically from a scarlet bonfire. To stir the fire that will produce much-needed biofuel for the icy winter months, they move her long-handled broom. After letting the leaflitters burn for fifteen to twenty minutes, water is sprayed on them to put out the flames. A little negligence can ruin the entire endeavour, leaving them with nothing but ash. To prevent the leaflitters from fully burning, they must calmly wait to put out the fire at the appropriate time. When the *Chinar* leaflitters get half-burnt, water is sprinkled over the heap to extinguish them completely. When the fire is put out, they have the required biofuel, but if the fire burns for an extended period of time, they only get ash. To ensure that no leaf is left burning; after extinguishing the fire, more water is sprinkled on the biofuel. Approximately 3.5 kg of biofuel may be produced from a head load of roughly 10 kg of dried leaflitter; one woman can produce two bags of *Chinar* biofuel after working all day.

Fig. 3: Biofuel making

Fig. 4: Drying of *Chinar* biofuel

Drying of *Chinar* Biofuel

With extreme caution to prevent breakages, the *Chinar* biofuels are sun-dried for 7-8 hours in an open area (Fig. 4). The time should not be exceeded since it may cause the biofuel's quality to decline. A small amount of moisture is necessary for the *Chinar* biofuel to prevent breakage while packing. The drying area is typically found in the farmhouse and is mostly composed of mud.

Storage of *Chinar* Biofuel

The plastic bags are filled with the *Chinar* biofuel loosely rather than tightly to avoid pulverization (Fig. 5). To keep air out of the bags, they must be airtight. The bags are stored in the stockrooms made for them in the home. The *Chinar* biofuel bags should not be placed near other combustible items that could accidentally catch fire. In order to prevent any accidents, a handy rose can that is filled with water is also kept to mist the biofuel.

Fig. 5: Storage of biofuel

Fig. 6: *Kangri* burning with biofuel

Kangri Burning with *Chinar* Biofuel

The *kangri* is a portable personal warmer composed of clay pots that are filled with blazing embers and elegantly wrapped in handcrafted wicker baskets. People use this traditional fire pot to keep themselves warm during the chilly winter months. Kashmiri people carry this unique, lightweight, portable, affordable and multipurpose heater (*kangri*) in their *pheran* (a long, knee-length woollen veil) during the chilly winter.

With a wooden or paper torch, just 250 grammes of *Chinar* biofuel are needed to light *kangris* (Fig. 6). It costs between ₹ 70 and ₹ 1500, and it is less expensive than wood-fired, gas, and oil heaters (Fig. 7).

Seasonality of *Chinar* Biofuel Making

Chinar leaflitter collecting is seasonal, lasting three months from October to December. *Chinar* biofuel is used for *kangri* burning for approximately nine months, with the exception of June to August. *Chinar* leaflitter collection is typically not feasible from January to September since during this time the tree develops new leaves and stays evergreen, dropping only a small amount of its dried leaves to maintain its health and growth. The seasonal occupation of the locals, which includes crop cultivation and related agricultural activities, affects the processing of *Chinar* leaflitter and the production of biofuel.

Fig. 7: Body warming by *Chinar* biofuel

Fig. 8: Drudgery of women in biofuel burning

Livelihood Mainstay of *Chinar* Biofuel

Chinar biofuel production is a common cottage enterprise that has provided the indigenous people with significant employment and revenue prospects for ages in the region (Islam *et al*., 2021). Many indigenous people depend on making biofuel from *Chinar* leaves for their subsistence, though some also sell it informally for extra money. Local markets offer labour-intensively made *Chinar* biofuel for sale at low prices. Raw *Chinar* biofuel has a lower profit margin and is not worth the work required to produce it. This is hardly enough to survive on, and even this trivial income is seasonal. The makers of *Chinar* biofuel use this as a supplemental source of revenue rather than their main source of work. *Chinar* biofuels are either sold directly to consumers or through small-scale local vendors.

Gender Dimension in *Chinar* Biofuel Making

The majority of the routine tasks involved in producing *Chinar* biofuel, such as gathering dried leaflitters, packaging and transportation, burning biofuel, drying, storing, lighting *kangri* with biofuel, and selling biofuel, were only carried out by women (Fig. 8). Decisions on all the regular activities related to *Chinar* biofuel making were taken independently by women. Making *Chinar* biofuel is a labour-intensive, clumsy, and time-consuming process. They experience burn injuries and various other diseases linked to smoking; therefore, the hardships must be lessened through the implementation of eco-friendly inventions and technologies, such as installing alternative energy sources in homes, providing affordable kilns for the production of biofuel, encouraging entrepreneurship in the biofuel manufacturing industry, etc.

Way Forward

Making biofuel from *Chinar* leaflitter is a novel intervention that is essential to the rural economies, energy security and welfare of Kashmir's indigenous communities. Therefore, it is imperative

to enhance the energy security derived from *Chinar* biofuel and provide secondary employment opportunities by establishing cottage businesses centred around *Chinar* biofuel, enhancing its value, and instituting a structured marketing system for *Chinar* biofuel. The ITKs of *Chinar* biofuel production will be visualized as the foundation for its potential in the future through mechanization-based value addition. Planning is required for the advancement of technology for producing *kangri* biofuel from *Chinar* leaflitters and for relieving rural women of their drudgery by developing eco-fuel.

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Capacity Building of Farmers through Digital Learning Platforms

M. S. Anarase and G. K. Sasane

Abstract

Agriculture is the backbone of the Indian economy and the major source of livelihood for rural communities. In the present era, agriculture is rapidly transforming from traditional farming to knowledge-based and technology-driven farming systems. Farmers now require updated knowledge, technical skills, and timely information regarding crop management, climate change adaptation, market intelligence, pest management, and sustainable farming practices. Traditional extension systems alone are often unable to satisfy the increasing information demands of farmers due to limited manpower and communication barriers. Therefore, digital learning platforms have emerged as innovative and effective tools for capacity building of farmers. Digital learning platforms include mobile applications, social media, e-learning portals, online training programmes, artificial intelligence-based advisory systems, and virtual communication technologies that provide real-time agricultural information and technical guidance. These technologies improve farmers' knowledge, decision-making abilities, productivity, and income while promoting sustainable agricultural development. Government programmes such as Digital India, e-NAM, Kisan Call Centres, and mKisan Portal are promoting digital transformation in Indian agriculture. This article highlights the concept capacity building through Digital Learning Platforms, major digital learning platforms, future prospects of digital learning in agriculture.

Introduction

Agriculture plays a crucial role in food security, employment generation, and rural development in India. Farmers today face multiple challenges such as climate variability, declining soil fertility, water scarcity, pest outbreaks, rising input costs, and fluctuating market prices. To overcome these challenges, timely access to scientific agricultural knowledge and modern technologies has become essential. Traditional agricultural extension methods such as demonstrations, field visits, and farmer meetings have contributed significantly to agricultural development. The advancement of digital learning platform has revolutionized agricultural communication systems. Farmers can now access agricultural information through smartphones, internet services, online videos, mobile applications, webinars, and social media platforms. Digital learning platforms provide continuous learning opportunities and support farmers in adopting

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modern farming practices. Thus, digital learning systems are becoming important tools for strengthening farmers' capacities and promoting sustainable agricultural transformation.

Concept of Capacity Building and Digital Learning Platforms

Capacity building refers to improving farmers' knowledge, technical skills, managerial competence, and decision-making abilities. Digital learning platforms strengthen this process by delivering scientific agricultural information through modern communication technologies. A digital learning platform is a software-based system or virtual environment designed to facilitate, manage, and deliver the information.

Objectives of Digital Capacity Building

- ✓ Improve farmers' access to agricultural knowledge
- ✓ Promote scientific farming practices
- ✓ Strengthen technical skills
- ✓ Increase agricultural productivity and income
- ✓ Promote climate-smart agriculture

Digital platforms provide continuous learning opportunities and enable farmers to learn anytime and anywhere.

Major Digital Learning Platforms

Mobile-Based Agricultural Learning: Mobile phones are becoming powerful tools for agricultural communication. Farmers use smartphones to receive: Weather forecasts, Crop advisory services, Pest and disease alerts, Fertilizer recommendations, Market price information.

Popular mobile applications in include: Kisan Suvidha App, Pusa Krishi App, AgriMarket App, IFFCO Kisan App.

These applications provide multilingual and location-specific agricultural information.

Importance of Mobile Learning: Quick access to information, Cost-effective communication, Real-time expert guidance, improved decision-making, increased technology adoption.

Online Training and Virtual Learning System: Online training programmes and webinars from Agricultural universities, Krishi Vigyan Kendras (KVKs), NGOs, and private organizations conduct virtual training programmes for farmers on modern agricultural practices.

Major Areas of Online Training: Organic farming, Precision farming, Dairy farming, Mushroom cultivation, Beekeeping, Food processing, Integrated farming systems.

Advantages of Online Agricultural Training: Wider outreach, Reduced training cost, Access to expert knowledge, Flexible learning opportunities, faster dissemination of information.

Social Media and YouTube Learning: Social med-

ia platforms such as YouTube, WhatsApp, Facebook and Telegram are increasingly used for agricultural extension and farmer education. Farmers use these platforms to: Watch practical farming demonstrations, Learn modern technologies, Interact with agricultural experts, Share farming experiences and Access market information. YouTube channels managed by agricultural universities and progressive farmers provide practical videos related to crop production, livestock management, and farm mechanization. WhatsApp group's help farmers receive:

Pest and disease alerts, Weather updates, Instant expert advice and Farm management recommendations.

Artificial Intelligence and Smart Advisory Systems: Artificial Intelligence (AI) is revolutionizing agricultural extension services. AI-based systems analyze agricultural data and provide personalized recommendations regarding: Crop management, disease diagnosis, irrigation scheduling, fertilizer application, yield prediction AI technologies improve farm efficiency, reduce production risks, and increase resource-use efficiency.

Climate-Smart Agriculture through Digital Learning: Climate change is creating serious challenges such as droughts, floods, and unpredictable weather conditions. Digital learning platforms help farmers adopt climate-smart agricultural practices.

Digital Climate Advisory Services: Weather forecasting, Drought warning systems, Water management guidance, Crop planning recommendations, Disaster preparedness information.

Digital Marketing and Farmer Empowerment: Digital platforms such as e-NAM provide direct market access to farmers and improve transparency in agricultural marketing systems.

Benefits of Digital Agricultural Marketing: Better market prices, wider market access, reduced dependence on intermediaries, Increased bargaining power, Improved farm income**.** Digital learning systems also strengthen women empowerment by improving access to agricultural education and entrepreneurship opportunities.

Future Prospects of Digital Learning in Agriculture: The future of digital agricultural learning is highly promising and transformative. Emerging technologies such as Artificial Intelligence (AI), Internet of Things (IoT), blockchain technology, drones, robotics, big data analytics, and virtual reality are expected to revolutionize agricultural extension and farmer education systems. Future digital learning systems will provide highly personalized and location-specific agricultural advisory services. Farmers will receive real-time recommendations based on soil conditions, weather patterns, crop health, and market trends through AI-powered platforms.

Conclusion

Capacity building of farmers through digital

learning platforms is transforming traditional agricultural extension systems into modern, technology-driven communication systems. Digital technologies such as mobile applications, online training programmes, social media platforms, e-learning portals, artificial intelligence, and digital advisory systems are helping farmers access scientific agricultural information and practical knowledge quickly and efficiently. Digital learning improves farmers' technical skills, decision-making abilities, productivity, and income while promoting sustainable and climate-smart agriculture. It also empowers women farmers and encourages youth participation in modern farming and agribusiness activities. Although challenges such as digital illiteracy, poor internet connectivity, and inadequate infrastructure still exist, technological advancement and government support are rapidly strengthening digital agricultural learning systems in India. Therefore, digital learning platforms will play a significant role in achieving sustainable agriculture, food security, rural development, and socio-economic transformation in the future.

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Biochar as a Long-Term Soil Amendment: Sustained Benefits for Crop Yield and Carbon Sequestration

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Abstract

Biochar is a carbon-rich pyrogenic material produced by thermochemical conversion of organic biomass under oxygen-limited conditions and has attracted considerable research interest as a sustainable soil amendment. Although earlier studies demonstrated short-term agronomic benefits, a critical knowledge gap persisted regarding long-term efficacy under realistic field conditions. Drawing on 29 long-term global field experiments (duration: 4-12 years), recent evidence (Yang *et al.*, 2025) demonstrates that annual biochar application sustains and progressively enhances crop yields, soil organic carbon (SOC) accumulation, and greenhouse gas (GHG) mitigation. Single-dose applications, by contrast, exhibit diminishing returns over time. This article reviews the current mechanistic understanding of biochar's effects on soil physical, chemical, and biological properties; its observed impacts on crop yield and carbon sequestration; and its role in climate-smart agriculture. The article also examines key issues related to dose optimization, feedstock selection, and policy integration.

Introduction

Global food security and climate change mitigation are two of the most pressing challenges of the twenty-first century, and sustainable soil management sits at their intersection. Soils anchor terrestrial food production and store approximately 1,500-2,400 Pg of organic carbon more than twice the quantity held in the atmosphere making them the largest active terrestrial carbon reservoir on Earth (IPCC, 2021). Degradation of soil health through intensive tillage, excessive synthetic fertilizer use, and declining organic matter inputs has accelerated the loss of this carbon stock, simultaneously eroded agricultural productivity, and amplified atmospheric greenhouse gas concentrations. Among the emerging strategies to reverse soil degradation, biochar has attracted growing scientific and policy attention. Biochar is produced by heating organic material, such as crop residues, wood, manure, or municipal waste in the absence or near-absence of oxygen through a process known as pyrolysis. The resulting material is highly porous, recalcitrant, and enriched in stable carbon capable of persisting in soils for centuries to millennia. Early field and greenhouse studies reported encouraging improvements in soil fertility and crop yields, but questions persisted about whether these benefits endure over the long term, particularly under repeated annual additions. Recent evidence most compellingly a landmark meta -analysis of 29 long-term field experiments spanning

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four to twelve years (Yang *et al.*, 2025) now provides compelling answers: annual biochar applications sustain and enhance the full suite of agronomic and environmental benefits, whereas single applications lose effectiveness with time. This article explores these findings and their implications for sustainable agriculture.

What is Biochar and how is it Made?

Biochar is a carbon-rich material that is produced by heating biomass such as wood, manure, or leaves at temperatures of 400-700°C in a closed container in which oxygen is absent or depleted (Khater, 2024). Common feedstocks include rice husks, wheat straw, sugarcane bagasse, wood chips, poultry manure, and sewage sludge.

Biochar and Soil Physical, Chemical and Biological Properties: Biochar enhances soil health by simultaneously altering its physical, chemical, and biological characteristics. Physically, biochar functions as a highly porous matrix. Its extensive surface area, often ranging between 100 and 400 m^2 g^{-1} significantly increases soil water-holding capacity. This provides a critical advantage for coarse, sandy soils that are otherwise susceptible to rapid desiccation. Biochar also helps to loosen things up by reducing the total bulk density of the soil, allowing the roots to push through more easily and improving both aeration and hydraulic conductivity. Chemically, the addition of biochar helps to neutralize acidic soils, therefore reducing the harmful effects of aluminium and manganese. Biochar generally has a high cation exchange capacity (CEC) of 20 to 100 $cmol_c$ kg^{-1} depending on the raw material and pyrolysis method. This elevated CEC allows the soil to effectively retain essential macronutrients, such as nitrogen, potassium and phosphorus; reducing nutrient leaching. Additionally, its highly reactive surface actively adsorbs heavy metals and organic pollutants, facilitating the remediation of contaminated land. From a biological perspective, the extensive internal porosity of biochar provides microhabitats for soil microorganisms, shielding them from larger predators and extreme desiccation. Within this protected microenvironment, microbial biomass and diversity flourish, leading to upregulated enzymatic activity essential for organic matter decomposition and nutrient cycling. Over the long term, biochar profoundly alters soil bacterial and fungal assemblages, promoting the proliferation of rare microbial taxa, suppressing soil-borne pathogens, and stimulating plant-growth-promoting rhizobacteria.

Impact on Crop Yield: Short-Term Versus Long-Term: Early meta-analyses of biochar's agronomic effects reported average yield increases of approximately 10-15% across diverse crops and soil types. However, these studies largely pooled short-duration experiments, obscuring important temporal dynamics. A landmark global meta-analysis of 29 long-term field experiments spanning rice, wheat, maize, and vegetable production systems across Asia, Euro-

pe and the Americas -demonstrated a clear distinction: single-application trials showed declining yield benefits over time, whereas annual applications produced sustained and progressively improving yields over 4-12 years. The mechanisms underlying long-term yield enhancement include continued improvements in soil water retention and aeration, progressive microbial colonisation of biochar pores, and sustained nutrient retention capacity. Dose-response relationships indicate that annual application rates of 10-20 Mg ha^{-1} yr^{-1} yield optimum results in most cropping systems, though optimal rates vary by feedstock type, soil texture, and climate. For smallholder farming systems, lower annual doses of 2-5 Mg ha^{-1} combined with compost co-application have demonstrated comparable long-term yield benefits.

Key crop yield benefits observed under long-term annual biochar application

- ✓ Improved germination rate and seedling establishment in biochar-amended soils
- ✓ Enhanced nitrogen use efficiency (NUE), reducing synthetic fertiliser requirements by 10-20%
- ✓ Greater crop resilience to moisture deficit and heat stress events
- ✓ Reduced incidence of soil-borne diseases attributable to biochar-mediated microbiome modulation
- ✓ Higher fruit quality indices (e.g. lycopene content, Brix value) in horticultural crops

Carbon Sequestration and Greenhouse Gas Mitigation: Biochar's most globally significant contribution lies in its capacity to sequester atmospheric carbon for centuries. When organic residues decompose or are burned, their carbon is rapidly mineralised and returned to the atmosphere as CO_2. Pyrolysis converts this labile carbon into a highly aromatic, condensed form that is biologically and chemically recalcitrant, with mean residence times in soil estimated at 100-1,000+ years. This renders biochar one of the few carbon dioxide removal (CDR) approaches capable of sequestering carbon in a stable, measurable, and independently verifiable pool. A comprehensive global meta-analysis found that annual biochar applications progressively accumulate soil organic carbon (SOC), building a growing carbon stock in contrast to single-application trials where the initial SOC gain plateaued and subsequently declined. Each unit increase in SOC simultaneously improves nutrient cycling, water retention, and biological activity, creating a positive feedback loop of soil health improvement. Beyond direct carbon sequestration, biochar significantly reduces two potent non-CO_2 greenhouse gases. Nitrous oxide (N_2O) with a global warming potential (GWP100) of approximately 273 times that of CO_2 on a 100-year timescale is suppressed through reduced denitrification activity and improved soil nitrogen retention. Methane (CH_4) emissions from flooded paddy soils are mitigated through enhanced aeration and modification of methanogenic archaeal communities. Long-term field experiments confirm that these GHG reductions persist across 4-12 years

of continued annual application, solidifying biochar's role in integrated climate change mitigation strategies.

Practical Considerations for Field Application: Translating biochar research into field practice requires careful attention to agronomic, economic, and safety factors. Feedstock availability and quality are paramount: locally sourced agricultural residues rice husks, sugarcane bagasse, and wheat straw are preferred for sustainability and cost reduction. Furthermore, pyrolysis temperatures must be tailored to the intended soil function: lower temperatures preserve nutrient content and improve immediate crop responses, whereas higher temperatures maximize carbon aromaticity and long-term soil persistence. Application timing and method significantly influence biochar efficacy. Incorporating biochar at planting through tillage or band placement near root zones maximizes contact with plant roots and soil microbial communities. Pelletized biochar formulations are increasingly favoured for mechanized application. Co-application with organic compost or nitrogenous fertilizer mitigates the short-term nitrogen immobilization effect sometimes observed at high biochar doses. Economic viability remains a primary constraint, particularly in smallholder agricultural settings. On-farm biochar production units utilizing crop residues can reduce input costs while simultaneously addressing field-burning of residue waste. Policy instruments including carbon credits under voluntary carbon markets, where verified biochar carbon removal (BCR) projects are currently valued at approximately 50-200 USD/tonne CO_2 equivalent (approximate market range reported in recent literature) are increasingly available and can substantially offset production costs, particularly for organized farmer collectives.

Conclusion

Biochar stands out as one of the most versatile and evidence-based technologies in the expanding paradigm of climate-smart, regenerative agriculture. The accumulating body of long-term field evidence anchored by the global meta-analysis of 29 multi-year experiments by Yang *et al.* (2025), published in Proceedings of the National Academy of Sciences firmly establishes that repeated annual biochar applications deliver sustained and improving benefits to crop yields, soil organic carbon, and greenhouse gas mitigation. These are not transient gains, but durable transformations in the physical, chemical, and biological architecture of the soil.

Particularly in South and Southeast Asian contexts, biochar offers a transformative opportunity to convert crop residue burning from a severe air pollution crisis into a definitive solution for soil health and climate change mitigation. The integration of biochar into national soil health policies, targeted fertilizer subsidy frameworks, and voluntary carbon market mechanisms will be crucial to scaling its adoption globally. The scientific evidence is robust and unambiguous; the prevailing challenge is now implementation. Future research should prioritize the development of farmer-participatory produc-

tion systems, region-specific dose optimization, and the integration of biochar with advanced slow-release nutrient technologies (such as polymer-clay composites) to further refine soil remediation in smallholder contexts.

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The Miracle Moringa Cutlery: Why Your Next Spoon Might be the Healthiest Part of Your Lunch

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Introduction

Have you ever finished a delicious bowl of soup, looked at your plastic spoon, and felt a pang of guilt? We use billions of pieces of plastic cutlery every year, most of which end up in landfills or oceans, takes hundreds of years to decompose. But what if your cutlery is not just eco-friendly? What if it is actually nutritious too? To combat the increasing problem of plastic pollution, edible cutlery was developed using the nutrient-rich leaves of *Moringa oleifera*, commonly known as the "Miracle Tree." This innovative product offers a sustainable, biodegradable, and nutritious alternative to single-use plastic cutlery while promoting the utilization of natural ingredients.

More than Just a Dish: Most biodegradable cutlery available today is made from plant-based materials that help reduce plastic waste but offer little or no nutritional value. To address this limitation, the present study developed functional edible cutlery by incorporating moringa leaf powder into food-grade flour-based formulations. Moringa (*Moringa oleifera*), often referred to as the "Miracle Tree," is a rich source of vitamins, minerals, dietary fiber, and natural antioxidants (Gopalakrishnan *et al*., 2016). The inclusion of moringa not only enhances the nutritional profile of the cutlery but also contributes to environmental sustainability by providing an eco-friendly alternative to single-use plastics.

Three innovative variants of moringa-based functional cutlery were developed to cater to different nutritional and sensory preferences:

Chocolate Moringa Cutlery: Combines the nutritional benefits of moringa with the appealing flavor of cocoa.

Multigrain Moringa Cutlery: Formulated using a blend of grains to enhance dietary fiber and nutritional diversity.

Oats Moringa Cutlery: Incorporates oats, a well-known source of soluble fiber, for added functional benefits.

Fig. 1: (a) Chocolate Moringa Cutlery, (b) Multigrain Moringa Cutlery, (c) Oats Moringa Cutlery

The edible cutlery formulations were prepared using a combination of wheat flour, multigrain flour, oats flour, corn starch, sugar, cocoa powder, and moringa leaf powder. Wheat flour and corn starch provided the necessary structural strength and texture, while oats and multigrain flour enhanced the dietary fiber content. Cocoa powder improved the

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flavor and overall sensory appeal of the products, whereas moringa powder enriched them with valuable nutrients, including vitamins, minerals, and antioxidants. Fresh moringa leaves were collected, thoroughly washed, and dried at 70°C for 7-8 hours. The dried leaves were then ground and sieved to obtain a fine powder. The ingredients were accurately weighed according to the selected formulations and mixed with water to form a uniform dough. The dough was rolled into thin sheets and shaped into various cutlery forms using suitable molds. The molded cutlery was baked at 180°C for 15-20 minutes, followed by cooling at room temperature (Roy, 2025). Finally, the products were packed in airtight containers to maintain their quality and shelf life. The resulting edible cutlery was sturdy enough for practical use, nutritionally enriched, fully biodegradable, and safe for consumption, offering a sustainable alternative to conventional single-use plastic cutlery.

The Science of the "Perfect Crunch"

Developing edible cutlery involves much more than simply combining ingredients and shaping them into spoons or forks. The product must possess the right balance of strength, texture, nutritional value, and environmental sustainability. It should be sturdy enough to hold food during use while remaining safe, palatable, and biodegradable after disposal. To assess the quality and performance of the developed cutlery, several scientific analyses were carried out. Physicochemical properties and nutritional composition were evaluated using standard laboratory methods. Parameters such as moisture, protein, fat, and mineral content were determined to understand the nutritional profile and storage stability of the products. Texture is another critical factor influencing the functionality of edible cutlery. Texture profile analysis was therefore conducted to measure characteristics such as hardness, cohesiveness, adhesiveness, and fracturability. These properties help determine whether the cutlery can withstand handling and food contact without breaking. The visual appearance of the products was assessed through color analysis using a Hunter Lab colorimeter. Color measurements provide valuable information about product uniformity and consumer acceptability. Functional properties such as water absorption capacity and oil binding capacity were also evaluated, as these characteristics influence the performance of edible cutlery when used with different types of foods.

In addition to quality assessment, the environmental impact of the developed cutlery was examined through biodegradability studies. The soil burial method was used to monitor the natural decomposition behavior of the products under environmental conditions. Such evaluations are essential for determining the potential of edible cutlery as a sustainable alternative to conventional single-use plastic utensils.

A Zero-Waste Future

The growing concern over plastic pollution has encouraged researchers and food innovators to explore environmentally friendly alternatives to

conventional single-use utensils. Edible cutlery represents one such innovative solution, combining sustainability with functionality. By utilizing natural and food-grade ingredients, these products offer a practical approach to reducing dependence on disposable plastics. The development of moringa-based edible cutlery demonstrates the potential of incorporating plant-derived ingredients into value-added food products. Moringa, often referred to as the "Miracle Tree," is widely recognized for its rich nutritional composition and versatility in food applications. Its incorporation into edible cutlery highlights an innovative way of utilizing under-exploited plant resources while promoting sustainable consumption practices. Beyond serving as an alternative to plastic utensils, edible cutlery aligns with the principles of a circular economy by minimizing waste generation and encouraging the use of biodegradable materials (Uthamaraj *et al*., 2016). Such products have potential applications in cafeterias, restaurants, food service establishments, outdoor events, and takeaway services, where large quantities of disposable cutlery are commonly used.

As consumers become increasingly conscious of environmental issues, the demand for sustainable food products is expected to grow. Innovations such as edible cutlery illustrate how food technology can contribute to addressing environmental challenges while creating novel and practical products. By rethinking everyday items such as spoons and forks, we can take small but meaningful steps toward a cleaner and more sustainable future.

Conclusion

Edible cutlery is a simple yet innovative idea that reimagines the way we use everyday utensils. By combining sustainability with functionality, moringa-based cutlery presents an environmentally friendly alternative to plastic spoons and forks. As awareness of plastic pollution increases, such eco-conscious innovations can help create a cleaner environment and encourage more sustainable food consumption practices for future generations.

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Mulberry Fruits: The Sweet Secret of Sericulture

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Abstract

Mulberry (*Morus* spp.) is widely recognized as the primary food source for silkworms in sericulture, but its fruits remain an underutilized biological resource. This article highlights the nutritional, phytochemical, economic, and agronomic significance of mulberry fruits. Rich in vitamins, minerals, antioxidants, and bioactive compounds such as anthocyanins and 1-deoxynojirimycin (DNJ), mulberry fruits demonstrate strong potential as functional foods and nutraceutical ingredients. Despite their perishability, advancements in processing and value addition offer opportunities for rural income diversification, especially in sericulture-based farming systems. Integrating fruit utilization with silk production can enhance the sustainability and profitability of mulberry cultivation. This paper emphasizes the need to re-evaluate mulberry as a dual-purpose crop supporting both sericulture and human nutrition.

Introduction

Mulberry (*Morus* spp.) has been cultivated for centuries as the backbone of sericulture, particularly for feeding the silkworm (*Bombyx mori*). In countries like India, China, and Japan, mulberry plantations form the foundation of the silk industry and rural livelihoods. Traditionally, the focus has remained almost entirely on mulberry leaves, while the fruits are often neglected or consumed locally in limited quantities. However, increasing scientific evidence suggests that mulberry fruits are not merely by-products of sericulture but nutritionally rich berries with significant health-promoting properties. Their sweet-tart flavour, attractive colour, and bioactive compounds make them a potential candidate for functional food development.

This article explores mulberry fruits as an emerging resource with dual importance in agriculture and human health.

Overview of Mulberry Fruits

Mulberry belongs to the genus *Morus* under the family Moraceae. The major cultivated species include:

- ✓ *Morus alba* (White mulberry)
- ✓ *Morus nigra* (Black mulberry)
- ✓ *Morus rubra* (Red mulberry)

Mulberry trees are deciduous, fast-growing perennial plants widely adapted to diverse agro-climatic conditions. They perform well in tropical and subtropical regions and can be successfully cultivated under both rainfed and irrigated systems, making them highly suitable for sericulture-based

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farming systems. In mulberry cultivation, leaves are harvested repeatedly throughout the year to support silkworm rearing, forming the backbone of sericulture production. In contrast, fruits develop during the reproductive phase of the plant and mature in clusters along the branches. These fruits are classified as aggregate drupes, characterized by their soft, juicy texture and high moisture content. Due to their delicate nature and rapid post-harvest deterioration, mulberry fruits are highly perishable and have limited shelf life, which restricts their long-distance marketing. Therefore, effective post-harvest handling and processing are essential to enhance their commercial utilization and value addition potential.

Multidimensional Value of Mulberry Fruits

Nutritional Composition

Mulberry fruits are nutrient-dense and low in fat, making them suitable for health-oriented diets. Their major nutritional components include:

Carbohydrates: Natural sugars such as glucose and fructose

Dietary fiber: Supports digestive health

Vitamins: High levels of vitamin C and vitamin K

Minerals: Iron, calcium, potassium, magnesium

Proteins: Present in small but significant amounts

The fruit's deep purple-black varieties are particularly rich in anthocyanins, which contribute to their antioxidant capacity.

Phytochemical and Functional Properties

Mulberry fruits contain several bioactive compounds that provide health benefits:

Anthocyanins: Strong antioxidant and anti-inflammatory agents

Flavonoids: Protect against oxidative stress

Resveratrol: Associated with cardiovascular health and anti-aging effects

1-Deoxynojirimycin (DNJ): Helps regulate blood glucose levels

These compounds position mulberries as a functional food, meaning they offer health benefits beyond basic nutrition.

Health Benefits

Scientific studies and traditional knowledge suggest multiple health-promoting properties:

Antioxidant activity: Reduces oxidative stress and cellular damage

Anti-diabetic potential: Helps regulate post-meal blood sugar levels

Cardiovascular support: Improves lipid profiles and blood vessel function

Immune enhancement: Strengthens defense mechanisms through vitamin C

Digestive health: Dietary fiber supports gut microbiota balance

Regular consumption of mulberries may

contribute to overall wellness and disease prevention.

Sericulture and Economic Importance: In sericulture systems, the primary focus is leaf production for silkworm feeding. However, mulberry fruits offer an additional income stream:

- ✓ Fresh fruit sales in local markets
- ✓ Processing into jams, juices, and dried products
- ✓ Production of nutraceutical powders and extracts

Integrating fruit harvesting into sericulture systems supports income diversification and enhances farm profitability. This is particularly important for small and marginal farmers in silk-producing regions.

Post-Harvest Handling and Value Addition

Mulberry fruits are highly perishable, requiring immediate processing after harvest. Several value-added products can be developed:

- ✓ Mulberry jam and jelly
- ✓ Juice and squash
- ✓ Wine and vinegar
- ✓ Dried mulberries (sun-dried or freeze-dried)
- ✓ Natural food colorants

Modern technologies such as vacuum drying and microencapsulation can improve shelf life while preserving nutritional quality.

Conclusion

Mulberry fruits represent an underutilized yet highly valuable component of the sericulture ecosystem. While mulberry leaves remain central to silk production, the fruits offer significant nutritional, functional, and economic benefits. Their rich bioactive profile supports human health, while their processing potential enables income diversification for farmers. By promoting integrated utilization, mulberry can evolve from a single-purpose sericulture crop into a sustainable dual-purpose system that strengthens both rural livelihoods and nutritional security.

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AI-Driven Precision Agriculture: Transforming Traditional Farming Systems

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The agricultural sector is undergoing a technological revolution, driven by the integration of Artificial Intelligence (AI) and precision farming techniques. As global challenges such as climate change, population growth, and resource scarcity intensify, traditional farming methods are increasingly proving insufficient to meet rising food demands. In this evolving scenario, AI-driven precision agriculture has emerged as a transformative approach, enabling farmers to optimize productivity while minimizing resource use and environmental impact. Precision agriculture refers to the use of advanced technologies to monitor, analyze, and manage agricultural practices at a highly granular level. AI enhances this approach by enabling real-time data analysis, predictive modeling, and automated decision-making. Through the integration of sensors, drones, satellite imagery, and machine learning algorithms, farmers can now gain detailed insights into soil health, crop conditions, weather patterns, and pest infestations.

One of the most significant advantages of AI in agriculture is its ability to improve resource efficiency. Traditional farming often relies on uniform application of water, fertilizers, and pesticides across entire fields, leading to wastage and environmental degradation. In contrast, AI-powered systems enable site-specific management, where inputs are applied only where and when needed. For instance, soil moisture sensors combined with AI algorithms can determine the exact irrigation requirements of different field zones, thereby conserving water and energy. AI-driven technologies also play a crucial role in crop monitoring and disease management. Computer vision systems, powered by machine learning, can analyze images captured by drones or smartphones to detect early signs of crop diseases, nutrient deficiencies, or pest attacks. This early detection allows farmers to take timely corrective measures, reducing crop losses and improving yield quality. Furthermore, predictive analytics can forecast potential risks based on historical and real-time data, enabling proactive decision-making.

Another important aspect of precision agriculture is yield optimization. AI models can analyze multiple variables, including soil compos-ition, weather forecasts, and crop genetics, to recommend the best planting schedules, crop varieties, and farming practices. This data-driven approach not only enhances productivity but also reduces uncertainty and financial risks for farmers.

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Additionally, automation technologies such as auto-nomous tractors and robotic harvesters are reducing labor dependency and increasing operational efficie-ncy. Despite its immense potential, the adoption of AI in agriculture faces several challenges. High initial investment costs, limited digital literacy among farmers, and inadequate infrastructure in rural areas can hinder widespread implementation. Data privacy and accessibility also remain critical concerns. However, with increasing government support, private sector innovation, and the development of user-friendly technologies, these barriers are gradually being addressed.

In conclusion, AI-driven precision agricu-lture represents a paradigm shift in modern farming systems. By leveraging data and technology, it enables efficient resource utilization, enhances crop productivity, and supports sustainable agricultural practices. As the global agricultural landscape continues to evolve, the integration of AI will play a pivotal role in ensuring food security and building a resilient farming ecosystem for the future.

Phosphocompost from Organic Wastes: Quality Assessment and Soil Response

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Introduction

Phosphorus occupies a position of paramount importance in plant nutrition, second only to nitrogen in terms of its quantitative requirement and multifunctional physiological roles. (Meena *et al* 2025). In soil systems, phosphorus exists in both inorganic and organic pools. Inorganic P predominantly occurs as phosphate anions likes $H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-} the availability of which is governed by soil pH, cation exchange capacity, iron and aluminium oxide content and the activity of the microbial biomass (Meena and Biswas, 2014). Organic phosphorus, housed in humic substances, plant residues, animal manures and microbial biomass, requires enzymatic mineralization before becoming available to plants. This fixation phenomenon repeated and often excessive fertilizer applications, escalating input costs and contributing to environmental degradation through eutrophication of water bodies (Moharana and Biswas, 2016).

Phosphocompost the deliberate enrichment of compost with LGRP and PSM during the composting process has emerged as a technically sound and cost-effective strategy. The microbial decomposition of organic matter generates a cascade of low-molecular-weight organic acids (citric, malic, fumaric, succinic, oxalic and others) that lower the pH microenvironment around rock phosphate particles, dissolving the insoluble calcium phosphate minerals and converting TCP into more soluble MCP. The resulting phosphocompost is a slow-release, multi-nutrient amendment that simultaneously improves soil physical, chemical and biological properties. The cost of obtaining one kg P_2O_5 through phosphocompost is approximately Rs. 9.00, compared to Rs. 16-17 through SSP or DAP saving that translates to Rs. 400-500 per hectare per crop cycle when P is applied at 60 kg P_2O_5 ha^{-1} (IISS Bhopal).

Limitations of chemical phosphorus fertilizers

At the soil-chemical level, phosphorus fixation is the dominant limiting factor. In alkaline and calcareous soils, soluble phosphate reacts rapidly with calcium ions to form dicalcium phosphate dihydrate (DCPD), which further transforms to less soluble octa calcium phosphate (OCP) and ultimately to thermodynamically stable apatite minerals over time. In acidic soils, ferric and aluminium oxyhydroxides adsorb phosphate through ligand exchange reactions, forming inner-sphere

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surface complexes of very low solubility. From an environmental standpoint, over-application of P fertilizers in response to fixation losses contributes to the accumulation of reactive P in surface soils, which it is mobilized to water bodies through surface runoff and erosion. Elevated dissolved P concentrations drive eutrophication of lakes, reservoirs and estuaries, with cascading ecological consequences including hypoxic dead zones, harmful algal blooms and biodiversity loss.

Phosphocompost: Concept and Preparation

Definition: Phosphocompost also termed rock phosphate-enriched compost (RPEC) is defined as a compost prepared through the co-composting of organic wastes-crop residues, farm yard manure, green manures, agro-industrial by-products with low-grade rock phosphate and phosphate-solubilizing microorganisms (PSM) under aerobic, thermophilic conditions. The microbial decomposition of organic matter, which produces an acidic chemical environment through the generation of organic acids and the pH-dependent solubilization of rock phosphate minerals, which is facilitated by these acids (Reddy *et al*., 2002).

Preparation methodology: The standard phosphocompost preparation follows a structured pit-composting protocol. Crop residues or other organic waste materials are layered in pits at a defined ratio a commonly reported formulation involves vegetable waste, grass and pine needles in a 3:2:1 ratio. Low-grade rock phosphate is incorporated at 3% by weight of the composting mass, along with bone meal at an equivalent proportion. Cow dung inoculum (1:2 cow dung: water) is added to introduce native microflora and provide initial nitrogen for C:N ratio adjustment. A microbial consortium-comprising organisms such as *Bacillus subtilis* actinomycetes and *Aspergillus niger* is applied at 10% by weight to augment P solubilization capacity. Urea may be incorporated at 0.252 kg N per 100 kg of composting material to maintain an optimal C:N ratio for microbial activity (Meena and Biswas, 2014). The composting mass is turned at regular intervals (every 15-30 days) to ensure aerobic conditions throughout the pile.

Quality parameters of phosphocompost during maturation

The maturation of phosphocompost is accompanied by changes in physical, chemical and biological parameters that collectively define compost quality (Moharana and Biswas 2016). Temperature dynamics reflect the intensity of microbial activity, peak thermophilic temperatures (55.5°C at day 7) rapidly decompose pathogens and weed seeds, followed by a gradual return toward ambient temperature as labile substrates are exhausted. The pH shows a characteristic biphasic pattern-an initial decline during the active decomposition phase (minimum pH 5.92 at day 15 due to organic acid accumulation), followed by a progressive rise as organic acids are metabolized and ammonia is released from protein decomposition (pH 7.06 at day 90). This transient acidification is precisely the window during which maximum rock phosphate

solubilization occurs, underscoring the importance of ensuring sufficient RP is incorporated before the acidification phase (Moharana and Biswas, 2016). Organic carbon declines steadily from 28.8% at day 0 to 17.7% at day 90, reflecting the progressive mineralization of labile carbon fractions. Concurrently, total nitrogen increases from 0.49% to 0.98% on a dry weight basis an apparent concentration effect driven by carbon loss while the C:N ratio narrows dramatically from 58.7 to 18.1 and organic matter content correspondingly decreases from 49.6% to 30.6%, indicating advanced humification (Meena and Biswas, 2014). Electrical conductivity increases from 1.01 to 1.86 dS m^{-1} over the maturation period, reflecting solubilization of mineral salts and nutrient release. Water content declines from 62.2% to 25.3% consistent with evaporative losses during the thermophilic and cooling phases.

Effects on soil pH, buffering and soil available phosphorus

The pH dynamics by incorporating PSM (both alone and in combination with rock phosphate) exhibited progressive pH decline from day 15 to day 90, reflecting sustained organic acid production. In contrast, treatments with SSP or rock phosphate alone showed slight pH increases over time, consistent with the alkalizing effect of calcium accompanying phosphate dissolution. These pH responses have implications for the management of micronutrient availability and aluminium toxicity in acid soils where such amendments might be deployed. The synergistic interaction between partial acidulation, organic matter and phosphate-solubilizing microorganisms produces the most effective P availability outcomes in soil (Moharana and Biswas, 2016).

Environmental implications and sustainability perspectives

The adoption of phosphocompost as a P management strategy delivers a constellation of environmental benefits. The recycling of crop residues, agricultural wastes and agro-industrial by-products through composting diverts these materials from open-field burning a practice responsible for significant emission of greenhouse gases (CO_2, CH_4, N_2O) and particulate matter in northern India (Meena *et al.*, 2025). The slow-release nature of phosphor-compost substantially reduces the risk of P runoff and eutrophication relative to water-soluble chemical P fertilizers. By improving soil aggregate stability and water retention, regular phosphocompost application reduces erosion-associated P loss. Increased soil organic matter under phosphocompost regimes sequesters atmospheric carbon contributing to climate change mitigation goals. The shift from high-input chemical-intensive P management to biologically mediated compost-based systems also reduces dependence on non-renewable phosphate rock reserves, advancing the transition toward a more circular and sustainable phosphorus economy.

Conclusions

The phosphocompost as a scientifically sound, economically advantageous and environmen-

tally sustainable alternative to conventional chemical phosphatic fertilizers. The core biochemical principle that organic acids generated during microbial decomposition of organic wastes solubilize tricalcium phosphate from low-grade rock phosphate, converting it into plant-available mono-calcium phosphate. The phosphocompost approach slow-release, multi-nutrient soil amendment that improves biological activity, enzymatic capacity and soil organic matter and it delivers yield and quality outcomes consistently comparable or exceeding those of chemical fertilizers at a fraction of the input cost.

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Interior Space Management Techniques: Improving Living Conditions in Rural and Urban Homes

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Introduction

Home is not only a place for shelter but also a space that influences health, comfort, and productivity. In present times, both rural and urban households face challenges such as limited space, improper storage, and overcrowding. Interior space management techniques help in the scientific and efficient utilization of available space. These techniques ensure that even small houses can be organized in a way that supports better living conditions.

Need for Interior Space Management

With increasing population and shrinking land availability, houses are becoming smaller, especially in urban areas. In rural households, multiple activities such as cooking, storage of grains, and living take place in the same space. Poor space management leads to clutter, stress, and unhygienic conditions. Therefore, adopting simple space management practices is essential for maintaining cleanliness, safety, and comfort.

Objectives

The main objectives of interior space management are to maximize the use of available space, improve functionality, enhance aesthetic appeal, and reduce clutter. It also aims to create a comfortable and organized living environment suitable for all family members.

Key Interior Space Management Techniques

Multi-functional Furniture: Furniture that serves more than one purpose, such as sofa-cum-beds, storage beds, and foldable tables, helps in saving space and increasing utility.

Vertical Storage: Using walls for shelves, racks, and hanging systems allows better storage without occupying floor area. This is especially useful in kitchens and small rooms.

Decluttering: Removing unused and unnecessary items helps in maintaining cleanliness and improves the overall appearance of the house.

Space Zoning: Dividing the available space into different functional areas like cooking, sleeping, and storage helps in better organization.

Lighting and Color: Proper lighting and the use of light colors make rooms appear bigger and more comfortable.

Relevance to Agricultural and Rural Households

In farming families, homes often serve multiple purposes, including storage of seeds, grains, and agricultural tools. Efficient space management helps in safe storage, reduces damage and pest infestation, and improves accessibility. Organized spaces also save time during daily activities and reduce physical strain.

Benefits of Interior Space Management

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Interior space management provides several benefits such as improved quality of life, better hygiene, reduced stress, increased efficiency in daily tasks, and enhanced aesthetic appeal. It also promotes sustainable living by encouraging minimalism and optimal use of resources.

Practical Suggestions

Families can adopt simple practices like regular cleaning, proper arrangement of items, use of locally available storage solutions, and involvement of all family members in maintaining the space. Awareness programs and extension activities can also help in educating rural households about these techniques.

Conclusion

Interior space management is a practical and cost-effective approach to improve living standards. By adopting simple techniques, households can transform their homes into organized, functional, and comfortable spaces. This is especially important in rural and agricultural settings where efficient use of space can support both household and occupational needs.

Innovative Technologies to Reduce Post Harvest Vegetable Waste

S. Teja, V. Boomika and J. Devika

Abstract

Vegetables are highly perishable and if they aren't handled properly, a lot of the harvest is lost before it gets to customers. New ideas after the harvest make it possible to cut down on waste, make food last longer and protect farmer's income. Techniques like curing, drying, grading, quick cooling and refrigeration help keep things fresh. More advanced methods make sure that things stay fresh during shipping and selling. Smallholders can now use these new ideas thanks to low-cost storage buildings, solar-powered cold rooms, and biodegradable packaging. Despite challenges such as limited infrastructure and high costs, these technologies open new opportunities for building efficient and sustainable post-harvest systems by combining traditional practices with modern innovations, farmers can reduce losses, improve food security and enhance economic viability. Post-harvest management is no longer just about storage, it is a strategic pathway to resilience, sustainability and better livelihoods in vegetable farming.

Introduction

Vegetables lose their significant portion of harvest before reaching consumers due to their perishability. These losses not only reduce farmer incomes but also weaken food security and nutrition. Post-harvest waste occurs due to poor handling, inadequate storage and limited infrastructure, especially in developing regions. Addressing this challenge requires innovative solutions that combine traditional wisdom with modern technology. Recent advances in precision harvesting tools, improved storage structures, rapid cooling systems, and smart packaging technologies are helping farmers preserve quality and extend shelf life. At the same time, digital platforms and cooperative models are connecting producers to markets more efficiently, reducing delays and spoilage. By adopting these innovations, farmers can transform post-harvest management from a weak link into a strong foundation for sustainable vegetable farming. This article explores practical and emerging post-harvest innovations that reduce waste, enhance food security and secure farmer livelihoods, highlighting their role in building resilient agricultural systems for the future.

Causes of Post-Harvest Vegetable Waste:

Harvesting: The stage of ripening at harvest strongly influences quality and shelf life. Immature fruits are acidic, low in sugar and easily damaged

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while over-ripe fruits deteriorate quickly. Incorrect timing, rough handling, lack of containers and absence of pre-cooling increase losses, often amounting to 4-12%.

Storage: Cold chain management is essential to preserve freshness. Without pre-cooling, cold storage or controlled atmosphere facilities, perishable produce spoils rapidly. In developing countries, inadequate storage infrastructure is a major cause of losses, with up to 23% of perishables wasted due to lack of cooling.

Transportation: Moving produce from farms to markets introduces delays and risks. Poor roads, lack of refrigerated vehicles and careless handling during loading/unloading cause bruising and decay. In rural areas, rain and mud worsen losses, while broken cooling systems in vehicles also.

Packaging: Proper packaging extends shelf life and prevents damage. However, low-quality sacks, cloth bundles, or open baskets are widely used, especially in developing regions. These materials fail to protect delicate produce and often accelerate spoilage. Studies show nearly half of horticultural crops are packed in unsuitable containers.

Consumer Waste: At the household level, fruits and vegetables account for the largest share of food waste up to 40-50%. Over-purchasing, poor planning, and weak home storage practices are the main drivers. Socio-cultural factors such as lifestyle, income, and storage facilities also influence the magnitude of waste (Elik *et al*., 2019 and Verma *et al*., 2025).

Figure 1: Pictorial representation of post-harvest loss of crops at various stages from producers to consumers (Verma *et al*., 2025)

Innovative Technologies to Reduce Post-Harvest Waste

Edible Coatings & Biofilms: Natural coatings from chitosan, alginate, pectin, or plant gums form protective barriers on fruits and vegetables. They reduce moisture loss, slow respiration, and inhibit microbial growth, extending shelf life without chemical residues. Essential-oil enriched coatings (thyme, cinnamon, oregano) have shown up to 50-70% reduction in spoilage.

Modified Atmosphere Packaging (MAP): Smart packaging alters oxygen and carbon dioxide levels to slow ripening and microbial activity. Recent advances include nanomaterial membranes, ethylene absorbers, and biosensors for real-time monitoring. MAP can cut berry losses by up to 74% and is moving toward biodegradable, compostable materials.

Solar-Powered Cold Storage: Off-grid refrigeration units powered by solar panels provide affordable cooling in rural areas. Mobile solar coolers and evaporative cooling chambers have extended tomato and leafy vegetable shelf life by several days, reducing weight loss by more than half.

Phase Change Materials (PCMs): PCMs stabilize temperatures during transport and storage by absorbing and releasing heat during phase transitions. They reduce energy use and maintain consistent cooling even with intermittent power supply.

IoT & Smart Sensors: Cold chain monitoring with IoT sensors tracks temperature, humidity, and gas composition in real time. Alerts allow immediate corrective action, preventing spoilage and ensuring traceability across the supply chain.

Nanotechnology Applications: Nano-coatings act as moisture and microbial barriers, while nano-encapsulation enables controlled release of antioxidants and antimicrobials. Nano-sensors embedded in packaging detect spoilage early, ensuring food safety and quality.

Digital Solutions (AI & Blockchain): AI predicts optimal harvest and storage conditions using weather and crop data, while blockchain ensures transparent, traceable supply chains. Together, they reduce inefficiencies and improve accountability from farm to fork.

Hypobaric & Controlled Atmosphere Storage: Reduced-pressure storage slows respiration and ethylene production, ideal for high-value crops like broccoli and peppers. Dynamic controlled atmosphere systems adjust conditions based on real-time crop respiration data.

Hermetic Dry Chain Systems: For grains and seeds, hermetic bags and inert atmosphere silos prevent insect damage and mold without pesticides. They maintain viability and quality for months to years, offering cost-effective storage for smallholders (Oyewole *et al*., 2025, Reddy *et al*., 2025, Verma *et al*., 2025 and Rajapakshe *et al*., 2026).

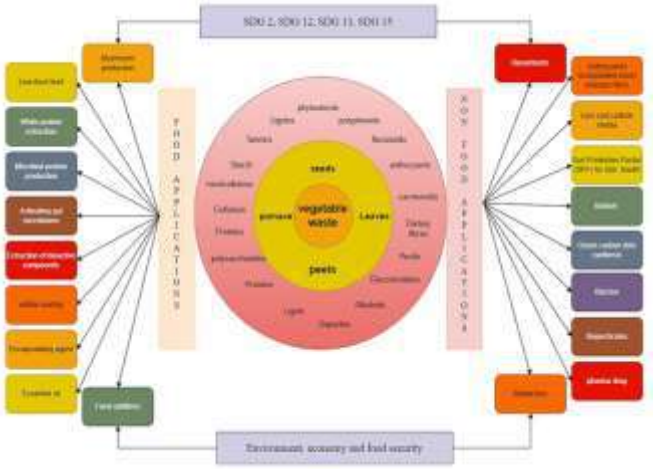

Fig. 2: Multifaceted application of vegetable waste across various food and non-food sectors (Balakrishnan *et al*., 2025)

Applications of Vegetable Processing Waste

- ✓ Livestock feed
- ✓ Substrate for mushroom production
- ✓ Activating gut microbiome for promoting human health
- ✓ Substrate for microbial protein production
- ✓ Source of essential oil
- ✓ Source of bioactive compounds
- ✓ Encapsulating agent
- ✓ Food additive
- ✓ Edible coating to improve quality
- ✓ Sorbents in decontaminating heavy metals
- ✓ Developing meat freshness indicating biofilms by incorporating bio pigments
- ✓ Phytochemicals in promoting skin health
- ✓ Biofuel generation as a substitute for fossil fuel
- ✓ Green carbon dots in nano delivery systems
- ✓ Activated carbon for soil amendments

- ✓ Organic fertilizers in substituting chemical fertilizers
- ✓ Pharma drug
- ✓ Bio pesticide
- ✓ Bioplastic (Balakrishnan *et al*., 2025)

Conclusion

Innovative post-harvest technologies, ranging from natural edible coatings and smart packaging to solar-powered cold storage, phase-change materials, IoT monitoring, nanotechnology and digital tools like AI and blockchain-offer powerful solutions to reduce fruit and vegetable losses. These approaches extend shelf life, preserve quality and improve farmer incomes while aligning with sustainability goals.

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Beauveria bassiana: A Potential Biocontrol Agent in Sustainable Agriculture

Vishal D. Pawar and Kishor T. Thakare

Introduction

Beauveria bassiana is a naturally occurring soil-borne fungus that is widely used as a biological control agent against insect pests. It belongs to a group of entomopathogenic fungi that have the ability to infect and kill insects, making them highly useful in sustainable agriculture. In recent years, the excessive use of chemical pesticides has led to problems such as environmental pollution, pesticide resistance, and harmful effects on non-target organisms. Due to these issues, there is an increasing demand for eco-friendly and safe pest management alternatives. *Beauveria bassiana* is considered an effective alternative because of its unique mode of infection. The fungus infects insects by attaching to their outer body surface, germinating, and penetrating the cuticle. Once inside, it multiplies and produces toxins that lead to the death of the host. This fungus is known to cause white muscardine disease in insects, which is characterized by white fungal growth on the dead insect body. It has a broad host range and is effective against several important agricultural pests such as aphids, whiteflies, thrips, and beetles. Due to its safety, biodegradability, and compatibility with Integrated Pest Management (IPM) programs, *Beauveria bassiana* is widely used in modern and organic farming systems.

Taxonomy and Classification: *Beauveria bassiana* belongs to the kingdom Fungi and is widely used as a biocontrol agent.

- ✓ Kingdom: Fungi
- ✓ Phylum: Ascomycota
- ✓ Class: Sordariomycetes
- ✓ Order: Hypocreales
- ✓ Genus: *Beauveria*
- ✓ Species: *bassiana*

It is commonly associated with white muscardine disease of insects.

Morphology: *Beauveria bassiana* shows characteristic morphological features which help in its identification.

- ✓ Produces white, cottony mycelial growth
- ✓ Mycelium is septate and hyaline
- ✓ Conidiophores are short and branched
- ✓ Conidia (spores) are round to oval and hyaline
- ✓ Spores are produced in clusters at the tip of conidiophores
- ✓ Under high humidity, infected insects are covered with white fungal growth

This white growth gives a characteristic

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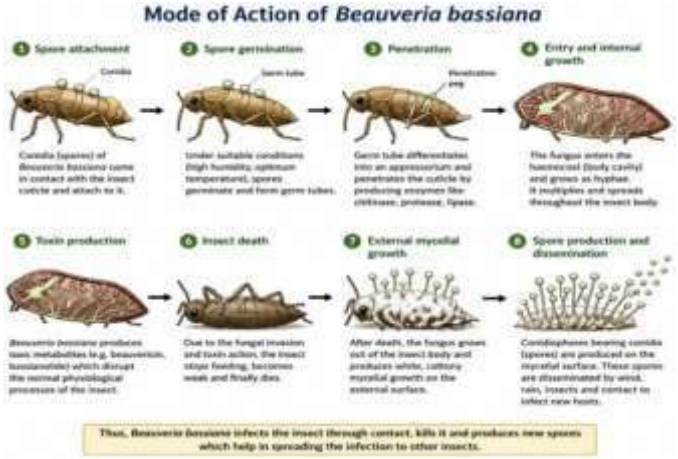
"white muscardine" appearance.

Mode of Action



Beauveria bassiana infects insects through a unique mechanism without being ingested.

- ✓ Fungal spores (conidia) attach to the insect cuticle, spores germinate under favourable conditions
- ✓ Germ tube penetrates the insect body using enzymes like chitinase and protease
- ✓ Fungus enters the hemocoel and multiplies inside the insect body
- ✓ Produces toxins such as beauvericin, these toxins disrupt normal body functions of the insect
- ✓ Insect eventually dies due to infection, after death white fungal growth appears on the insect body
- ✓ New spores are produced, which spread infection to other insects

This process helps in natural spread and long-term control of insect pests.

Target Insects / Host Range: *Beauveria bassiana* has a broad host range and is effective against many economically important insect pests.

- ✓ Effective against sucking pests like aphids, whiteflies, and thrips
- ✓ Controls chewing insects such as caterpillars and beetles
- ✓ Also affects weevils and other storage pests
- ✓ Widely used in crops like cotton, vegetables, cereals, and fruits
- ✓ Can infect insects belonging to different orders

Due to its wide host range, it is widely used in pest management programs.

Applications in Agriculture: *Beauveria bassiana* is widely used as a biological control agent in modern agriculture for managing insect pests.

- ✓ Used as a biopesticide in crop protection programs
- ✓ Applied as foliar spray on crop plants
- ✓ Can be used in soil treatment against soil-dwelling insects
- ✓ Plays an important role in Integrated Pest Management (IPM)
- ✓ Used in organic farming as a safe alternative to chemicals
- ✓ Helps in controlling pests in vegetables, cotton, cereals, and horticultural crops
- ✓ Reduces dependence on synthetic chemical pesticides
- ✓ Maintains ecological balance in agro-ecosystems
- ✓ Its use supports sustainable and eco-friendly agriculture.

Advantages

- ✓ Eco-friendly and biodegradable
- ✓ Safe for humans, animals, and beneficial insects
- ✓ No harmful residues in environment
- ✓ Suitable for organic farming

- ✓ Helps reduce pesticide resistance
- ✓ Supports sustainable agriculture

Limitations

- ✓ Requires high humidity for effectiveness
- ✓ Slow acting compared to chemical pesticides
- ✓ Sensitive to UV radiation
- ✓ Performance depends on environmental conditions
- ✓ Field efficiency may vary

Conclusion

Beauveria bassiana is an important biological control agent with great potential in sustainable agriculture. It offers an eco-friendly alternative to chemical pesticides and plays a significant role in Integrated Pest Management programs. With proper application and favourable conditions, it can effectively manage a wide range of insect pests and support environmentally safe agriculture.

Hydrochar and Biochar: Production, Properties and Applications in Sustainable Agriculture

Chauhan Aditi, Susheel Singh and Trupti Vyas

Abstract

Hydrochar and biochar are carbon-rich materials emerging as important for their potential in promoting sustainable agriculture and effective waste management. They are produced through different thermochemical processes, namely hydrothermal carbonization (HTC) for hydrochar and pyrolysis for biochar, using various types of organic biomass. Hydrochar is suitable for wet feedstocks and offers nutrient-rich properties while, biochar is produced from dry biomass and is characterized by its high stability and long-term carbon sequestration potential. Both materials play a significant role in improving soil health by enhancing physical, chemical and biological activity. In addition to agricultural benefits, hydrochar and biochar contribute to environmental sustainability by enabling waste valorisation, reducing greenhouse gas emissions, and supporting carbon sequestration. Despite their advantages, challenges related to production optimization, economic feasibility, and long-term field performance remain. Therefore, further research is required to ensure their efficient and safe application. Overall, hydrochar and biochar represent promising tools for advancing sustainable agricultural systems and circular economy approaches.

Introduction

Sustainable agriculture is increasingly important due to challenges such as soil degradation, declining fertility, climate change and the accumulation of organic waste. In this context, carbon-based materials like hydrochar and biochar have gained significant attention as effective soil amendments that support environmental sustainability and resource recycling (Lehmann and Joseph, 2015). Hydrochar is a carbon-rich material produced through hydrothermal carbonization (HTC) of wet biomass such as agricultural residues, food waste, and sewage sludge under moderate temperatures and high-pressure conditions in the presence of water (Libra *et al*., 2011). This process allows efficient utilization of high-moisture feedstocks without the need for prior drying. In contrast, biochar is produced from dry biomass through pyrolysis, a thermochemical process carried out at high temperatures in the absence of oxygen. Biochar is known for its stable carbon structure and long-term persistence in soil. Both hydrochar and biochar are widely used to improve soil quality due to their beneficial effects on soil physical, chemical, and biological properties.

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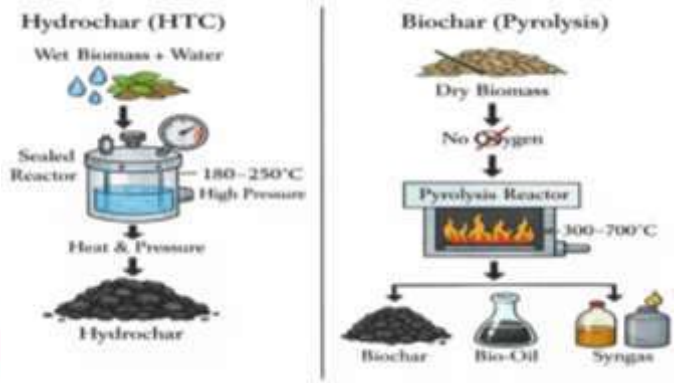
They enhance soil structure, increase water-holding capacity, improve nutrient retention, and promote microbial activity, thereby contributing to better crop productivity. Additionally, their ability to sequester carbon and reduce environmental pollution makes them important tools in climate change mitigation and sustainable waste management (Lehmann, 2007). However, differences in their production methods, composition, and stability influence their performance in soil systems (Libra *et al*., 2011). Therefore, understanding their characteristics and applications is essential for their effective use in agriculture. This article focuses on the production, properties, and role of hydrochar and biochar in sustainable agricultural practices.

Production of Hydrochar and Biochar: Hydrochar is produced through hydrothermal carbonization (HTC) under controlled conditions involving moderate temperatures of about 180-250 °C and high pressure ranging from 2 to 10 MPa in a closed system. The process is carried out in the presence of water under oxygen-limited conditions, making it suitable for wet biomass such as food waste, sewage sludge, and agricultural residues without the need for prior drying. The reaction typically takes a few hours (2-12 hours), during which the pressure is generated internally due to heating of water in a sealed reactor (Reza *et al*., 2014). In contrast, biochar is produced through pyrolysis, which involves heating dry biomass at higher temperatures ranging from 300 to 700 °C under anaerobic conditions. This process is usually conducted at atmospheric pressure and requires pre-dried feedstock. The duration of pyrolysis may vary from a few minutes to several hours depending on the system and temperature. Unlike hydrothermal carbonization, pyrolysis does not involve water and results in the formation of biochar along with by-products such as bio-oil and syngas (Lehmann and Joseph, 2015).



Chemical Composition of Hydrochar and Biochar : Hydrochar and biochar differ significantly in their chemical composition due to their distinct production processes. Hydrochar, produced through hydrothermal carbonization under relatively low temperature and high-pressure aqueous conditions, contains a moderate amount of carbon (about 50-70%) along with higher proportions of oxygen and hydrogen (Reza *et al*., 2014). It is rich in oxygen-containing functional groups such as hydroxyl (-OH), carboxyl (-COOH), and carbonyl (C=O), which make it more polar and chemically reactive. These functional groups enhance its cation exchange capacity (CEC) and nutrient retention ability in soils (Libra *et al*., 2011). In contrast, biochar, produced through pyrolysis at high temperatures in the absence of oxygen, has a much higher carbon content (around 70-90%) and lower amounts of oxygen and hydro-

gen. Its structure is dominated by stable aromatic carbon rings, making it highly recalcitrant and resistant to decomposition. Biochar also contains mineral ash elements such as potassium, calcium, magnesium, and phosphorus. Due to its highly carbonized and porous nature, biochar is less reactive but more stable, making it suitable for long-term carbon sequestration and soil improvement.

Applications of Hydrochar and Biochar in Soil:

The application rate of hydrochar in soil generally ranges between 10-60 t ha^{-1}, depending on soil type, feedstock and experimental conditions, while biochar is commonly applied at moderate rates to avoid negative effects at higher doses. Studies indicate that very high application rates may adversely affect plant growth, so optimum and repeated lower doses are recommended. The application rate of biochar generally ranges from 5 to 20 t ha^{-1} under field conditions. Lower doses (2-5 t ha^{-1}) may also be applied repeatedly over time for sustainable benefits (Lehmann and Joseph, 2015). In some cases, especially in highly degraded or sandy soils, higher rates up to 30-50 t ha^{-1} have been used, but such high doses are applied cautiously to avoid negative effects like nutrient imbalance or excessive alkalinity (Jeffery *et al*., 2017). For most agricultural crops, an optimum rate of 10-15 t ha^{-1} is widely recommended for improving soil fertility, structure, and crop productivity (Agegnehu *et al*., 2016). Hydrochar and biochar are typically applied by broadcasting and incorporating into soil before planting, or by mixing with compost or organic manures to improve nutrient availability and microbial activity. Proper incorporation into soil is essential to enhance soil properties and avoid nutrient losses (Jager and Giani, 2021).

Role of Hydrochar and Biochar on Soil Quality and Agricultural Sustainability

Hydrochar is more reactive and nutrient-rich, so it is used for short-term and functional benefits:

Soil fertility improvement (short-term): Supplies nutrients quickly

Waste management: Converts wet biomass (sewage sludge, food waste) into useful product

Soil remediation: Adsorbs heavy metals and pollutants

Energy source: Can be used as a solid fuel due to higher volatile content

Microbial stimulation: Enhances soil biological activity

Liquid fertilizer precursor: Used in producing nutrient-rich solutions

Biochar is mainly used for long-term soil and environmental benefits due to its stable carbon structure:

Soil amendment (long-term): Improves soil structure, aeration, and fertility over many years

Carbon sequestration: Stores stable carbon in soil, helping in climate change mitigation

Compost enrichment: Mixed with compost/FYM to enhance nutrient retention

Water filtration: Used in removing contaminants due to high adsorption capacity

Soil remediation: Immobilizes heavy metals and organic pollutants

Reduced greenhouse gases: Helps reduce N_2O and CH_4 emissions from soil

Advantages of Hydrochar and Biochar

Hydrochar rapidly improves soil fertility, boosts microbial activity, enhances water retention, and converts wet biomass into a useful resource while aiding soil remediation.

- ✓ Improves soil fertility quickly due to higher nutrient availability
- ✓ Enhances microbial biomass and enzymatic activity
- ✓ Increases water retention and soil aggregation
- ✓ Suitable for wet biomass processing (e.g., sewage sludge, food waste)
- ✓ Acts as a waste management tool (waste to resource conversion)
- ✓ Can adsorb heavy metals and pollutants, aiding soil remediation
- ✓ Supports short-term crop growth and productivity
- ✓ Easier processing compared to dry biomass systems

Biochar enhances soil structure, water retention and nutrient retention, provides long-term carbon sequestration, supports microbial activity, and aids in soil remediation.

- ✓ Improves soil structure and porosity, enhancing aeration and root growth
- ✓ Increases water-holding capacity, especially in sandy soils
- ✓ Enhances cation exchange capacity (CEC), improving nutrient retention
- ✓ Provides long-term carbon sequestration due to its stable nature
- ✓ Reduces nutrient leaching and improves fertilizer use efficiency
- ✓ Helps in soil remediation by immobilizing heavy metals and pollutants
- ✓ Supports microbial activity by providing habitat
- ✓ Contributes to climate change mitigation by reducing greenhouse gas emissions

Disdvantages of Hydrochar and Biochar: Hydrochar is less stable, decomposes quickly, and may contain phytotoxic compounds; its long-term effects, economic feasibility, and process optimization still require further research.

- ✓ Low stability, decomposes faster in soil
- ✓ Provides short-term benefits only
- ✓ May contain phytotoxic substances (organic acids, phenolics)
- ✓ Less effective for carbon sequestration compared to biochar
- ✓ HTC technology is still developing and not widely available
- ✓ Issues with economic feasibility and scalability
- ✓ Limited long-term field studies and data

Biochar may initially immobilize nutrients and increase soil pH, and its effectiveness depends on feedstock and pyrolysis conditions; high production costs and potential toxic compounds are additional limitations.

- ✓ Causes initial nutrient immobilization (especially nitrogen)
- ✓ Quality varies depending on feedstock and

pyrolysis conditions

- ✓ May increase soil pH excessively, not suitable for alkaline soils
- ✓ High production and transportation cost
- ✓ Risk of toxic compounds (PAHs) if produced improperly
- ✓ Requires pre-treatment or enrichment before application
- ✓ Effects may take longer time to become visible

Conclusion

Hydrochar and biochar are emerging as valuable carbon-based materials with significant potential to improve soil health and promote sustainable agriculture. While biochar offers long-term benefits through its stability and carbon sequestration capacity, hydrochar provides rapid improvements in soil fertility and serves as an effective solution for managing wet organic waste. Both materials enhance soil physical, chemical, and biological properties, contributing to improved crop productivity and environmental sustainability. However, their effectiveness depends on factors such as feedstock type, production conditions, and application rate. Challenges such as cost, variability in properties, and limited long-term field studies, particularly for hydrochar, need to be addressed. Therefore, further research, proper standardization, and field-level validation are essential to ensure their safe, efficient and large-scale adoption in sustainable agricultural systems.

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