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Biochar for Farmers and Soil Health: Future Sustainability in Indian Agriculture

Ramjeet Meena, Ramawatar Meena, Kamlesh Meena and Mandhata Singh

Abstract

Biochar is a carbon-rich soil amendment produced from agricultural waste through pyrolysis. It enhances soil organic carbon, improves water retention by 10-25%, boosts nutrient availability, and increases crop yields by up to 15%. With over 20 million tonnes of paddy straw burned annually in Punjab and Haryana, biochar offers a practical solution to stubble burning while creating additional income streams for farmers through carbon credits and reduced fertiliser costs. This article discusses the science, benefits, and on-farm evidence of biochar, and outlines a roadmap for its adoption in Indian agriculture.

Introduction

Indian agriculture is at a critical crossroads. Rising fertiliser prices, declining soil fertility, erratic monsoons, and escalating cultivation costs are squeezing farmers across all agro-climatic zones. Large tracts of farmland today suffer from low soil organic carbon, poor water retention, reduced microbial activity, and chronic nutrient imbalance. As soil quality declines, farmers need ever-larger quantities of chemical inputs just to maintain existing yields a vicious cycle of rising costs and falling land health. At the same time, millions of tonnes of agricultural residue are burned openly every year, destroying nutrients, poisoning the air and degrading the very soil that India's food security depends upon. In this context, biochar emerges as a transformative solution a carbon-rich soil amendment that can turn agricultural waste into a valuable resource for building long-term soil health and climate resilience.

Whatis Biochar andhowisit Produced?

Biochar is a carbon-rich organic material produced through the pyrolysis of biomass under high temperature (300-700°C) and low or no oxygen conditions. Unlike open burning, which releases stored carbon as CO_2 and destroys nutrients, pyro-lysis converts biomass into a stable charcoal-like material that persists in soil for hundreds to thousands of years. The result is twofold: waste is eliminated without pollution, and the soil gains a permanent carbon reservoir. When plant biomass is converted into biochar, at least 50% of the total carbon is permanently captured, making biochar a carbon-negative process. Agricultural residues such as paddy straw, maize stalks, coconut leaf stalks,

Ramjeet Meena and Ramawatar Meena
Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh
Kamlesh Meena and Mandhata Singh
ICAR-IIVR, KVK, Deoria, Uttar Pradesh

sugarcane bagasse, and other crop wastes can be converted into biochar using simple, low-cost technologies. Portable, tractor-mounted pyrolysis machines are now available that can transform agricultural waste into biochar directly on the farm. These innovations can reduce smoke emissions by up to 95% compared to open burning and increase farmer income by turning waste into saleable products.

How Biochar Enhances Soil Health

Enhancing Soil Organic Carbon: Biochar application offers the primary benefit of boosting soil organic carbon (SOC) levels, providing a stable carbon reservoir in the soil. A field experiment conducted at ICAR-Indian Institute of Soil Science, Bhopal in the rice-wheat system revealed a significant increase in SOC content with biochar application. The highly porous structure of biochar provides a conducive environment for beneficial microorganisms that aid in retaining soil organic matter. A meta-analysis of 147 peer-reviewed studies across India's major agro-ecological regions found that biochar application resulted in the highest SOC gain among all regenerative practices, outperforming farmyard manure, green manure, compost, and fertiliser management.

Improving Soil Structure: Biochar improves soil porosity and aggregate stability. Better soil aeration and reduced compaction promote healthier root growth, improved water infiltration, and less erosion, ultimately building a resilient agroecosystem.

Enhancing Nutrient Availability: Biochar has a high surface area and negative charge that helps absorb and retain essential nutrients such as nitrogen, phosphorus, and potassium. Soils incorporated with biochar can store nutrients for longer periods, reducing the need for frequent application of chemical fertilisers. When integrated with fertilisers, compost, or microbial inputs, biochar improves nutrient retention, reduces nutrient loss, and builds long-term soil fertility. Biochar combined with compost or fertilisers can reduce chemical fertiliser use by 20-40%.

Boosting Water Retention: The porous structure of biochar acts like a reservoir for water and nutrients. Studies have indicated that biochar can improve water-holding capacity by 10% to 25%, particularly in soils low in organic matter.

Biochar: A Solution to India's Stubble Burning Crisis

Punjab and Haryana burn more than 20 million tonnes of paddy straw in their open fields every year due to short post-harvest periods and a lack of practical alternatives. Thisburning releases large quantities of greenhouse gases and fine particles, causing severe air pollution and a major loss of organic matter. Biochar offers a practical alternative. Instead of burning crop residue, farmers can convert it into biochar using simple, low-cost technologies. Farmers using biochar production equipment have reported not only reduced stubble burning but also improved soil health and additional income.

Evidence from Indian Fields

ICAR research demonstrates that biochar

application can enhance soil fertility, increase crop yields by up to 15%, and improve water retention directly addressing key agronomic challenges faced by Indian farmers. Research from Kerala showed that biochar made from coconut leaf stalks increased soil quality in different cropping systems, emphasising the need to use local resources effectively. Long-term studies have shown that biochar enhances soil health and maintains higher crop output over time.

EconomicOppurtunitiesfor Farmers

Additional Income Streams: Instead of burning residues, farmers can sell biochar as a soil amendment, biofuel, or activated carbon. The carbon credit market is also opening new revenue channels. Initiatives like Biochar are working to sequester up to 106,000 tons of CO_2 annually and benefit millions of smallholder farmers.

Reduced Input Costs: By improving nutrient retention and water-holding capacity, biochar helps reduce dependence on chemical fertilisers and irrigation. Biochar combined with compost or fertilisers can reduce chemical fertiliser use by 20-40%.

Carbon Credits: Large-scale conversion of crop residue to biochar in India can generate significant carbon credits and rural income.

Summary

Biochar represents a rare opportunity to address multiple challenges simultaneously: improving soil health, reducing stubble burning, enhancing fertiliser efficiency, reducing environmental damage and creating new income streams for farmers. As droughts, heat waves, and erratic rainfall become more frequent and intense, improving soil health will be crucial to sustaining agricultural productivity. This is particularly important for small and marginal farmers who are often the most exposed to the climate's vagaries. Biochar, when integrated into natural farming and soil health programmes, can deliver environmental and economic benefits at scale. The path to a more prosperous and environmentally-friendly future for India's rural heartland lies in turning waste into wealth and biochar is the key to that transformation.

The Future of Organic Farming: Direct Marketing for Greater Prosperity

Sunil Kumar, A. L. Meena, Jagan Singh Gora, M. Arif, Ved Prakash, Parmod Kumar, Nalawade Rohit Dilip and Ranjit H. P.

Organic farming is an agricultural approach that advocates healthy products free from components that may harm humans and nature. They include but are not limited to industrial pesticides, insecticides, fertilizers, clones, GMOs, chemical medications, hormones, growth-boosters, etc. The basic idea of organic agriculture is to provide food with optimum nutritional value and minimum dangerous ingredients, with only permitted substances used. The principle also requires 100% natural forage for livestock and its further processing without synthetics. Organic farming practices involve care for field employees, and aim at maintaining the harmonious balance in the environment keeping it as alive and productive as possible.

Principles of Organic Agriculture

Organic farming methods accord with the four basic principles that reveal their essence: health, ecology, fairness and care. They are the driving force of the concept, interrelating and enhancing each other. For instance, pesticides used in organic farming spare the ecology and do not evoke side effects in living beings, promoting health. These principles of agriculture govern all the process stages including production, processing, delivery, storage, and consumption. No prohibited additives are applied.

Health: The principle of health in organic farming suggests avoiding dangerous chemicals leaving poisonous residues that have a negative impact on multiple levels, affecting microscopic soil organisms, crops, animals, and humans. Expanding the common saying to agriculture, we can state that healthy soil produces healthy crops, and healthy crops foster a sound mind in a sound body with good immunity, regeneration properties, and no disease suffered.

Ecology: The principle of ecology in farming involves utilizing environmentally friendly techniques like the ones fostering soil quality (preventing depletion, erosion, degradation) or eliminating nature pollution. It also means providing favorable living conditions for all ecosystem members since they closely interconnect. Eco-practices in agriculture maintain the proper balance and save natural resources, for example, restore soil fertility with non-synthetic matters (green and animal manures), encourage recycling and genetic diversity of species in the area.

Fairness: The principle of fairness in organic farming advocates a decent and respectful attitude to all participants of the business: farmers, suppliers,

Sunil Kumar, A. L. Meena, Jagan Singh Gora, M. Arif, Ved Prakash, Parmod Kumar, Nalawade Rohit Dilip and Ranjit H. P.
ICAR-Indian Institute of Farming Systems Research, Modipuram, Meerut, Uttar Pradesh

traders, consumers. It promotes appropriate working and living conditions and supports people's needs for sufficient supplies of quality food products. Fairness in farming also suggests providing proper feeding and environment for livestock and cattle responding to their physiology. Pricing policies should be justified and affordable.

Care: The principle of care in agriculture encourages sparing consumption of resources with upcoming generations and nature in mind. Applied farming technologies should be thoroughly assessed as to negative consequences. Precaution and timely risk management must govern any decision making. Even though innovations may prove efficient, the organic farming followers prefer traditional methods of agriculture validated by time. Nowadays, they combine common sense, reliable knowledge, applicable novelties, and indigenous experience dating back to the pre-chemical age.

Organic Farming Practices

The organic agriculture concept requires strict compliance with established standards that define and restrict applicable techniques. The common and approved ones include the following.

Crop Rotation: Crop rotation means changing species on the same field season by season. This agriculture technique may also include a fallow period within a certain interval of time.

Compared to monoculture farming practices, crop rotation

- ✓ Eradicates pest and weed infestations and chemical contaminations to tackle the issues (since different species suffer from different pests);
- ✓ Prevents soil erosion with different root systems;
- ✓ Protects soil from depletion as diverse plants boost nutrient release, thus eliminating synthetic fertilizer applications that are disapproved in organic agriculture;
- ✓ Boost yields and reduces costs.

Cover Cropping: This farming approach implies covering the field with any plant species, either for a certain season or perennially, partially between the crop rows or completely. Cover crops tackle soil erosion, improve water filtration and aeration with their roots. They also eliminate weeding with upper parts, by hiding unwanted vegetation from the sunlight.

Green Manures: Mixing green plants with the soil enriches it with organic matters and nitrogen in particular. It also increases moisture levels and adds nutrients for microorganisms, thus improving the soil quality. The described method of agriculture also reduces weed infestation.

Animal Manures: This organic farming practice enriches the soil with natural components that originated from animals, either raw or composted (excluding slaughter by-products). The method has restrictions though, as the material must not contain any synthetic additives, the soil must be tested before applications, and manures are allowed at least three months prior to harvesting. Composted forms are preferable since they are more compact in volume and contain fewer potential pathogens and contamin-

ants.

Integrated Weed Management: Heavy chemicals are prohibited in organic farming. That's why weed control is performed via other options of integrated weed management (prevention, biological, physical, and cultural):

- ✓ Avoiding weed penetration onto the field with machinery, animals, irrigation waters;
- ✓ Manual weeding;
- ✓ Crop rotation;
- ✓ Mulching;
- ✓ Natural chemicals to stop germination;
- ✓ Hay making before weed seeding;
- ✓ Introducing populations of birds/insects to consume weed seeds, etc.

Integrated Pest Management: To combat pests, organic farming does not intend to destroy them completely as it will cause ecosystem changes. This concept of agriculture strongly relies on the alternative methods of pest control: prevention, constructing natural barriers, physical removal, and tackling pest invasions with their biological enemies (predators) like ladybugs vs aphids. As to synthetic additives, the concept allows only mild pesticides approved for organic farming, without disputable properties and minimum harm to humans and nature. Such additives include soap, hydrogen peroxide, baking soda, sulfur, or natural pest repellents like neem, citronella, lavender oil, among others.

Livestock Management: The organic agriculture guidelines exclude dangerous and dubious additives to breed poultry and cattle like synthetic medications, growth-boosting drugs and hormones, antibiotics, non-organic forage, GMOs, clones, etc. Farming practices must provide proper conditions for raising and grazing, and create a suitable environment to ensure livestock natural behavior indoors and outdoors.

Used in complex, the methods bring the desired results.

Advantages of Organic Farming: The concept and practices of organic agriculture have certain pluses:

- ✓ Refused health-threatening chemicals;
- ✓ Avoided costs for expensive synthetic additives;
- ✓ Ensured food quality and certification;
- ✓ Improved product taste and nutritional value;
- ✓ Protected environment;
- ✓ Recycled natural wastes for manure;
- ✓ Boosted soil quality.

Disadvantages of Organic Farming

The drawbacks of organic agriculture include:

- ✓ Reduced production volumes;
- ✓ Increased farming labor and time consumption for manual and mechanical work, crop observation and uncompromised compliance with standards;
- ✓ Frequent pest and weed control instead of one-time chemical applications;
- ✓ shortened shelf-life (natural organic food usually spoils faster due to the absence of preservatives);
- ✓ Higher prices of organic products vs conventional ones.

Is Organic Farming Sustainable?

Organic agriculture supports the ecosystem

balance and spares natural resources. This approach ensures the availability and productivity of lands in the future. It echoes with sustainable agriculture in this regard:

- ✓ Improves the soil quality
- ✓ Reduces pollution with recycling and limitations of chemicals
- ✓ Enhances the ecosystem biodiversity;
- ✓ Saves energy and resources, disapproves their excessive exploitation;
- ✓ Applies non-chemical methods of pest and weed management;
- ✓ Provides natural conditions to support livestock needs and behavior.

Organic Management Issues

- ✓ Certification
- ✓ Environmental concerns
- ✓ Marketing
- ✓ PR

Direct Marketing Channels and Strategy for Organic Products

There are many approaches to farm direct marketing. Some have been around for decades others are have been developed more recently. The most common types of direct marketing are:

- ✓ Community Supported Agriculture (CSA)
- ✓ Farmers' Markets
- ✓ U-Pick farms
- ✓ Farm Stands
- ✓ Restaurants
- ✓ Farm to School and Institutions
- ✓ Agritourism

Online Marketing

Community Supported Agriculture-CSA: Community supported agriculture is a relatively recent and innovative concept that is intended to create a relationship between farmers and consumers wherein risks and bounties are shared. CSA customers buy shares for a season by paying a fee in advance. In return, they receive a regular (in most cases weekly) selection of food. Having cash in advance of the growing season and a regular customer following provide financial security for farmers. The regular supply of food grown on the farm provide nutritional security and a sense of community for customers. On some farms, get-togethers with customers or workdays are part of the agreement. In its purest form, customers share in the risk of low production and crop failures, as well as any abundance, by receiving less or more food. This aspect has seen a variety of adaptations on CSA farms. Generally, families pay about $400 to $600 per share. Operating a CSA requires excellent crop management skills to provide attractive and diverse weekly food baskets, as well as good customer service. CSA can be integrated with farmers' market sales and other techniques. It has been an excellent start-up strategy for many small organic farms, providing crucial cash flow at the beginning of the growing season and allowing farmers to "boot strap" their way into farming.

CSA Resources

- ✓ Robyn's resources for CSA's [Online]. Robyn Van En Center. Wilson College. Available at:

: http://www.wilson.edu/robyns-resources

- ✓ Food Network: Community Supported Agriculture [Video]. Cooking Up a Story. http://cookingupastory.com/show/food-network-community-supported-agricul... (verified 5 Mar 2010)
- ✓ Community Supported Agriculture (CSA) offers a holistic approach to the production of sustainable food grown in urban areas. In this story, we learn of one urban farmer who successfully uses the CSA model to produce long-term sustainable crops that are fresh, cost efficient to produce, environmentally friendly, and that offers local members a stake in the harvest crops."
- ✓ Community supported agriculture in California, Oregon and Washington: Challenges and opportunities. R. Strochlic and C. Shelley. 2004. California Institute for Rural studies (Available online at: http://www.cirsinc.org/ Documents/Pub0504.1.pdf) (verified 5 Mar 2010).
- ✓ Community Supported Agriculture - Local Harvest. LocalHarvest, Inc. Avabilable at: http://www.localharvest.org/csa/ (verified 5 Mar 2010).

Farmers' Markets

- ✓ A farmers' market is a place where a number of growers assemble on a particular day to sell farm products directly to consumers. The sites are often parking lots, streets closed during the market, parks, etc. Farmers at these markets sell their products from "stands" that may consist of the back of a farm truck or a simple tabletop to elaborate and attractive covered displays.
- ✓ Farmers generally receive retail prices or higher for their products. Start up costs for becoming involved in a farmers' market can be very inexpensive just a stall fee in some instances. Because of the low start up investment, farmers' markets can provide a low risk setting for new farmers or an opportunity to try out new products. Many farmers participate in more than one market to increase their sales.
- ✓ Farmers' markets also provide the opportunity to build a customer base. Some farms advertise other outlets for buying their products (other farm direct marketing methods, or retail stores for instance).

Farmers' Market Resources

- ✓ Tools for rapid market assessments. L. Lev, L. Brewer, and G. Stephenson. 2008. Oregon State University Extension Service. (Available at: http://smallfarms.oregonstate.edu/sites/default/files/small-farms-tech-report/eesc_1088-e.pdf) (verified 5 Mar 2010)
- ✓ Most farmers' markets lack information to make effective changes and improvements. This publication by Larry Lev, Linda Brewer, and Garry Stephenson of Oregon State University describes three simple, low-cost methods to address the information gaps: attendance counts, dot surveys, and comments and observations.
- ✓ Starting and operating a farmers' market: Freque-

ntly asked questions [Online]. B. McKelvey, M.Hendrickson, and C. Weber. 2008. University of Missouri Extension. Available: http://extension.missouri.edu/explore/agguides/hort/g06223.htm (verified 5 Mar 2010).

- ✓ From University of Missouri Extension, this guide is intended to be a resource for people who are either starting a new farmers' market or improving an existing market. The guide follows a frequently asked questions format, provides brief answers to each question and then directs readers to free, online publications that answer the questions in more detail. In addition to addressing questions faced by market organizers across the country, the guide includes information about legal and regulatory issues for farmers' market organizers in Missouri.
- ✓ The art and science of farmers' market display. Entrepreneurs and their Communities Community of Practice. extension. Available at:http://www.extension.org/pages/10986/the-art-and science-of-farmers-market display#.U87YRBD5eTQ (verified 5 Mar 2010).
- ✓ Enhancing the success of northwest farmers' markets. G. Stephenson, L. Lev, and L. Brewer. 2006. Oregon Small Farm Technical Report Number 22. Oregon State University Extension Service. Available at:
- ✓ http://smallfarms.orego nstate.edu/sites/files/TechReport22.pdf (verified 5 Mar 2010). This executive summary of a large project examines the conditions associated with success and failure of individual farmers' markets and provides information and recommendations for market organizers to assist with their decision making and strategic planning. It explores historic trends related to growth and decline in market numbers; it examines the management organization associated with markets of specific sizes; it looks at the characteristics and issues associated with markets that fail; and it synthesizes a model that illustrates how farmers' market organizers successfully adapt to barriers and challenges in their environment.

U-Pick Farms: U-Pick or Pick-Your-Own farms grow crops specifically to be harvested by customers. In this manner, the task of picking the crop, one of the higher costs of growing fruits and vegetables, is passed on to customers. U-Pick farms have traditionally appealed to families who do home canning. There continues to be an interest by families in picking produce for fresh use and, in some instances, having their children experience where their food comes from. As with many direct marketing techniques, U-Pick operations can be blended with other marketing techniques such as roadside markets, farmers' markets, and so on.

Farm Stands: Farm stands or markets are structures of some type from which the farm's products are sold. They can range in sophistication from a stand with a coffee can for purchases by honor system to a building with refrigerated storage and several employees. They tend to be located on the farm, often on a well-traveled road with good access and

parking. They can operate seasonally or all year and focus on one product or a full line of products. Roadside markets usually charge near retail prices. Given that farm stands or markets are structures, they are subject to local building codes and highway setback regulations.

Restaurants

Many farms are now marketing directly to restaurants providing the specific products and the high quality that chefs are demanding. Many restaurants cultivate relationships with farms even noting the farm name and its product on their menu. These restaurants serve a niche of customers who find high quality food produced locally appealing. Supporting local farms is a philosophical goal for these restaurants. Similar opportunities for farm direct sales are to institutions that serve food to large or "captive" groups such as:

- ✓ Hospitals
- ✓ Retirement and nursing facilities
- ✓ More

Restaurant Marketing Resources

Selling to restaurants. J. Bachmann. 2004. National Center for Appropriate Technology (ATTRA). Available at: https://attra.ncat.org/attra-pub/download.php?id=266 (verified 24 May 2019). "Upscale restaurants serving locally-grown produce are in the headlines nationwide. Growing for this market is both lucrative and demanding. Profiles of growers from around the country illustrate successful strategies and points to remember when working with chefs. A Spanish language version of this publication is available as Nuevos Mercados para Su Cosecha."

Recommendations for Farmers and Chefs who want to Work Together

The Local Food Connection and Farmer-Chef Connection are programs that bring farmers and chefs together for a day of networking and deal making. Read Notes to a Farmer and a Chef to learn how farmers and chefs can best work with each other. The Farmer-Chef Connection is a project of the Portland Chefs Collaborative and the Local Food Connection is a project of the Cascade Pacific RC&D.

Tip Sheets: Selling directly to restaurants, retailers and institutions can be a great way to expand your business and develop a reliable customer base. Created by Community Involved in Sustaining Agriculture (CISA), these tipsheets are designed to help farmers respond to the unique challenges in reaching out to and maintaining relationships with buyers.

- ✓ Tools for selling to restaurants, retailers and institutions: Keys to a successful relationship. 2008. Community Involved in Sustaining Agriculture. Available at: http://www.buylocal food.org/upload/resource/relationship-building %20fina... (verified 5 Mar 2010).
- ✓ Tools for selling to restaurants, retailers and institutions: Pricing and Invoicing. 2008. Community Involved in Sustaining Agriculture.

Available: .buylocalfoodresource/Pricing%20and% 20invoicing%20... (verified 5 Mar 2010).

Farm to School and Institutions

Resources: Bring local food to local institutions: A resource guide for farm-to-school and farm-to-institution programs. B.C. Bellows, R. Dufour, and J. Bachmann. 2003. National Center for Appropriate Technology (ATTRA). Available at: https://attra.ncat.org/attra-pub/download.php?id=261 (verified 4 Jun 2019). This provides farmers, school administrators, and institutional food-service planners with contact information and descriptions of existing programs that have made connections between local farmers and local school lunchrooms, college dining halls, or cafeterias in other institutions. To help communities initiate similar programs, this publication includes: resource lists of publications on how to initiate and manage local food programs, funding and technical assistance sources, and provisions of the 2002 Farm Bill that support farm-to-school and other community food programs.

Farm to school: Urban and Environmental Policy Institute, Occidental College. Available at: : http://www.farmtoschool.org/ (verified 5 March 2010). "Farm to School programs are popping up all over the U.S. These programs connect schools with local farms with the objectives of serving healthy meals in school cafeterias, improving student nutrition, providing health and nutrition education opportunities that will last a lifetime, and supporting local small farmers."

Sustainable food purchasing guide, first ed. Yale Sustainable Food Project. Yale University. Available at: http://www.yale.edu/sustainablefood/purchasing_guide_002.pdf.pdf (verified 5 March 2010). "In 2007, the Yale Sustainable Food Project received a SARE grant to write an expanded set of definitions for dining halls to use across the northeast. Unlike other guides, this one focuses on agricultural practices, because these practices are inseparable from nutrition and sustainability. This guide establishes best and worst practices in the field. It provides a list of questions you need to ask to get the very best product for your institution. It also offers helpful hints, so that you can learn from work that has been done."

Rethinking school lunch guide: Center for Ecoliteracy. Center for Ecoliteracy. Available at: http://www.ecoliteracy.org/programs/rsl-guide.html (verified 5 Mar 2010). "The Rethinking School Lunch guide provides a planning framework that contains tools and creative solutions to the challenges of improving school lunch programs, academic performance, ecological knowledge, and the well-being of our children. In its chapters, experts and practitioners highlight goals and challenges, showcase success stories, and offer resources for further exploration."

Farm-to-cafeteria connections: Marketing opportunities for small farms in Washington State. K. Sanger and L. Zenz. 2004. Small Farm and Direct Marketing Program, Washington State Department of Agriculture. Available at: http://agr.wa.gov/Marketing/SmallFarm/docs/102-FarmToCafeteria Connection... (verified 5 Mar 2010). An extensive resource guide for those interested in starting farm-

to-cafeteria programs at all levels, with information for food services, farmers and others. Includes case studies of programs and a list of resources.

Farm-to-college. Community Food Security Coalition. Available at: http://farmtocollege.org/ (verified 5 Mar 2010). "Farm-to-college programs connect colleges and universities with producers in their area to provide local farm products for meals and special events on campus. These programs may be small and unofficial, mainly involving special dinners or other events, or they may be large and well-established, with many local products incorporated into cafeteria meals every day."

Farm to hospital: Supporting local agriculture and improving health care. Center for Food & Justice, a division of the Urban & Environmental Policy Institute at Occidental College. Available at: http://www.foodsecurity.org/F2H_Brochure.pdf (verified 5 Mar 2010). "This brochure introduces interested farmers and hospital food service departments to the ins and outs of developing partnerships between hospitals and local farms. Included are examples of ways hospitals can improve the food they offer, issues for farmers to consider if they are interested in selling products to area hospitals, and specific case studies of successful programs."

Agritourism: Agritourism appeals to customers who have a desire to visit a farm and experience its activities. As Americans lose family ties with agriculture, many are interested in maintaining some sort of contact with farming; especially for their children. This is a theme with most types of direct marketing but is a key feature of agritourism. There are a variety of approaches.

On-farm bed and breakfasts allow overnight stays to relax in a bucolic atmosphere or, in some instances, work on the farm. The concept of "farm stays," popular in Europe, is catching on in the U.S. Hay rides to gather Halloween pumpkins or Christmas trees and other family-oriented activities are popular on farms. Other activities such as cattle drives attract customers who are willing to pay to experience a celebrated part of our past and present. Agritourism and entertainment techniques can work in both urbanized areas and very rural areas. As with many direct marketing techniques, people skills are crucial.

Online Marketing: The internet provides a convenient method to advertise the farm business, sell products, and communicate with customers. Most households have access to the internet in their homes. This is a potentially large market for specialty farm products. Farms may advertise on the internet by developing their own web sites or by participating in web-based farm directories. Farm homepages are an effective means for informing customers of products the farm grows, when they are available, and how to obtain them. Related blogs report on-farm or family activities. A farm may offer details on its CSA or identify which farmers' markets it sells at. These types of web pages allow customers to see the farm and the people who work there. This enhances the personal aspect of farm direct marketing that many people find appealing. There are also

opportunities for sales via the internet. Value-added or even fresh food products may be shipped to customers throughout the country. The internet is a quick and easy method for communicating with established customers. The latest information on product availability, farm news, and other information may be distributed to customers through an email list.

Online Marketing Tip Sheets: Looking to create or improve your online marketing? Download one of these four tip sheets for pointers and guidance. They're full of useful tips and real-life experiences from local farmers. This series was created by Community Involved in Sustaining Agriculture (CISA).

Creating a farm web site [Online]. Community Involved in Sustaining Agriculture. Available at http://buylocalfood.org/upload/resource/CISA_TipSheets_WebSites.pdf ">: http://buylocalfood.org/upload/resource/CISA_TipSheets_WebSites.pdf (verified 5 April 2011).

Online stores [Online]. Community Involved in Sustaining Agriculture. Available at http://buylocalfood.org/upload/resource/CISA_TipSheets_Stores.pdf (verified 5 April 2011).

Blogs [Online]. Community Involved in Sustaining Agriculture. Available at http://buylocalfood.org/upload/resource/CISA_TipSheets_Blogs.pdf (verified 5 April 2011).

Email Newsletters [Online]. Community Involved in Sustaining Agriculture. Available at http://buylocalfood.org/upload/resource/CISA_TipSheets_PermissionMarketing.pdf (verified 5 April 2011).

Nanotechnology Based Management of Diseases in Fruits and Vegetable Crops

Akshiti Kamboj and Ashu Sharma

Introduction

Fruit and vegetable cultivation plays a crucial role in global food security, human nutrition, and rural livelihoods. However, crop productivity is severely affected by fungal pathogens, which account for a major share of yield and post harvest losses. Diseases such as anthracnose, early blight, late blight, powdery mildew, downy mildew, grey mould, wilt and fruit rots reduce both the quantity and quality of marketable produce. Chemical fungicides have been extensively used to manage these diseases because of their rapid action and reliable performance. Nevertheless, continuous dependence on chemical fungicides has raised several concerns, including the evolution of fungicide resistant pathogen populations, accumulation of pesticide residues, adverse effects on beneficial microorganisms, and environmental pollution. In many cases, only a small proportion of the applied fungicide reaches the target pathogen, while the remaining quantity is lost through runoff, volatilization, degradation or leaching. Nanotechnology, which involves the manipulation of materials at the nanoscale (1-100 nm), offers innovative solutions for improving crop protection. Nano based fungicides increase the efficiency of disease management by enhancing the delivery, stability and effectiveness of active ingredients while reducing the amount of chemicals required. Consequently, nanotechnology is emerging as an important component of sustainable disease management strategies for fruit and vegetable production.

Nanotechnology and Nano Fungicides

Nanotechnology refers to the design, synthesis and application of materials with dimensions ranging from 1 to 100 nanometers. At this scale, materials exhibit unique physical, chemical and biological properties because of their high surface area and increased reactivity. Nano fungicides are fungicidal formulations in which nanoparticles either possess intrinsic antifungal properties or function as carriers that deliver conventional fungicides in a controlled manner. These formulations improve the availability of active ingredients, reduce degradation, and enhance disease control efficiency. Nano fungicides can be applied as foliar sprays, seed treatments, soil drenches or post-harvest coatings depending on the target crop and pathogen.

Types of Nanoparticles Used in Fungicides

Silver Nanoparticles (AgNPs): Silver nanoparticles exhibit broad spectrum antifungal activity. They effectively inhibit fungal pathogens such as *Alternaria alternata*, *Botrytis cinerea*, *Rhizoctonia solani*, *Macrophomina phaseolina* and *Sclerotinia*

Akshiti Kamboj and Ashu Sharma
Division of Plant Pathology, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan, Himachal Pradesh

sclerotiorum. Green synthesis using plants and microorganisms has further improved their environmental compatibility.

Copper and Copper Oxide Nanoparticles: Copper nanoparticles provide excellent protection against oomycete pathogens, including *Phytophthora* species. Compared with conventional copper fungicides, nano copper formulations require lower application rates and exhibit better adhesion to plant surfaces.

Zinc Oxide Nanoparticles: ZnO nanoparticles possess strong antimicrobial activity and effectively suppress several fungal pathogens by interfering with fungal metabolism and spore germination.

Titanium Dioxide Nanoparticles: Titanium dioxide nanoparticles exhibit photocatalytic activity that generates reactive oxygen species capable of damaging fungal cells under light conditions.

Chitosan Nanoparticles: Chitosan nanoparticles are biodegradable, biocompatible and environmentally safe. Besides their direct antifungal activity, they stimulate plant defense responses and improve resistance against pathogens.

Polymeric Nanocarriers: Biodegradable polymers such as chitosan, cellulose, and lignin are increasingly used as carriers for fungicides because they provide controlled release, reduced toxicity, and improved environmental safety.

Mechanism of Action

Disruption of Fungal Cell Membrane: Nano based fungicides initially interact with the fungal cell wall and plasma membrane because of their extremely small particle size (1-100 nm) and large surface area. The nanoparticles attach to the cell surface, penetrate the membrane and create structural damage by increasing membrane permeability. This results in leakage of essential intracellular components such as proteins, nucleic acids, enzymes, sugars, amino acids and potassium ions, ultimately causing loss of cellular integrity and death of the fungal cell. Metal nanoparticles such as silver, copper and zinc oxide are particularly effective in disrupting fungal membranes due to their strong interaction with negatively charged membrane components.

Generation of Reactive Oxygen Species (ROS): Many nanoparticles induce the formation of reactive oxygen species (ROS), including hydroxyl radicals, superoxide anions, hydrogen peroxide and singlet oxygen. Excessive ROS production creates oxidative stress within fungal cells by damaging membrane lipids, proteins, DNA, mitochondria and other cellular organelles. This oxidative damage interferes with normal metabolic activities, disrupts energy production and eventually leads to apoptosis-like cell death or complete destruction of the pathogen.

Inhibition of Spore Germination and Mycelial Growth: Nano based fungicides effectively inhibit fungal spore germination by preventing water uptake, interfering with enzyme activity and blocking germ tube formation, thereby stopping the initiation of infection. They also suppress the growth of fungal mycelia by inhibiting cell division, disrupting the synthesis of cell wall components such as chitin and β-glucans and damaging fungal hyphae. These actions significantly reduce fungal colonizati-

on, disease development and spread within plant tissues.

Controlled Release of Fungicides: Many nano formulations act as efficient delivery systems by encapsulating fungicidal active ingredients within nano carriers. These formulations release the fungicide gradually over an extended period, ensuring continuous protection against pathogens. Controlled release reduces the frequency of fungicide applications, minimizes degradation caused by sunlight, rain and environmental factors, improves the stability of active ingredients and lowers the total amount of fungicide required for effective disease management.

Improved Adhesion and Penetration: Nano based fungicides possess superior adhesion and spreading properties compared to conventional formulations. Their small particle size allows them to form a thin, uniform coating on plant surfaces, enhancing retention and reducing wash off by rainfall or irrigation. They penetrate leaf cuticles and reach hidden infection sites more effectively, ensuring better coverage and increased contact between the fungicide and fungal pathogens.

Advantages of Nano Fungicides

Nano fungicides offer several advantages over conventional fungicides due to their unique nanoscale properties. They exhibit higher antifungal activity by effectively inhibiting fungal growth even at lower concentrations, thereby reducing the amount of fungicide required for disease control. Their controlled and sustained release ensures prolonged protection, reducing the frequency of fungicide applications. Nano formulations also provide greater stability under environmental conditions such as sunlight, rainfall, and temperature fluctuations, increasing their field effectiveness. In addition, they show better adhesion and penetration on plant surfaces, improving fungicide retention and uptake by target pathogens. The reduced application rate minimizes environmental contamination, lowers pesticide residues on harvested produce and decreases adverse effects on non target organisms. Furthermore, nano fungicides are compatible with Integrated Disease Management (IDM) programs and have significant potential for use in precision agriculture, enabling targeted, efficient and sustainable crop protection.

Limitations and Challenges

Despite their considerable potential, nano fungicides face several limitations and challenges that restrict their widespread adoption. Limited information is available on their long-term environmental fate and ecological impacts and there are concerns about their possible toxicity to beneficial soil microorganisms, pollinators and other non target organisms. The accumulation of metallic nanoparticles in soil and water may also pose risks to ecosystems and food chains. In addition, the high cost of nanoparticle production, limited field scale validation under diverse agro climatic conditions and the lack of internationally accepted regulatory guidelines for their development, safety assessment, and commercialization remain significant barriers.

Applications in Fruit and Vegetable Crops

Crop	Disease	Nanoparticle	Mode of action
Tomato	Fusarium wilt	Chitosan nanoparticles	Disrupt fungal cell membrane, inhibit spore germination, induce defense enzymes
Potato	Late blight	Copper nanoparticles	ROS generation, disruption of fungal membrane, inhibition of sporangia
Potato	Dry rot	Chitosan nanoparticles	Antifungal activity and induced host resistance
Cucumber	Powdery mildew	Zinc oxide nanoparticles	Disrupt fungal cell membrane and inhibit spores
Onion	Purple blotch	Zinc oxide nanoparticles	Damage fungal cells and suppress mycelial growth
Brinjal	Phomopsis blight	Silver nanoparticles	Cell wall disruption and inhibition of fungal growth
Mango	Anthracnose	Chitosan nanoparticles	Inhibit fungal growth, stimulate plant defense, edible coating
Grapes	Powdery mildew	Zinc oxide nanoparticles	ROS generation and inhibition of fungal development
Banana	Crown rot	Chitosan nanoparticle	Antifungal coating and delayed pathogen development

Therefore, comprehensive biosafety studies, long-term environmental monitoring and standardized regulatory frameworks are essential to ensure the safe, effective and sustainable use of nano fungicides in agriculture.

Future Prospects

Future research should focus on developing biodegradable nano fungicides using green synthesis techniques. Integration of nanotechnology with biological control agents, precision agriculture, smart delivery systems and nano sensors may revolutionize disease management in horticultural crops. Continued field evaluation, risk assessment and regulatory support will accelerate the adoption of nano based fungicides for sustainable fruit and vegetable production.

Conclusion

Nanotechnology-based fungicides represent a significant advancement in modern plant disease management. By improving fungicide delivery, increasing efficacy and reducing environmental risks, nano fungicides provide an effective alternative to conventional disease control methods. Silver, copper, zinc oxide, titanium dioxide and chitosan nanoparticles have demonstrated considerable potential against important fungal pathogens affecting fruits and vegetables. However, their safe and sustainable application requires comprehensive studies on toxicity, environmental fate and large scale field performance. With continued scientific progress and appropriate regulatory frameworks, nanotechnology is expected to play a major role in ensuring sustainable and eco friendly disease management in horticultural crops.

References

Kah, M., Tufenkji, N. and White, J. C. (2019). Nano enabled strategies to enhance crop nutrition and protection. *Nature Nanotechnology*. 14 (6): 532-540.

Roberto, S. R., Youssef, K., Hashim, A. F. and Ippolito, A. (2019). Nanomaterials as alternative control means against postharvest diseases in fruit crops. *Nanomaterials*, 9(12): 1752.

Kutawa, A. B., Ahmad, K., Ali, A., Hussein, M. Z., Abdul Wahab, M. A., Adamu, A., Ismaila, A. A., … and Hossain, M. I. (2021). Trends in nanotechnology and its potentialities to control plant pathogenic fungi: A review. *Biology*, 10(9): 881.

Seed Priming: A Climate-Smart Strategy for Sustainable Crop Production

Manisha Patter, Anita Kumari and Alisha Goyal

Introduction

In the present scenario climate change is the primary problems of modern agriculture, causing various types of biotic and abiotic stresses. The arable areas lands are decreasing due to rapid urbanisation, soil fertility reducing due to over-dependency on chemical pesticides and fertilizers. Climate change is a great challenge for agriculture globally, loss of agricultural production and lower food security. Poor seed germination and weak seedling establishment being as most important stages reduce the crop production (Mittler *et al.*, 2025). Seed germination is a crucial phase in the plant life cycle that can be the deciding factor for successful establishment and growth of seedlings. It starts with imbibition of water by dry seed and is ended by the protrusion of a radicle. The process is impaired under stress conditions while improving germination and seedling vigour is critical to ensure good crop establishment and higher productivity. Seed priming has become one of the most successful methods among the various seed improvement technologies. Seed priming is a partial hydration process of seeds under controlled conditions which does not allow the radicle to emerge, unlike simple seed soaking. The seeds are then dried to the original moisture content prior to storage and seeding (Paul *et al.*, 2022). Primed seeds have faster and more uniform germination, higher germination percentages and better seedling vigor. Metabolic activities that are necessary for seedling emergence are started during the priming stage, which shortens the lag period and improves the nutrients utilization (Jarrar *et al.*, 2024). Priming techniques are most effective for seeds that have naturally low or poor germination rates. Additionally, the seed priming method has the potential to obtain uniform germination under sub-optimal environmental conditions and thus can be used to increase stress tolerance during germination (Jatana *et al.*, 2024).

Types of seed priming

The following are the major techniques:

Halopriming: The salt solution of NaCl, potassium nitrate (KNO_3) and potassium dihydrogen phosphate (KH_2PO_4) are used for halopriming. This treatment results in better water absorption, stimulation of metabolism, and better seed germination in stressful situations. Under drought and salinity stress, halopriming has been found to enhance seedling vigor, water use efficiency and grain yield of crops like maize and tomato (El-Sanatawy *et al.*, 2021).

Biopriming: Seeds are treated with beneficial micro

Manisha Patter and Anita Kumari
Department of Botany and Plant Physiology, CCS Haryana Agricultural University, Hisar, Haryana
Alisha Goyal
Maharana Pratap Horticultural University, Karnal, Haryana

organisms to have the ability to withstand different environmental conditions is called biopriming. Use of plant growth promoting rhizobacteria (PGPR) can be used in this process. Biopriming with beneficial micro-organisms enhances plants' ability to fight against the attacks of pests and other stresses. This method may act as an alternative to synthetic chemical and a promising priming technique to enhances germination rate, vigour indices and biotic stress resistance (Fiodor *et al*., 2023).

Osmopriming: It is a procedure in which the seeds are immersed in an osmotic solution, for example polyethylene glycol (PEG), in which water is taken up under control, without triggering the emergence of the radicle. This treatment is beneficial for germination, seedling growth rates and abiotic stress tolerance of various crops (Lei *et al*., 2021).

Chemical priming: The use of chemical substances like potassium nitrate, urea to make seeds more resilient to stressors. These chemicals trigger defense responses at physiological and molecular levels which enhances germination, water relations of tissues, chlorophyll content and plant growth under drought and salinity stress (Sako *et al*., 2020).

Solid matrix priming: In solid matrix priming, a moist solid carrier material being mixed with seeds and the water being absorbed slowly to avoid radicle emergence. This technique enhances germination, field emergence and establishment of seedlings especially in poor quality seed and in poor environmental conditions (Rawal *et al*., 2024).

Hydro-priming: This is the easiest way to prime, in which seeds are soaked in water for a certain amount of time and then dried to the original moisture content. It stimulates metabolism, increases germination and seedling development and growth of crops under normal and stress conditions (Adhikari *et al.*, 2021).

Hormonal priming: Plant growth regulators (PGRs) are used for hormonal priming, which includes ascorbic acid, salicylic acid (SA), gibberellic acid (GA_3) and abscisic acid (ABA), depending on the seed type. These hormones are responsible for germination, seedling growth and stress responsive metabolic pathways which can ultimately improve crop performance under biotic and abiotic stresses (Rhaman *et al.*, 2020).

Nanopriming: It is the process of applying nanoparticles (1-100 nm) to the seed to enhance germination and early plant growth. The exclusive physic-chemical properties such as high surface area/volume ratio, controlled nutrient release, give better uptake, enzyme activity and phytohormone regulation. The responses strengthen seedling vigour, enhance abiotic stress tolerances and facilitate sustainable crop production under altered climate (Palengara *et al.*, 2026).

Seed Priming to overcome Climate Stress

Early seedling establishment and germination is greatly compromised by major abiotic stresses such as drought, salinity, heat, chilling and flooding caused by climate change. These stresses prevent water absorption, membrane stability, proper enzyme function and hormone levels which results in

poor establishment and yield of crops (Pagano *et al*., 2023).

Drought stress: Limited water causes a decrease in cellular water potential, turgor pressure and prevents cell proliferation and elongation, which impacts seed germination and establishment of seedlings. Salicylic acid, chitosan, and nanoparticles priming of seeds has been reported to have a beneficial effect on drought stress tolerance (Ghadirnezhad *et al*., 2024). Seed priming with these substances enhances antioxidant defense, decreases the level of oxidative damage, and activates the necessary genes that lead to the mobilization of reserves and adaptation to drought stress (Giovannini *et al.*, 2024).

Chilling stress: Chilling stress adversely affects germination and early seedling growth by affecting the activity of enzymes, membrane permeability, and hormone imbalance and oxidative stress. In rape-seed, application of salicylic acid (SA), gibberellic acid (GA_3), abscisic acid (ABA), calcium chloride ($CaCl_2$) and nitric oxide donors has been reported to enhance the photosynthetic efficiency, antioxidant enzyme activity, and endogenous hormone balance in low-temperature stress (Zhu *et al.*, 2021).

Heat stress: Heat stress, caused by rising global temperatures, adversely affects seed germination and early seedling growth by disrupting membrane stability, enzyme activity, and cellular metabolism. It also accelerates the production of reactive oxygen species (ROS), leading to oxidative damage and poor crop establishment. Seed priming helps alleviate these adverse effects by enhancing antioxidant defense, maintaining hormonal balance, and improving membrane stability, resulting in better germination, vigorous seedlings, and improved tolerance to high- temperature conditions (Jatana *et al.*, 2024).

Salinity stress: Salinity stress results in reduced water uptake by seeds delaying germination. The build-up of Na^+ and Cl^- ions also results in ionic toxicity, oxidative stress and hormonal imbalance, affecting key metabolic pathways (Ghadirnezhad *et al.*, 2024). Priming counteracts these adverse effects by boosting antioxidant enzyme activity, eradicating ion imbalance and inducing accumulation of Osmo protectants and other protective compounds, which results in better germination and seedling growth under saline salt regime.

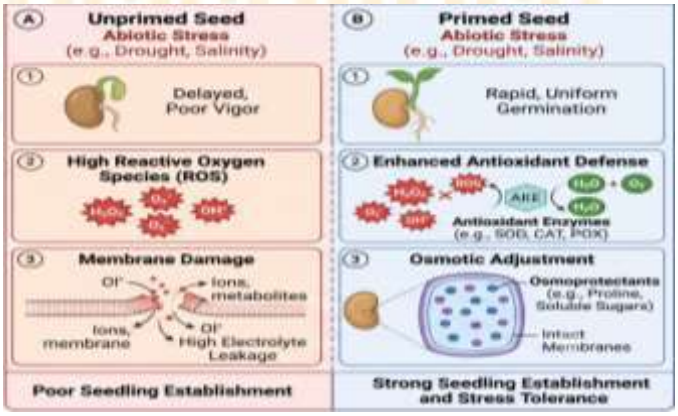


Fig. 1: Effect of seed priming treatment under abiotic stress conditions

Conclusion

Seed priming is a simple, low cost and environmentally friendly technique which improves seed performance by stimulating pre-germinative metabolic processes before sowing. It stimulates the mobilization of reserves, regulates plant hormones, strengthens the antioxidant defense mechanisms,

enhances water and nutrient uptake and aids in DNA repair. This results in faster and more uniform germination, strong seedling growth and good crop establishment. Seed priming is especially important for agronomically important crops where enhanced early seedling establishment will result in enhanced drought, salinity and temperature stress tolerance. The physiological and biochemical responses of seed priming under abiotic stress have shown in figure 1. Considering seed priming as a component within climate-smart farming systems can be pivotal in enhancing the resilience of crops to climate change, resource-use efficiency and sustainable food production.

References

Adhikari, B., Dhital, P. R., Ranabhat, S. and Poudel, H. (2021). Effect of seed hydro-priming durations on germination and seedling growth of bitter gourd (*Momordica charantia*). *Public Library of Science, ONE* 16(8): e0255258.

El-Sanatawy, A. M., Ash-Shormillesy, S. M., Qabil, N., Awad, M. F. and Mansour, E. (2021). Seed halo-priming improves seedling vigor, grain yield, and water use efficiency of maize under varying irrigation regimes. *Water*, 13(15): 2115.

Fiodor, A., Ajijah, N., Dziewit, L. and Pranaw, K. (2023). Biopriming of seed with plant growth-promoting bacteria for improved germination and seedling growth. *Frontiers in Microbiology,* 14: 1142966.

Ghadirnezhad Shiade, S. R., Rahimi, R., Zand-Silakhoor, A., Fathi, A., Fazeli, A., Radicetti, E. and Mancinelli, R. (2024). Enhancing seed germination under abiotic stress: exploring the potential of nano-fertilization. *Journal of Soil Science and Plant Nutrition,* 24: 5319.

Giovannini, L., Pagliarani, C., Cañizares, E., Sillo, F., Chitarra, W., De Rose, S., Zampieri E. and Balestrini, R. (2025). Mycorrhization and chemical seed priming boost tomato stress tolerance by changing primary and defence metabolic pathways. *Journal of Experimental Botany,* 76(21): 6410-6433.

Jarrar, H., El-Keblawy, A., Albawab, M., Ghenai, C. and Sheteiwy, M. (2024). Seed priming as a promising technique for sustainable restoration of dryland. *Restoration Ecology,* 32: e14182.

Jatana, B. S., Grover, S., Ram, H. and Baath, G. S., (2024). Seed priming: molecular and physiological mechanisms underlying biotic and abiotic stress tolerance. *Agronomy,* 14: 2901.

Lei, C., Bagavathiannan, M., Wang, H., Sharpe, S. M., Meng, W. and Yu, J. (2021). Osmo-priming with polyethylene glycol (peg) for abiotic stress tolerance in germinating crop seeds: A review. *Agronomy*, 11(11): 2194.

Pagano, A., Macovei, A. and Balestrazzi, A., (2023). Molecular dynamics of seed priming at the crossroads between basic and applied research. *Plant Cell Reports*, 42: 657-688.

Mittler, R., Karlova, R., Bassham, D. C. and Lawson, T. (2025). Crops under stress: can we mitigate the impacts of climate change on agriculture and launch the 'Resilience Revolution'? *Philosophical Transactions of the Royal Society B: Biological Sciences*, 380: 20240228.

Palengara, D., Kalathingal, S. B. and Edakkandiyil, S. (2026). Nanopriming as a strategic tool to boost abiotic stress tolerance in wheat (*Triticum aestivum* L.). *Discover Plants*, 3 (1): 9.

Paul, S., Dey, S. and Kundu, R. (2022). Seed priming: an emerging tool towards sustainable agriculture. *Plant Growth Regulation*, 97(2): 215-234.

Rawal, J. S., Puspa, R. C. and Mandal, A. (2024). A review on seed priming to combat climate variability in agriculture. *Archives of Agriculture and Environmental Science*, 9(3), 593-605.

Rhaman, M. S., Imran, S., Rauf, F., Khatun, M., Baskin, C. C., Murata, Y. and Hasanuzzaman, M. (2020). Seed priming with phytohormones: An effective approach for the mitigation of abiotic stress. *Plants*, 10(1): 37

Sako, K., Nguyen, H. M. and Seki, M. (2020). Advances in chemical priming to enhance abiotic stress tolerance in plants. *Plant and Cell Physiology*, 61(12): 1995-2003.

Zhu, Z. H., Sami, A., Xu, Q. Q., Wu, L. L., Zheng, W. Y., Chen, Z. P., Jin, X. Z., Zhang, H., Li, Y., Yu, Y. and Zhou, K. J. (2021). Effects of seed priming treatments on the germination and development of two rapeseed (*Brassica napus* L.) varieties under the coinfluence of low temperature and drought. *Public Library of Science ONE*, 16: e0257236.

Finger Millet: A Climate Resilient and Multi Nutrient Crop for Hill Region

Manoj Kumar, Rita Nongthombam, Doni Jini and Wangnem Rekhung

Finger millet an ideal crop for use as a staple food and for famine reserve. Finger millet is recognised as highly climate resilient crop. Its remarkable ability to withstand extreme temperatures, drought condition and poor soils makes vital resource for sustainable agriculture and food security. The crop has dual importance as source of food grain as well as straw for fodder. Millets are small-seeded, hardy, and drought-tolerant cereal grains that have been cultivated for thousands of years. It includes crops such as Finger Millet, Foxtail Millet, Proso Millet, Kodo Millet, Little Millet and Barn Yard Millet. Millets have tolerance to insect-pests and diseases, compared to major cereals. The characteristics like fast maturation and all-season growth makes them a desirable crop for a more intensive cropping system. Millets are useful for people suffering from gluten allergy and celiac disease. They are non-acid forming and non-allergenic and hence, easy to digest.



They are the principal source of energy, protein, vitamins, and minerals such as calcium, iron, magnesium, and zinc (Table 1).

Table 1: Nutritional composition of finger millet

Sl. No.	Parameters	Composition (per 100 g)
1.	Calcium	350 mg
2.	Protein	7.7 g
3.	Fat	1.5 g
4.	Ash	2.6 g
5.	Carbohydrates	72.6 g
6.	Iron	3.9 mg
7.	Crude fibre	3.6 g
8.	Magnesium	137 mg
9.	Phosphorus	283 mg
10.	Zinc	2.3 mg
11.	Thiamin (B_1)	0.42 mg
12.	Riboflavin (B_2)	0.19 mg
13.	Niacin	0.90 mg
14.	Energy (Kcal)	336
15.	Mineral	2.5 g

Millets are a vital part of the agricultural landscape and traditional diet in Arunachal Pradesh. Millets are used in various food preparations, including traditional beverage like *Apong*, as well as steamed dishes. Area and production of Finger Millet in Arunachal Pradesh is 21872 ha and 20531 tonnes respectively, along with productivity 938.7 kg/ha. Most of the Finger Millet cultivated area is dominating by the traditional variety with low productivity and long duration of the crop.

Manoj Kumar
Senior Scientist & Head, ICAR-KVK, West Siang, Arunachal Pradesh
Rita Nongthombam
SMS (Plant Breeding), ICAR-KVK, West Siang, Arunachal Pradesh
Doni Jini
Head, ICAR Arunachal Pradesh Centre, Basar, Arunachal Pradesh
Wangnem Rekhung
Programme Assistant, ICAR-KVK, West Siang, Arunachal Pradesh

The average productivity of Finger Millet is about 1524 kg ha^{-1} at national level, however in Arunachal Pradesh it is about 938.7 kg ha^{-1}. Leperada District, Headquarter in Basar is an agrarian District in Arunachal Pradesh. Where Finger millet (Ragi, Locally called Tami) is officially designated as the One District One Product (ODOP). However, production is localized and traditional with productivity 700-900 kg ha^{-1}. Therefore, Krishi Vigyan Kendra (KVK) West Siang had taken the initiative to increase the production and productivity of finger millet through improved cultivation practice.

Brief package of practices (POP)

Climate and Soil: Ragi is cultivated on a variety of soils ranging from rich loam to poor shallow upland soils. It prefers porous and well drained loam to light red loam and sandy loam soils of good fertility but reasonable water holding capacity. It can tolerate some water logging. Black soils with sufficient drainage capacity also support to cultivate Ragi crop. The soil should be rich in organic matter. Deep vertisols and rocky soils are not suitable for this crop owing to poor drainage and low fertility. The soil should be rich in organic matter. It also suitable for *Jhum* cultivation. It can be grown in soils with pH of 4.5-7.5.

Recommended varieties: Finger millet variety suitable for different climatic condition of Arunachal Pradesh. The varieties are VL Mandua 376, VL Mandua 378, VL Mandua 379, VL Mandua 380, VL Mandua 400, and VL Mandua 352. Most of the varieties matures about 100-120 days depending upon the locations. Number of fingures on main ear varied from 5-12 and seed rate between 2.0 to 4.0 g/1000 seed.

Land Preparation: The land is prepared separately for irrigated and rainfed conditions. In areas with a rainfall of 60 to 75 cm, ragi is cultivated as a rainfed crop. So the field should be deeply ploughed for moisture conservation. But in irrigated crop, plough the field immediately at the arrival of monsoon until gets fine tilth.

Nursery Sowing and Transplanting: For nursery bed, choose well drain area with good fertility and mixed well rotten FYM or Vermicompost @ 1 kg m^{-2} into the soil for healthy nursery. A plant population of 4 to 5 lakhs per ha is optimum for getting higher yields and higher or lower population than the optimum will reduce the yield. There are various methods practiced for cultivation, but seedling transplanting is very good for higher yield.

Transplanting the seedlings

- ✓ Irrigate the beds during transplanting.
- ✓ 3 to 4 weeks seedlings should be transplanted in the field.
- ✓ Transplant 2 to 3 seedlings $hill^{-1}$ in normal planting and 4 to 6 seedlings in delayed planting.
- ✓ For *kharif* season, plant 25-30 days old seedlings at a spacing of 30-40 cm cm x 15-20 cm
- ✓ Plant the seedlings at a depth of 2 to 3 cm. Deeper planting delays tillering and root regeneration, increases duration and flowering at different times
- ✓ Transplant in lines at proper spacing to maintain

the correct level of panicles per metre. This also eases subsequent operations. Random planting leads to uneven growth of tillers and reduce panicles per metre.

- ✓ Prepare slurry with 5 packets (1000g) per hectare of Azospirillum in 40 litres of water and dip the root portion of the seedlings in the solution for 15 to 30 minutes and transplant.
- ✓ Dip the leafy portion of the seedlings in 0.1% carbendazim solution before planting to arrest the transfer of blast to main field.
- ✓ The beds should be irrigated on the third day after transplantation
- ✓ Replace the dead hills with new seedlings from the same nursery within one week

Nutrient management

Organically: Finger millet responds well to nutrient application. For bumper crop, about 4.0-5.0 t farm yard manure (FYM), 1.0 t Vermicompost, 500 kg lime and 250 kg rock phosphate may be mixed well before 15 days of transplanting.

Inorganically: A recommended fertilizer dose of 40-50 kg nitrogen, 30 kg phosphorus, and 30 kg potassium ha^{-1} should be applied along with FYM @ 5 t ha^{-1}. Full doses of phosphorus and potassium along with half of the nitrogen should be applied at the time of transplanting as basal application to support early plant growth and root development. The remaining nitrogen should be applied after 30-35 days of transplanting. The combined use of organic manure and chemical fertilizers through integrated nutrient management helps in improving soil health, increasing nutrient use efficiency and enhancing yield and quality under the agro-climatic conditions of Arunachal Pradesh.

Intercultural Practices: Intercultural operations help in keeping the soil loose and friable and also permit the retention of moisture as well as adding organic fertilizer to the soil. Weeding is a practice of removing unwanted plant in the field. Weeding is considered as one of the important intercultural operations in this crop. Hand weed twice on the 10th and 20th day after transplanting. The inter cultivation and weeding should be done with hand hoe after 25 days of sowing. Two to three hoeing would be sufficient.

Water Management: It is very hardy, deep rooted crop and good crop grown in annual rainfall 180 mm. Since, it is a rainy season crop, it doesnot require irrigation. Proper drainage channel is essential in heavy rainfall area. However, if there is dry spell for longer period, the irrigation is needed for better crop of finger millet especially critical stages such as seedling stage, tillering, flowering, and grain-setting.

Pest and disease management: Although finger millet is hardy crop as compared to rice and maize. It is affected by number of insect, pest and diseases. Pest like pink borers (*Sesamia inferens*), Bihar caterpillar's etc. are most common in finger millet. Apart from collection and destruction of infested tillers, it is advised to spray formulation (1500 ppm)@ 3 ml lit^{-1} of water at 20 days interval. Among diseases, blast (*pyrecularia setariae*) and seedling blight or foot rot (*Cochliobolus nodulasus*) are most

common. Selection of disease free seed for sowing and proper sanitation are very important for preventing the disease.

Harvesting: The crop matures in about 100-120 days depending upon altitude and variety. Maturity is finger millet is uneven and harvesting is finger millet is done when the finger turn into brown. The over maturing of finger millet lead to shattering the millet in field.

Yield: The seed yield of fingermillet ranged 10.0-17.0 q ha^{-1}, depending upon the management practices and varieties. The seed yield may up to 20 q ha^{-1} if more care and management will take. The trial yield of different variety by KVK West Siang, Basar presented in the Table 2.

Table 2: Yield of different variety

Variety	Duration (in days)	Yield (q ha^{-1})
VL Mandua 376	105-115	13.6-15.4
VL Mandua 378	110-120	14.2-17.3
VL Mandua 379	110-120	14.4-16.2
VL Mandua 380	110-120	14.3-16.7
VL Mandua 400	115-125	14.2-17.1
VL Mandua 352	110-120	12.4-14.2
Mandua Local	135-140	9.2-11.8

The above result based on the trial conducted by the KVK West Siang, Basar considering that the duration of improved variety as 25-30 days earlier than traditional variety. It may be concluded that improved variety of Finger Millet varieties from VPKAS Almora are thriving well in the climatic conditions of West Siang and Leparada District region of Arunachal Pradesh, and providing higher productivity, profitability and nutrient security to the farmers.

Possible climate resilient cropping system

- ✓ Finger Millet-Green Gram
- ✓ Finger millet + Soybean
- ✓ Finger millet + Bhindi
- ✓ Finger Millet + upland rice
- ✓ Finger Millet-Frenchbean
- ✓ Finger Millet-Green Gram/frenchbean- *rabi* vegetables

Future Scope

Crop intensification and diversification with millet and green gram in upland situation including *Jhum* cultivation for increasing the cropping intensity.



Fig. 1: Photograph of different millet variety

Environmental Clearances in Landscape and Urban Development: Processes and Policies

Srishty Kumari, Meenakshi Basoli and Swati

Abstract

Large-scale development projects have significant ecological, social and spatial impacts, creating a rigorous framework of statutory permissions to ensure environmentally responsible and scientifically designed landscape planning. This article contains the multi-tiered regulatory approvals required for major projects, with emphasis on Environmental Impact Assessment (EIA) protocols, land-use and zoning compliance, forest and wildlife clearances, groundwater extraction permissions, pollution control consents, and landscape-specific authorizations mandated by national and state-level environmental legislation. The article include current regulatory mechanisms such as environmental clearance (EC), consent to establish (CTE), consent to operate (CTO), compensatory afforestation mandates, biodiversity impact evaluations and heritage-landscape assessments. It evaluates their relevance to soil conservation, hydrological stability, ecological corridor integrity, and urban microclimate management. The analysis further highlights the functional role of landscape planning in large projects, including its contributions to habitat protection, phytoremediation, storm-water regulation, heat-island mitigation and public health outcomes.

Introduction

Modern landscape planning is a multi-disciplinary science integrating ecology, soil science, horticulture, hydrology, environmental psychology, and urban design. The goal of landscape planning in large projects is to; restore or stabilize degraded soils, manage storm-water runoff and hydrological flows, create ecological corridors for biodiversity, mitigate pollution through vegetation (including phytoremediation), provide therapeutic and recreational green spaces and improve microclimate, reduce heat-island intensity along with enhancing the visual appeal of built environments. In large-scale projects, particularly those situated within industrial corridors, peri-urban growth areas or ecologically sensitive zones, landscape planning plays a critical ecological and functional role rather than serving merely aesthetic purposes. It contributes directly to soil restoration and remediation, buffer-zone development, habitat conservation, pollution mitigation, and a range of public health outcomes, including improved air quality, enhanced psychological well-being and reduced urban heat-island effects. Owing to these interconnected ecological functions, inadequately planned landscape modifications can result in accelerated soil erosion, habitat fragmentation, groundwater imbalance, heightened pollution levels, and the depletion of native biodiversity.

Srishty Kumari, Meenakshi Basoli and Swati
Department of Floriculture and Landscape Architecture, Dr. YSP UHF, Nauni, Solan, Himachal Pradesh

This is why many nations, including India, have established strict environmental clearance frameworks to evaluate large projects before it starts. The Environment (Protection) Act, 1986, the Environmental Impact Assessment (EIA) Notification, 2006, the Forest (Conservation) Act, 1980, regulations for Eco-Sensitive Zones (ESZ) and Coastal Regulation Zones (CRZ) collectively ensure that project have analysed environmental risks, propose mitigation strategies and design landscapes that are ecologically resilient. Research has shown that large projects without proper environmental permissions often result in long-term ecological degradation, poor landscape sustainability, water disruption and reduced biodiversity value. Therefore, understanding and complying with permission frameworks is essential not only for legal point of view but also for achieving sustainable, scientifically sound and socially beneficial landscape outcomes.

Different Permits for Large Scale Landscaping Projects

Environment (Protection) Act, 1986 and EIA Notification, 2006: The Environment (Protection) Act, 1986 is the legislation that allows the central government to regulate activities that may harm the environment. Under this Act, the EIA Notification, 2006 (as updated) mandates that certain categories of development projects, especially those with significant environmental impacts must obtain prior Environmental Clearance (EC) before any construction, land preparation or site modification begins. The Notification classifies projects into Category A and Category B depending on scale, type and potential environmental impacts. Category A projects are assessed by the national-level body (Ministry of Environment, Forest and Climate Change, MoEFCC), while Category B projects are reviewed at the state level by the State Environment Impact Assessment Authority (SEIAA). Projects may further be classified as B1 (requiring full EIA) or B2 (lesser impact, may not require full EIA). The clearance process broadly involves:

- ✓ Screening (to decide if EIA is needed)
- ✓ Scoping (defining terms of reference for EIA)
- ✓ Public consultation (public hearing)
- ✓ Appraisal by expert committees (EAC / SEAC)
- ✓ Grant or rejection of Environmental Clearance

Post-clearance, project proponents must submit periodic compliance reports (commonly every six months) to regulatory authorities.

Forestry, Biodiversity and Land-Use Laws: If a project involves forest land diversion, i.e., converting forest to non-forest use, then clearance under the Forest (Conservation) Act, 1980 is mandatory. For projects near protected areas like national parks, wildlife sanctuaries, eco-sensitive zones (ESZ), additional restrictions apply under wildlife and biodiversity conservation norms. Eco-sensitive zones rules are designed to regulate land use in buffer zones to protect fragile ecosystems. For coastal projects, Coastal Regulation Zone (CRZ) norms govern clearance that require a Coastal Zone Management Plan (CZMP), EIA and coastal-zone-specific permissions.

Table 1: Overlapping Permits: Land Use, Zoning and Urban Planning

Permission Type	Applicable Projects	Purpose
Environmental Clearance (EC) under EIA Notification	For any new project or expansion if listed in the EIA schedule (industrial units, large-scale infrastructure, townships, heavy landscaping or land-modification)	To assess and mitigate environmental impacts (air, water, soil, ecology, social) before development; ensures sustainable environmental management.
Forest Clearance (under Forest (Conservation) Act, 1980)	When forest land is diverted to non-forest land use (e.g., for industrial units, infrastructure, landscaping involving forest patches)	To prevent unauthorized deforestation, conserve forest ecosystems, ensure compensatory afforestation or biodiversity conservation.
Biodiversity Zone Clearance	Projects near protected areas, national parks, wildlife sanctuaries, or in eco-fragile zones	To regulate land use and activities so that biodiversity, wildlife habitats, and ecological corridors aren't disturbed.
Coastal Zone Clearance	For coastal, estuarine, or tidal-zone developments (ports, tourism, infrastructure)	To protect coastal ecosystems, mangroves, estuaries, regulate land use, safeguard against erosion, and ensure sustainable coastal development.
Site-Development Permit	Converting land use; e.g., agriculture to industrial / residential / landscaped urban project; soil grading	Ensures compliance with master plans, prevents unplanned sprawl, protects soil, hydrology, and local ecology.
Urban Planning Approvals	For township, large landscaped campuses, industrial parks, urban green zones or institutional developments	Approves layout plans, drainage, storm-water management, landscape plans and ensures compliance with municipal standards.
Resource-based Permissions	Projects involving groundwater extraction, large-scale earthwork / soil excavation, groundwater-dependent landscaping or irrigation	To regulate resource use (water, soil), ensure soil conservation, prevent over-extraction of groundwater, manage waste, and prevent pollution.
Community Clearances	Projects affecting local communities, requiring resettlement, or involving common land or community resources	Ensures community participation, social safeguards, fair compensation, and considers socio-environmental equity.

Overlapping Permits: Land Use, Zoning and Urban Planning: Large landscape or land-development projects often trigger land-use change or change of land use (CLU) requirements specially when converting agricultural, forest or open land into industrial, commercial, residential or landscaped urban zones. For urban or municipal projects, local town-planning authorities, municipal corporations and sometimes state urban development departments must also approve master plans, layout plans, site grading and landscaping plans as a part of building-permit or site-development permit workflows.

Procedural steps for obtaining permission

According to the official guidance manual for environmental clearance:

Screening: This stage determines whether the proposed project requires a full EIA (Category A or B1) or not (Category B2).

Scoping: If EIA is required, the Expert Appraisal Committee (EAC) or State EAC (SEAC) determines the Terms of Reference (ToR) for the EIA Report, based on application details, site visit and project type.

Preparation of EIA Report: The project proponent prepares a full EIA report as per ToR, covering potential environmental impacts (air, water, soil, ecology, noise, health, socio-economic).

Public Consultation / Hearing: The draft EIA report must be made available to the public for a specified period (commonly 30 days) before the public hearing. People affected (directly or indirectly) can review and raise objections or submit data.

Appraisal: After public hearing, the SEAC reviews the EIA, objections, mitigation measures, proposed Environmental Management Plan (EMP) and submits recommendation to regulatory authority.

Decision / Clearance Grant: The competent authority (MoEFCC for Category A; SEIAA for Category B) grants or rejects Environmental Clearance. If granted, the project proponent can proceed with construction or land preparation.

Post-clearance Compliance and Monitoring: The proponent must submit environmental compliance reports (typically twice a year), implement mitigation and EMP measures and adhere to conditions mentioned in clearance.

If forest land is involved, or the project lies in eco-sensitive or coastal zones, additional parallel clearances (forest clearance, biodiversity clearance, CRZ clearance) must be obtained before or along with the EC. These clearances have their separate procedures, documentation requirements, and scrutiny by specialized committees (e.g., Forest Advisory Committee).

Challenges and Limitations

Although the clearance framework is comprehensive, academic and policy reviews highlight limitations, implementation gaps, and areas needing improvement:

- ✓ A systematic review of EIA studies in India found significant variability in quality, thematic coverage, and follow-up compliance. Some EIAs lacked rigorous baseline data, undervalued social impacts or failed to adequately monitor ecological consequences post-approval.
- ✓ There have been concerns over delays and institutional inefficiency, for example, backlog of projects awaiting appraisal or reconstitution of appraisal authorities at state level. This can stall projects or lead to informal violations.
- ✓ Overlapping jurisdictions; e.g., urban planning authorities, forest departments, pollution control boards often lead to procedural delays, confusion or inconsistent compliance.
- ✓ Post-clearance monitoring and enforcement are often weak as some projects are granted EC but fail to implement mitigation measures or environmental management plans, leading to long-term ecological damage. This has been widely critiqued in environmental governance literature.

Refrences

Botequilha-Leitão, A. and Ahern, J. (2002). Applying landscape ecological concepts and metrics in sustainable landscape planning. *Landscape and Urban Planning*, 59(2): 65-93.

Glasson, J., Therivel, R. and Chadwick, A. (2013). *Introduction to Environmental Impact Assessment*.

Hartig, T., Mitchell, R., de Vries, S. and Frumkin, H. (2014). Nature and health. *Annual Review of Public Health*, 35: 207-228.

Ulrich, R. S. (1984). View through a window may influence recovery from surgery. *Science*, 224(4647): 420-421.

Ignatieva, M., Stewart, G. and Meurk, C. (2011). Planning and design of ecological networks in urban areas. *Landscape and Urban Planning*, 100(4): 344-349.

Pataki, D., Carreiro, M., Cherrier, J., Grulke, N., Jennings, V., Pincetl, S., Pouyat, R., Whitlow, T. and Zipperer, W. (2010). Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. *Frontiers in Ecology and the Environment*, 11(10): 341-350.

Rajvanshi, A., Brown, A. L., Mathur, V. B. and Kohli, K. (2011). *Environmental Impact Assessment: A Guide for Practitioners in India*. Wildlife Institute of India.

Agroforestry Systems in Telangana: Implications for Sustainable Land Management and Climate Resilience

Ch. Sucharitha, Sriram Vaishnavi, Karthika M. and Packialakshmi M.

Abstract

Agroforestry is a land use system that combines crops and animal species with trees and woody shrubs (Naik, 1993). Agroforestry systems (AFS) emphasize local, small-scale farming with ecologically friendly, resource efficient agricultural practices to increase environmental sustainability and productivity. They not only mitigate climate risks through improved microclimate regulation and water conservation but also contribute to socio-economic stability by diversifying income sources. Despite constraints such as delayed economic returns and limited policy support, agroforestry presents a sustainable pathway for climate resilient agriculture in Telangana. Strengthening institutional frameworks and promoting farmer awareness are crucial for large-scale adoption.

Introduction

Agriculture in Telangana is predominantly rainfed and highly vulnerable to climate variability, land degradation and declining soil fertility. In this context, agroforestry systems offer a multifunctional land-use approach that integrates ecological sustainability with economic viability. Agroforestry combines trees, crops and livestock in spatial or temporal arrangements to optimize resource use efficiency and enhance productivity. It is a critical, climate-smart farming system for marginal lands in Telangana. These systems are gaining prominence due to their potential to restore degraded lands, improve biodiversity, and strengthen resilience against climate change

Agroforestry Systems in Telangana

A diverse assemblage of tree species has been documented with a strong predominance of indigenous species (approx. 86%). Commonly observed species include teak (*Tectona grandis*), mango (*Mangifera indica*), neem (*Azadirachta indica*) and other multipurpose trees. The presence of such diversity reflects traditional ecological knowledge and site-specific adaptability.



Fig. 1: Typical agroforestry landscape in Telangana showing scattered trees in rainfed farming systems



Fig. 2: Boundary plantation system widely practiced by farmers in Telangana

Ch. Sucharitha, Sriram Vaishnavi and Karthika M.
Department of Agronomy, Kaveri University, Siddipet, Telangana
Packialakshmi M.
Department of Forest Products and Wildlife, FC and RI, TNAU, Tamil Nadu



Fig. 3: Mango-based agroforestry system with intercrops under orchard conditions



Fig. 4: Silvopastoral system integrating livestock with tree components



Fig. 5: Timber-based agroforestry system (teak plantation) in Telangana



Fig. 6: Tree planting under Telangana's Haritha Haram programme supporting agroforestry.

Telangana has planted millions of saplings under Haritha Haram to increase green cover. These systems vary in structure and function but collectively contribute to enhancing farm resilience.

Ecological Significance

Agroforestry systems provide multiple ecological benefits that are critical for sustainable land management (Jose, 2009);

Soil Health Improvement: Tree litter and root biomass enhance soil organic matter, improve nutrient cycling, and increase microbial activity. This leads to improved soil structure and fertility over time.

Carbon Sequestration: Trees in agroforestry systems act as carbon sinks, storing carbon both above and below ground. This contributes significantly to climate change mitigation.

Biodiversity Conservation: The integration of diverse plant species supports a wide range of flora and fauna, promoting ecological balance and resilience.

Water Conservation: Tree canopies reduce evapo-transpiration, while root systems improve water infiltration and reduce runoff, making agroforestry particularly suitable for dryland regions.

Climate Resilience and Adaptation: Agroforestry enhances resilience to climate variability through several mechanisms:

- ✓ **Microclimate regulation:** Trees reduce temperature extremes and wind velocity, creating a favorable environment for crops.
- ✓ **Drought mitigation:** Improved soil moisture retention helps sustain crops during dry spells.
- ✓ **Risk diversification:** Multiple outputs (timber, fruits, fodder) reduce dependency on a single crop.

Socio-Economic Benefits: Agroforestry systems contribute significantly to rural livelihoods in Telangana:

- ✓ **Income diversification:** Farmers gain additional income from timber, fruits, and non-timber forest products.
- ✓ **Employment generation:** Activities such as

nursery raising, pruning, and harvesting create rural employment opportunities.

- ✓ **Economic stability:** Tree-based systems act as financial security during crop failures.

Constraints and Challenges

- ✓ Lack of awareness and technical knowledge among farmers
- ✓ Long gestation period for tree components
- ✓ Limited access to quality planting material
- ✓ Market and policy constraints related to tree harvesting and transportation

Conclusion

Agroforestry systems in Telangana, particularly in Siddipet district, demonstrate significant potential for sustainable land management and climate resilience. By integrating ecological, economic, and social benefits, these systems provide a holistic solution to the challenges faced by dryland agriculture. Scaling up agroforestry practices through policy support, research, and farmer participation can pave the way for a resilient and sustainable agricultural future.

References

Yerrawada, N., Mhaiskar, P. R., Milkuri, C. R., Sarvade, S., Gouthami, G., Sri Ram, M., Ravula, R., Venkateshwar Reddy, B. and Anish, K. (2025). Evaluating agroforestry systems for sustainable land management and climate resilience in Siddipet District, central agroclimatic zone, Telangana, India. *Agro-ecology and Sustainable Food Systems*, 49 (8): 1349-1367.

Murmu, S., Garg, S. and Padhi, G. K. (2026). Synergizing agroforestry practice: Sustainable land management, ecological resilience and socio-economic prosperity**.** In *Advanced Approaches for Climate Resilient Water Resource Management* (pp. 133-158). Soil Conservation Society of India, New Delhi, India.

Nair, P. K. R. (1993). An introduction to agroforestry. Kluwer Academic Publishers.

Shibu Jose (2009). Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems*, 76(1): 1-10.

Food and Agriculture Organization. (2013). Advancing agroforestry on the policy agenda: A guide for decision-makers. FAO.

Sustainable Agricultural Development in Rajasthan: Emerging Innovations and Trends

Kiran Hingonia, Priyanka, Sarita Kumari, Annu Devi Gora and M. L. Taterwal

Abstract

Agriculture in Rajasthan, a state characterized by its arid climate and diverse agro-ecological zones, is undergoing a transformative phase driven by technological innovation, policy reforms, and sustainability initiatives. This abstract explores the emerging trends and potential pathways for the future of agriculture in the region. Key areas of focus include the adoption of advanced irrigation techniques, such as drip and sprinkler systems, to address water scarcity; the integration of precision farming technologies to enhance crop productivity and resource-use efficiency; and the promotion of climate-resilient crop varieties suited to the region's harsh environmental conditions. Additionally, government policies, including subsidies and support for research and development, play a critical role in shaping the sector's future. The advancement of agriculture in Rajasthan also depends on empowering local farmers through education, skill development, and improved access to modern tools and agricultural practices. This forward-looking analysis highlights the opportunities and challenges associated with achieving sustainable agricultural growth while ensuring food security, economic stability, and environmental sustainability in one of India's most distinctive agricultural landscapes.

Introduction

Agriculture and allied sectors constitute a critical component of Rajasthan's economy, contributing substantially to the State's Gross State Domestic Product (GSDP) while serving as the principal source of livelihood for a significant proportion of the rural population. The agriculture and allied sectors comprise crop cultivation, animal husbandry, fisheries, and forestry, all of which play an indispensable role in ensuring food security, generating employment, and fostering rural socio-economic development. Despite the progressive structural transformation of the State's economy, agriculture continues to occupy a

Kiran Hingonia
Assistant Professor, Department of Agronomy, CoA, Sumerpur, Pali (Agriculture University, Jodhpur), Rajasthan

Priyanka
Assistant Professor, Department of Plant Pathology, CoA, Sumerpur, Pali (Agriculture University, Jodhpur), Rajasthan

Sarita Kumari
Assistant Professor, Department of Plant Biotehnoloy, CoA, Sumerpur, Pali (Agriculture University, Jodhpur), Rajasthan

Annu Devi Gora
Assistant Professor, Department of Extension Education, CoA, Sumerpur, Pali (Agriculture University, Jodhpur), Rajasthan

M. L. Taterwal
Assocate Professor, Department of Plant Pathology, CoA, Sumerpur, Pali (Agriculture University, Jodhpur), Rajasthan

central position in sustaining economic growth and supporting rural livelihoods. The agricultural system of Rajasthan is predominantly rain-fed and is characterized by considerable dependence on the southwest monsoon. The State experiences a relatively short monsoon season, with a delayed onset and early withdrawal compared with many other regions of India. Furthermore, rainfall is marked by pronounced spatial and temporal variability and is frequently inadequate, erratic, and unevenly distributed. These climatic characteristics, together with the persistent decline in groundwater resources resulting from excessive extraction and limited natural recharge, constitute major constraints to agricultural productivity and sustainability. Nevertheless, agriculture and allied sectors continue to represent the backbone of the State's economy by maintaining a significant contribution to overall economic output and employment. The economic significance of the sector is reflected in its contribution to the Gross State Value Added (GSVA). At constant (2011-12) prices, the GSVA of agriculture and allied sectors increased from ₹1.76 lakh crore in 2019-20 to ₹2.05 lakh crore in 2023-24, registering a Compound Annual Growth Rate (CAGR) of 3.86 percent. At current prices, the GSVA increased from ₹2.61 lakh crore to ₹3.82 lakh crore during the same period, corresponding to a CAGR of 9.99 percent. During 2023-24, the sector recorded an overall growth rate of 2.13 percent over the preceding year at constant prices. Sectoral estimates indicate growth rates of -1.61 percent for crop production, 5.83 percent for livestock, 2.82 percent for forestry and logging, and 15.21 percent for fisheries. The crop sector alone contributed ₹1.70 lakh crore to the State's GSVA at current prices during 2023-24, reaffirming its dominant role within the agricultural economy. The cropping pattern of Rajasthan reflects the diversity of its agro-climatic regions. The principal *kharif* crops include pearl millet (*Pennisetum glaucum*), groundnut (*Arachis hypogaea*), sesame (*Sesamum indicum*), moong bean (*Vigna radiata*), and moth bean (*Vigna aconitifolia*). The major *rabi* crops comprise wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), rapeseed and mustard (*Brassica* spp.), and gram (*Cicer arietinum*). In addition, commercially important crops such as cumin (*Cuminum cyminum*) and isabgol (*Plantago ovata*) make a substantial contribution to agricultural income and export earnings. The cultivation of these crops enhances farm income diversification and strengthens the resilience of the State's agricultural production Millets occupy a strategically important position within Rajasthan's agricultural economy owing to their exceptional adaptability to arid and semi-arid environments, comparatively low water requirements, and high nutritional value. The observance of the International Year of Millets under the theme “Healthy Millets, Healthy People” has further emphasized their potential to promote sustainable agricultural development, nutritional security, and climate-resilient farming systems. Given the increasing frequency of climatic extremes and the growing scarcity of water resources, the

expansion of millet cultivation represents an important strategy for improving agricultural resilience while addressing food and nutritional security, particularly among resource-constrained farming communities.

According to the Advance Estimates for 2025-26, the total food grain production in Rajasthan is projected to reach 283.98 lakh tonnes, representing a decline of 8.28 percent compared with the previous year's production of 309.62 lakh tonnes. The estimated *kharif* food grain production is 89.55 lakh tonnes, reflecting a decrease of 21.61 percent from 114.24 lakh tonnes recorded in 2024-25. Similarly, rabi food grain production is projected at 194.43 lakh tonnes, marginally lower than the 195.38 lakh tonnes produced during the previous year, indicating a decline of 0.49 percent. Despite the overall reduction in food grain production, the production of pulses is expected to increase, with *kharif* pulses rising by 2.34 percent and *rabi* pulses by 22.34 percent over the previous year. Furthermore, oilseed production is projected to increase to 100.46 lakh tonnes, representing a growth of 7.18 percent compared with 2024-25. These trends reflect the continuing influence of climatic variability, particularly fluctuations in rainfall and water availability, on agricultural production in Rajasthan while highlighting the resilience of pulse and oilseed cultivation. Consequently, strengthening climate-resilient agricultural practices, promoting efficient irrigation systems, improving water resource management, and encouraging the adoption of sustainable and climate-smart farming technologies remain essential for ensuring long-term agricultural productivity, food security, and environmental sustainability in the State.

Traditional and Modern Agricultural Practices in Rajasthan

Traditional agricultural practices involve indigenous methods such as manual weeding, use of organic manures, local seeds, traditional seed treatment, irrigation, and grain storage techniques. Modern practices include farm mechanization, custom hiring services, high-yielding varieties, synthetic fertilizers, pesticides, herbicides, and advanced irrigation technologies. A balanced integration of traditional knowledge and modern innovations can promote sustainable agricultural development.

The Future of Agriculture in Rajasthan: Key Factors and Challenges

The future trajectory of agriculture in Rajasthan will be determined by the effective management of natural resources, technological advancement, climate adaptation strategies, and supportive institutional frameworks. The agricultural sector faces several challenges that require sustainable and innovative approaches to ensure long-term productivity, economic viability and environmental sustainability.

Water Resource Management: Water scarcity remains one of the most critical constraints to agricultural development in Rajasthan due to its arid and semi-arid climatic conditions. The adoption of water-efficient irrigation technologies, including

drip and sprinkler systems, along with integrated water conservation and groundwater management practices, is essential for enhancing water-use efficiency.

Development of Climate-Resilient Crops: The promotion and adoption of drought-tolerant and climate-resilient crop varieties are crucial strategies for minimizing production risks associated with increasing climatic variability and water stress.

Soil Resource Conservation: Soil degradation, including erosion, salinity, and nutrient depletion, poses a significant threat to agricultural sustainability. Integrated soil fertility management and conservation-based agricultural practices are required to maintain soil productivity.

Technological Advancement: The integration of modern agricultural technologies, such as precision farming, remote sensing, artificial intelligence-based advisory services, and digital platforms, can enhance decision-making, productivity, and resource-use efficiency.

Renewable Energy Integration: Rajasthan's high solar energy potential provides significant opportunities for the adoption of solar-powered irrigation systems and renewable energy-based agricultural operations, thereby reducing dependence on conventional energy sources.

Policy Support and Institutional Interventions: Continued implementation of government programmes, financial incentives, research support, and effective extension services will play a vital role in promoting sustainable agricultural practices and improving farmers' economic resilience.

Promotion of Organic and Sustainable Farming: Expansion of organic farming practices can contribute to soil health improvement, biodiversity conservation, and access to emerging markets for sustainably produced agricultural commodities.

Capacity Building and Farmer Empowerment: Strengthening agricultural education, skill development, and extension services is essential for enabling farmers to adopt advanced technologies and sustainable production practices.

Market Access and Infrastructure Development: Improved storage facilities, transportation networks, value addition, processing infrastructure, and efficient market linkages are necessary to reduce post-harvest losses and enhance farmers' income.

Economic Constraints: Agricultural profitability is affected by fluctuating market prices, rising input costs, limited access to institutional credit, and inadequate risk management mechanisms.

Climate Change Adaptation: Developing and implementing climate-smart agricultural strategies will be essential to address changing rainfall patterns, temperature variability, and increasing frequency of extreme weather events.

Agricultural Diversification: Encouraging diversification towards horticulture, livestock, fisheries, and integrated farming systems can enhance income stability, reduce production risks, and improve the resilience of farming communities.

Technology Advancement for Role in Transforming Agriculture in Rajasthan

Technological advancements are playing a significant role in transforming agriculture in Rajasthan

Precision Farming: The use of GPS and GIS technologies allows farmers to monitor and manage their fields more accurately. This leads to optimized use of inputs like fertilizers and pesticides, reducing costs and environmental impact.

Drip and Sprinkler Irrigation: These irrigation methods help conserve water, a critical need in Rajasthan's arid climate. They ensure that water is delivered directly to the plant roots, reducing wastage and improving water use efficiency.

Remote Sensing and Drone: Remote sensing technology and drones are being used for monitoring crop health, soil conditions, and water levels. These technologies provide real-time data, enabling better decision-making and timely interventions.

Mobile Apps and ICT Tool: Several mobile applications and ICT tools have been developed to provide farmers with information on weather forecasts, crop prices, pest control, and best farming practices. Apps like kisan suvidha.

Soil Health Cards: The Soil Health Card scheme provides farmers with information on the nutrient status of their soil and recommendations for appropriate fertilizers. This helps in optimizing fertilizer use and improving crop yields.

Solar-Powered Equipment: Given Rajasthan's abundant sunlight, solar-powered pumps and other agricultural equipment are being increasingly adopted. This reduces dependency on conventional energy sources and lowers operational costs.

Greenhouse and Polyhouse Farming: These controlled environment agriculture methods allow for the cultivation of high-value crops throughout the year, regardless of external weather conditions, thus increasing productivity and income.

Biotechnology: Advances in biotechnology, including the development of high-yield and drought-resistant crop varieties, are helping farmers deal with the challenges of water scarcity and climate variability.

e-Marketing Platforms: Digital marketplaces and e-NAM (National Agriculture Market) are enabling farmers to sell their produce directly to buyers, ensuring better prices and reducing the role of intermediaries.

Smart Sensors and IoT: Sensors and IoT devices are being used to monitor soil moisture, nutrient levels, and other critical parameters in real-time. This data helps in precise irrigation and fertilization, enhancing crop growth and reducing waste.

Diversification in Agriculture: Agricultural diversification offers significant potential for enhancing farm income and improving agricultural growth through the promotion of high-value crops, horticulture, livestock and fisheries. However, diversification strategies must be implemented without compromising the State’s food security. The revival of sustainable traditional practices, including the use of organic manures, green manuring, intercropping with legumes, and systematic crop rotation, is essential for maintaining soil health and productivity.

Promotion of horticulture, particularly in rainfed regions of Rajasthan, can contribute to a second green revolution by increasing production, income, employment opportunities, trade, and the growth of agro-based industries. Diversification towards high-value, low-volume commodities such as fruits and vegetables can be economically beneficial, especially for small and marginal farmers. Region-specific crop planning, supported by appropriate backward and forward linkages, is necessary to maximize the benefits of agricultural diversification.

Advancements in Protected Cultivation of Horticultural Crops: Protected cultivation is an emerging technology that addresses the challenges of climate change, water scarcity, declining agricultural land, and increasing pest and disease pressures. It provides a controlled growing environment by regulating temperature, humidity, light, and other factors to optimize plant growth and productivity. Rajasthan has significant potential for protected cultivation of high-value horticultural crops, including fruits and vegetables, through structures such as greenhouses, polyhouses, poly-tunnels, and net houses. This technology enhances resource-use efficiency, improves crop yield and quality, and supports sustainable horticultural development.

Adoption of Water-Saving Technologies: Micro-irrigation systems utilize precision-based technologies to enhance water and nutrient-use efficiency by delivering these resources directly to the crop root zone according to plant requirements. Compared with conventional flood irrigation, micro-irrigation methods such as drip, sprinkler, micro-sprinkler, and bubbler systems minimize water losses through evaporation and runoff, which is particularly important under rising temperatures and increasing water scarcity. The major advantages of micro-irrigation include precise application of water at frequent intervals, improved conveyance efficiency, reduced weed and pest incidence, enhanced nutrient uptake through fertigation, and improved crop productivity. Therefore, the adoption of micro-irrigation technologies is essential for sustainable water management and climate-resilient agricultural production.

Rainwater Harvesting and Use of Solar Pump Sets: Rainwater harvesting plays a crucial role in conserving water resources in arid and semi-arid regions. The practice involves in-situ conservation of rainwater, collection of runoff water in traditional and modern structures such as *Khadin*, *Tankas*, and farm ponds, and its utilization for supplemental irrigation and groundwater recharge. The integration of solar pump sets further promotes sustainable water management by providing an efficient and renewable energy source for irrigation. These practices enhance water availability, improve agricultural productivity, and support climate-resilient farming systems.

Adopted Integrated Farming System (IFS): Adoption of Integrated Farming System (IFS), including crop production, dairy, horticulture, and livestock enterprises, promotes efficient utilization of natural resources and ensures sustainable farm production.

It facilitates recycling of farm by-products, improves resource-use efficiency, and reduces dependence on chemical fertilizers, pesticides, and herbicides through eco-friendly practices. IFS enhances farm income, minimizes environmental pollution, and improves the overall benefit-cost ratio by integrating diverse agricultural activities.

Promoting of Organic Farming: Organic agriculture is a holistic production management system that promotes and enhances the health of agroecosystems by conserving biodiversity, strengthening biological cycles, and improving soil biological activity. It seeks to optimize agricultural productivity while maintaining ecological balance by utilizing the natural capacities of plants, animals, and the soil. Organic farming emphasizes the sustainability of agricultural ecosystems by prohibiting the use of synthetic fertilizers, herbicides, pesticides, growth hormones, antibiotics, and genetically modified organisms (GMOs). Instead, it relies on environmentally friendly practices that improve soil fertility, enhance biodiversity, and increase crop resilience to pests, diseases, and climatic stresses. Successful organic farming requires a high level of managerial expertise, careful planning, and the efficient use of locally available biological and natural resources.

The primary objectives of organic farming include

- ✓ Maximization of biological activity in soils.
- ✓ Maintenance of long-term soil health and minimization of soil erosion.
- ✓ Enhancing genetic and biological system and the surroundings.
- ✓ Raising of livestock with optimal living conditions for well -being and better health.
- ✓ Recycling of materials of plant and animal origins, nutrients to the soil.
- ✓ Minimization of the use of non-renewable resources.

Initiatives by towards Organic Farming by State Government: State Government of Rajasthan has adopted Dungarpur as first organic district to promote 100% organic farming in the district and also formulated policy on organic farming "Rajasthan Organic Farming Policy 2017" this will lead to sustainability in agriculture.

Conservation and Sustainable Agricultural Practices

- ✓ Improvement in Soil fertility through crop residue management, green manuring, Crop rotation, zero tillage, mulching and mixed cropping
- ✓ Adoption of water management practices as per water availability and increase in output productivity on per unit basis.
- ✓ Adoption of integrated nutrient and pest management
- ✓ Use of the latest technologies for judiciously use of the water through drip irrigation, sprinkler irrigation, instead of flood irrigation and traditional irrigation system.
- ✓ Use of plastic mulching to check the evaporation loss of water as well as growth of the weeds.
- ✓ Afforestation on wasteland or promotion of plantation/fruit crops

- ✓ Use of the drought resistant varieties which can be withstand in the drought like conditions/can be grown in less water areas.
- ✓ Ruminant animals emit methane which can be addressed by feeding practices (use of Chaff cutter, proper rationing or balanced diet), cow dung management (use of Gobar Gas plant and linkage with vermi-compost)
- ✓ Use of solar energy (Photo voltaic lighting system, solar pumps, solar cookers, solar lanterns, etc.) as use of solar energy will reduce the coal/fossil fuel consumption thus would help in mitigation.
- ✓ Adoption of integrated nutrient and pest management practices
- ✓ Weather advisory services
- ✓ Construction of ground water recharge structures
- ✓ Promotion of local breeds of cattle which are high yielders
- ✓ Recycling of water used for washing or cooking
- ✓ Diversification of cropping pattern as per rising temperature so that income of farmers is not adversely affected. Construction of improved cattle shed which minimizes the impact of climate change
- ✓ Capacity buildings of local communities / PRIs
- ✓ Diversification of farming system

Conclusion

The future of agriculture in Rajasthan depends on the adoption of technological innovations, efficient water resource management, protected cultivation, and supportive government policies. Advanced technologies such as precision farming and climate-smart agricultural practices can enhance productivity, improve resource-use efficiency, and strengthen resilience to climate change. Protected cultivation offers significant potential to increase the production and quality of high-value crops while reducing the impact of adverse climatic conditions, pests, and diseases. With continued investment in research, extension services, and farmer capacity building, Rajasthan can achieve sustainable agricultural growth, improve food and nutritional security, enhance farmers' livelihoods, and promote long-term environmental sustainability.

References

Directorate of Economics and Statistic, Raj Economic Survey of Rajasthan: 2025-26.

Hingonia, K., Priyanka, Seema, and Sharma A. (2024). Nutritional and agronomic potential of minor millets: A sustainable approach. *International Journal of Research in Agronomy*, 7: 907-9.

Kumar, J., Rana, S., Rani, V. and Ahuja, A. (2023). What affects organic farming adoption in emerging economies? A missing link in the Indian agriculture sector. *International Journal of Emerging Markets.*

Rai, A. K., Sengupta S., Sahay, S., Pandey, A. and Singh, G. P. (2023). Advancements in protected cultivation of fruit crops: A paradigm shift in agriculture. *The Agriculture Magazine*, E-ISSN: 2583-1755: Vol. 3, Issue-3.

Bhan, S. and Behera, U. K. (2014). Conservation agriculture in India-Problems, prospects and policy issues. *International Soil and Water Conservation Research*, 2(4): 1-12.

Reddy, B. S., Rao M. M. V. S. and Padmalatha Y. (2021). Integrated farming system models for arid and semiarid rainfed regions. *Indian Farming*, 71(11): 24-27.

Sekaran, U., Lai, L., David, A. N., Kumar, S. and Clay, S. (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security-A review. *Journal of Agriculture and Food Research*, 5: 100190.

Yadav, M. and Choudhary, R. (2023). Challenges and opportunities for agriculture in Rajasthan. *Marumegh Kisaan E-Patrika*, ISSN: 2456-2904: 8(2): 10-13.

Smart Fertilizers: Innovative Strategies for Sustainable and Ecologically Resilient Agriculture

V. D. Meena, M. L. Dotaniya, M. D. Meena, M. K. Meena, R. L. Choudhary, Harvir Singh and V. V. Singh

Abstract

Excessive use of mineral fertilizers and unsafe pesticides has caused pollution and severe health problems. In 2019, the fertilizer market was USD 95 billion and it projected that during the forecast period of 2020-2025, approximately a CAGR of 3.2% would be recorded. Fertilizers are critical to agricultural productivity. Balanced fertilization would involve both macronutrients (NPKs) and micronutrients, whereas unbalanced fertilization reduces crop yields and depletes the soil. There will be an increasing strain on global food systems soon, and agriculture will face the challenge of ensuring food safety for the growing world population. A new type of intelligent fertilizer that can control nutrient release is needed to improve nutrient use efficiency by synchronizing nutrient availability with plant needs. Agricultural soils should be used as a sink for carbon sequestration through best management practices to mitigate global greenhouse gas emissions. Smart fertilizers or smarter input management should target end-users economic benefits (i.e., farmers) to improve adaptability. In this way can we achieve sustainable agriculture and feed the next generation without damaging the environment.

Introduction

Chemical fertilizers have significant role in ensuring food security to the growing world population but, the low-average nutrient use efficiency of conventional chemical fertilizers to come up with feasible alternatives that have minimum environmental and human health hazards. Though solutions like controlled release fertilizers (CRF) and slow release fertilizers (SRF) are already in the market research efforts to develop more nutrient efficient fertilizers are still in progress throughout the world. Nano fertilizers also known as Smart Fertilizers are the new concept in the present scenario due to their smart delivery system of plant nutrients to specific targeted sites. Unlike conventional chemical fertilizers, nano-fertilizers mostly available as encapsulated nano nutrient particles, nano nutrient particles coated with polymeric film or as emulsions. Requirement of these smart fertilizers in small doses to meet the nutrient requirement may make them attractive to the farmers as farmers need to invest a lot of time in fertilizer application during each crop season. Also, usability of nano fertilizers as *in vitro* (hydroponics and aeroponics) and *in vivo*

V. D. Meena, M. L. Dotaniya, M. D. Meena, M. K. Meena, R. L. Choudhary, Harvir Singh and V. V. Singh
ICAR-Indian Institute of Rapeseed-Mustard Research, Bharatpur, Rajasthan

(soil application and foliar spray applications) makes them ideal for small home gardens too. The small dimensioned nano nutrient particles enable interaction with larger surface areas of the plant and that in turn lead to better nutrient uptake by crop plants. During the growth of crops, the release rate of nutrients is slow, reducing losses and improving the efficiency of nutrient use. In the sense of a circular economy, organic waste is produced in agricultural systems as harvest residues used to create innovative fertilizers from natural materials. There is an urgent need to ensure the sustainable intensification of agricultural systems. Compared to conventional fertilizers, quick fertilizers based on slow-release/ controlled-release or carrier delivery systems have shown to increase crop yields, soil productivity and reduce nutrient loss. By acting as a carrier matrix for nutrients and bacterial inoculants, clay, nano-clay, non-degradable and degradable polymers, and agricultural waste are suitable for the development of smart fertilizers. A smart fertilizer can be described as a type of bio-composed nanomaterial, which contains nutrients and has the capability to release those components on demand by the farmers. SMART (Specific, Measurable, Achievable, Relevant and Time-bound) fertilizers have become a viable remedy for these issues. These cutting-edge fertilizers make use of cutting-edge technology to maximize nutrient delivery, guaranteeing that plants get the proper quantity of nutrients at the appropriate time and in the most effective way possible. SMART fertilizers decrease nutrient waste, lessen environmental pollution and support healthier soil ecosystems by combining precision application methods, bio-based improvements, and controlled-release mechanisms and allow a controlled deployment of nutrients and other composites to the soil. Smart fertilizers permit farmers to control various factors related to the release of nutrients, like timing of deployment, rate, and duration of nutrient release. These fertilizers generally consist of nano-fertilizers, in the form of powder or liquid, and are delivered to the plants as per the command. These nano-fertilizers involve the synthesis of nutrients at the nanoscale and offer multiple benefits like increased crop yield, and cost-efficiency. Such fertilizers are also one of the most sustainable fertilizing solutions, which are drought resistant. The nutrient release timing of these smart fertilizers can be modified to suit different categories of crops, and it also offers adaptive features to improve the yield. Also, offer a lower environmental impact and cost efficiency. The use of smart fertilizers in the precision agricultural sector is sure to offer greater benefits to the farmers, as compared to the traditional system. One of the major benefits of smart fertilizers in the global precision agriculture market is their improved and wide-range application in the regions which generally have lower availability of water for farming. Precision agriculture, with the integration of smart fertilizers, offers a much lower consumption of water when compared to the traditional farming categories, and it offers greater crop yield with improved quality of production.

The major advantage of smart fertilizers is that they can be modified and designed to release pesticides and nutrients at fixed intervals, reducing the need for water by farms. The increasing prevalence of droughts across the globe is among the biggest challenges for farmers across the globe, which reduced the total agricultural production, and also reduced the quality of crops. Smart fertilizers represent a sustainable agricultural technology designed to deliver the exact amount of nutrients a plant needs at the precise time it needs them. This technology reduces nutrient waste by up to 40% and minimizes environmental pollution compared to traditional fertilizers. The growth in sustainable agricultural activities across the globe is also expected to expand the market demand for smart fertilizers in the precision agricultural sector. The use of precision agricultural techniques, allows the farmers to integrate new technologies, and procedures as per the change in the environmental conditions. Precision farming integrated with smart fertilizers, also helps in reducing the cost of agricultural operations, as it reduces the use of components used for farming, like reducing labor costs, and fertilizers costs. It also improves the sustainability of the farmland by reducing the use of water in agricultural areas. With the decrease in global agricultural land, the demand for more sustainable farming techniques, which can offer an improved yield of the crops, is expected to grow.

Climate smart fertilizers

Climate-smart fertilizers are not a single product but a category of nutrient technologies and application methods aimed at reducing emissions from nitrogen loss (e.g., nitrous oxide), improving nutrient use efficiency (NUE), adapting to weather variability and improving soil carbon and organic matter. These fertilizers includes:

Enhanced Efficiency Fertilizers (EEFs): Stabilized or slow-release nutrients

Bio-based Fertilizers: Organic or microbial formulations

pH-Controlled and site-specific blends: Tailored to soil conditions

Liquid and foliar fertilizers: Lower application rates, faster uptake

Principles of smart fertilizer management

The foundation of smart fertilizer use is based on the "4R Nutrient Stewardship" framework. According to the 4R principle, the usage of the correct fertilizer, in the right dose, at the right place, and at the right time gives the proper growth yield for the plants this has been established by the fertilizer business (Heffer and Prud'homme, 2010). The global food supply will be more secure if fertilization has done properly.

Right Source: Choosing suitable fertilizers according to crop and soil needs. For example: Urea for nitrogen, DAP for phosphorus, Potash for potassium etc.

Right Rate: Applying fertilizers in appropriate quantities to avoid excess or deficiency.

Right Time: Applying nutrients during critical growth stages ensures maximum absorption.

Right Place: Placing fertilizers near root zones improves nutrient uptake efficiency.

The 4R approach helps improve productivity while protecting the environment.

Types of smart fertilizers

Controlled & slow-release: Fertilizers encapsulated in polymer or resin coatings that dissolve gradually based on soil temperature or moisture. Common examples include Osmocote Smart-Release Plant Food. By maximizing nutrient management, reducing environmental impact, and enhancing crop output and quality, the use of slow-release and controlled-release fertilizers supports sustainable agriculture overall. As a result, these fertilizers are becoming more and more well-liked as an important component of modern agricultural techniques.

Nano-fertilizers: Nutrients formulated at the nanoscale, offering a higher surface area for increased solubility, diffusion, and absorption by the plant.

Smart bio-fertilizers: Liquid or powder formulations containing beneficial endophytes or microbes that enhance a plant's natural ability to fix nitrogen and resist stress.

Smart fertigation & technology

- ✓ Beyond the fertilizer itself, "smart" often refers to automated delivery systems. These integrate IoT sensors, artificial intelligence, and mobile apps to track soil conditions and inject liquid nutrients into irrigation lines precisely when required.
- ✓ For tips on how to automate your nutrient and water distribution from a smartphone:

Primary benefits

Cost efficiency: Because plants absorb the nutrients more effectively, less fertilizer is needed per acre.

Environmental protection: It heavily limits chemical runoff and water contamination caused by the 40-70% of nutrients traditionally wasted in the environment.

Reduced crop stress: Prevents issues like leaf burning and provides a steady, prolonged feeding cycle.

Controlled-release & nano-enabled fertilizers

Polymer & mineral coatings: Fertilizers (such as urea) are encased in semipermeable polymers, sulfur, or natural materials like zeolites. These materials delay and control the dissolution of nutrients so that they are delivered gradually over the crop's lifecycle.

Nano-encapsulation: Nutrients are enclosed within nanoscale capsules or matrices. This increases the surface-area-to-volume ratio, significantly boosting uptake efficiency while preventing nutrient runoff.

Biodegradable innovations: Modern solutions such as ICL's *eqo.x* technology offer rapidly biodegradable release coatings that leave no harmful microplastics in the soil.

Bio-fertilizers and microbial consortia

Microbial inoculants: Rather than synthetic chemicals, smart farming utilizes targeted strains of bacteria and fungi like *Bacillus*, *Pseudomonas*, and *Trichoderma*.

Nutrient solubilization: Phosphate-solubilizing microorganisms (PSMs) and mycorrhizal fungi

release organic acids that make locked-up micronutrients available to crops while extending root reach for water.

Soil health regeneration: These biological approaches promote beneficial microbial communities, improving overall soil structure, porosity, and resilience against droughts and salinity

AI & IoT-driven precision application

Sensor feedback loops: Internet of Things (IoT) soil sensors constantly monitor real-time parameters such as soil moisture, temperature, pH, and nitrogen-phosphorus-potassium (NPK) levels.

AI forecasting: Machine learning algorithms evaluate this field data alongside local weather patterns to predict crop nutrient demands, generating automated, targeted application maps.

Drone and automated dispensers: Advanced drones and autonomous spreaders equipped with GPS execute micro-dosing applying the exact nutrient formulation exclusively where and when it is needed.

Broader benefits for ecology and yields

Less is more: Advanced precision and controlled release can decrease overall fertilizer use by up to 40% while simultaneously maintaining or boosting crop yields.

Pollution mitigation: By preventing nutrient volatilization and leaching, smart fertilizers safeguard surrounding aquatic ecosystems from eutrophication.

Adaptability: The combination of sensor data and microbial interactions allows crops to adapt to fluctuating abiotic stresses associated with climate change.

Examples of climate-smart fertilizer technologies

Urease and Nitrification Inhibitors: Delay nitrogen loss from urea.

Coated Urea (PCU, SCU): Releases nitrogen based on soil moisture and temperature.

Liquid Organic Extracts: From compost, seaweed, or microbial sources.

Sulfur-Coated or Stabilized Fertilizers: Reduce ammonia volatilization.

Smart fertilizers available in the market

In Indian farming conditions, several smart fertilizers are available that cater to the diverse needs of farmers across different regions and cropping systems. While the adoption of smart fertilizers may vary depending on factors such as crop type, soil fertility, and local agricultural practices, the following are some examples of smart fertilizers commonly used in Indian agriculture (Table 1).



(Adopted from Divya Shanmugavel *et al*., 2023)

These smart fertilizers offer innovative solutions to improve crop productivity, sustainability and profitability in Indian farming conditions. Farmers can choose the most suitable smart fertilizers based on their crop requirements, soil characteristics, and local agro-climatic conditions to achieve optimal results and ensure the long term

Table 1: Smart fertilizers available in the market (Bind *et al.*, 2024)

Smart Fertilizer	Description	Benefits	Examples
Polymer-coated urea	Urea granules coated with polymer for controlled nitrogen release.	Reduces nitrogen losses through leaching and volatilization, improving nitrogen use efficiency (NUE) and reducing fertilizer applications.	Skysulf Urea polymer coated by Maruthi Corporation
Chelated micronutrient fertilizers	Micronutrients (e.g., iron, zinc) in chelated form for better plant uptake.	Corrects micronutrient deficiencies, enhances crop growth, yield, and quality even in high pH soils.	Mahadhan Chelated Zn as Zn-EDTA by Smartchem Technologies Limited
Slow-release fertilizers	Nutrients are released gradually, ensuring a sustained supply over time.	Minimizes nutrient losses, improves NUE, extends nutrient availability, and reduces the need for frequent applications.	Nutricote 13-11-11 Type 180 by Dhanashree agro industries
Biofertilizers	Contains beneficial microorganisms that promote nutrient availability and soil health.	Enhances soil fertility, nitrogen fixation, and phosphorus solubilization, reducing dependence on chemical fertilizers.	Mrida Rakshak Gold by Indian Organic Biofertilisers
Fertigation fertilizers	Water-soluble fertilizers used in drip irrigation systems.	Ensures precise nutrient delivery, reducing nutrient losses and improving efficiency in challenging terrains.	Polyfeed drip by Nagarjuna fertilisers and chemicals limited
Customized NPK blends	Tailored blends of nitrogen, phosphorus, and potassium to meet specific crop and soil requirements.	Provides balanced nutrition based on crop growth stages, improving yield, quality, and crop resilience.	Polyfeed 19-19-19+MEN by Nagarjuna fertilisers and chemicals limited
Soil health enhancers	Organic or bio-based products that improve soil structure and fertility.	Enhances soil health by restoring organic matter, promoting water retention, and supporting microbial activity for sustainable agriculture.	Soil Shakthi Soil Health Conditioner from Khedut fertilisers; Kohinoor-Soil Health Improver from Agri Life

health of their agricultural ecosystems.

Adaptation advantages for farmers

Climate-smart fertilizers don't just help the environment they help farmers stay profitable:

- ✓ Higher yield stability during drought or excess rain
- ✓ Reduced input waste from better targeting
- ✓ Improved soil structure and organic matter
- ✓ Access to carbon credits in some countries for using EEFs
- ✓ Polymer-Coated Urea (PCU) for phased nitrogen delivery
- ✓ PK + Zn + S Smart Blends based on soil mapping
- ✓ Stabilized Urea with NBPT for reduced losses
- ✓ Seaweed-Enhanced Liquids for stress resilience
- ✓ Customized Fertilization Plans for climate-affected zones

Environmental benefits of climate-smart fertilizers

Benefit	Impact
Lower N_2O emissions	Reduced greenhouse gas intensity from synthetic N use
Less runoff & leaching	Protects surface and groundwater from eutrophication
Soil carbon preservation	Balanced nutrition supports root biomass and humus
Reduced acidification	Better fertilizer matching minimizes soil degradation
Improved biodiversity	Soil microbes thrive under efficient nutrient regimes

Enhancement of soil health

Soil health is essential for sustainable agriculture because it directly influences plant growth, water retention, and long-term soil fertility. However, the prolonged use of conventional fertilizers, particularly those with high nitrogen content, can disrupt soil microbial communities, leading to

nutrient imbalances, increased acidity, and soil degradation. In contrast, SMART fertilizers are specifically designed to enhance and maintain soil health through several mechanisms:

Promoting microbial diversity: Many SMART fertilizers contain bio-enhancers that stimulate the growth of beneficial microorganisms such as phosphorus-solubilizing fungi (Mycorrhiza) and nitrogen-fixing bacteria (Rhizobium and Azotobacter). These microbes improve nutrient cycling, support the decomposition of organic matter, and strengthen soil structure.

Soil organic matter (SOM) enhancement: Some SMART fertilizer formulations include organic components like humic acids, seaweed extracts, and composted materials, which improve soil texture, aeration, and water-holding capacity.

Soil erosion minimization: By improving soil structure and increasing microbial activity, SMART fertilizers contribute to greater soil stability, thereby reducing erosion caused by water and wind.

Through maintaining healthy soil ecosystems, SMART fertilizers support long-term agricultural sustainability, reduce dependence on excessive chemical inputs and encourage regenerative farming practices.

Challenges in using smart fertilizers

The adoption of smart fertilizers in India faces several challenges:

Cost: The high initial cost of smart fertilizers is a barrier, especially for small farmers with limited resources.

Lack of Awareness: Many farmers are unaware of smart fertilizers and their benefits due to limited access to extension services and training.

Complex Application: Specialized equipment and technical knowledge are often required for smart fertilizers, which may be unavailable in rural areas.

Limited Availability: Access to smart fertilizers is hindered by poor distribution networks and supply chain issues in remote regions.

Traditional Practices: Farmers may resist adopting new methods due to comfort with traditional practices and insufficient support for integrating smart fertilizers.

Risk Aversion: Fear of crop damage, yield variability, and financial loss makes farmers hesitant to try unfamiliar technologies.

Data Challenges: Effective use of smart fertilizers requires data on soil, crops, and environment, which many farmers lack the resources or expertise to obtain.

Regulatory Barriers: Inconsistent regulations and lack of policy support limit the development and accessibility of smart fertilizers.

Infrastructure Gaps: Poor infrastructure, including electricity, internet, and digital devices, hampers the use of technology-dependent smart fertilizers.

Addressing these challenges will require collaborative efforts from policymakers, researchers, and agribusinesses, focusing on education, policy support, and infrastructure development.

Summary

Sustainable agricultural practices are essen-

tial to ensure food security for the rapidly growing global population. Modern food production often relies heavily on mineral fertilizers and high nutrient inputs. However, continuous use of such practices has contributed to soil degradation and the release of harmful environmental pollutants. Smart fertilizers include bio-formulations integrated with mineral particles, nano-materials and plant growth-promoting microorganisms. Research should encourage utilizing ecological interactions to enhance plant nutrient-use efficiency. Climate-smart fertilizers represent the next generation of nutrient management technologies. They combine high agronomic performance with environmental sustainability, supporting both productive agriculture and ecological health. Overall, the use of smart fertilizers in precision agriculture offers significant advantages to farmers worldwide. These fertilizers enhance crop yield and quality while lowering operational costs and reducing excessive fertilizer use. Compared to conventional fertilizers, smart fertilizers provide more efficient nutrient management option in food production.

References

Divya, S., Iryna, R., Omar, S. F., Kamaraj, S, K. (2023). Sustainable SMART fertilizers in agriculture systems: A review on fundamentals to in-field applications. *Science of The Total Environment*, 904: 166729.

Heffer, P. and Prud'homme, M. (2010). Fertilizer Outlook 2010-2014. International Fertilizer Industry Association (IFA), Paris, France.

Bindu, G. S., Madhu, Sushma, S., Vijay Kumar, S., Pratyusha Kranthi, G. S., Padmaja, B. and Suresh. K. (2024). Smart Fertilizers: Transforming Agriculture for a Sustainable Future. *Chronicle of Bioresource Management,* 8(3): 095-100.

Pre Breeding: Concept and Its Application in Crop Improvement

Anushka Kuntal, Netram and Ganga Ram

Abstract

Pre-breeding, also known as germplasm enhancement, is an essential preliminary step in plant breeding that involves the identification and transfer of useful genes from wild relatives, landraces, and other unadapted germplasm into intermediate breeding materials suitable for crop improvement. This approach helps overcome the narrow genetic base and vulnerability of modern cultivars by introducing novel traits such as resistance to diseases and pests, and tolerance to abiotic stresses like drought, salinity, and temperature extremes. Since wild species are rich reservoirs of genetic diversity but often possess poor agronomic performance, pre-breeding employs strategies such as introgression, incorporation, wide hybridization, and genetic transformation to transfer desirable traits while minimizing undesirable ones. The evaluation of genotypes under drought stress revealed that RBL112 performed superiorly in terms of field performance, physiological and biochemical traits, and gene expression, showing minimum drought damage and maximum yield. Hence, RBL112 was identified as a highly drought-tolerant and high-yielding genotype with strong potential for use in future climate-resilient breeding programs.

Introduction

Pre-breeding, It refers to all the activities designed to identify desirable characteristics and genes from unadapted genotypes that cannot be used directly in breeding programmes and to transfer these traits into an intermediate set of materials that breeders can use in future to create new varieties, it is also known as germplasm enhancement, is an important preliminary step in plant breeding that involves the identification and transfer of useful genes from unadapted or wild plant materials into forms that can be effectively used in crop improvement programs. The Term "Pre-breeding" coined by Rick (1984). Many desirable traits such as resistance to diseases, pests, and environmental stresses like drought and salinity are often found in wild relatives or traditional landraces, but these materials are generally not suitable for direct cultivation due to their poor agronomic performance. Pre-breeding helps to overcome this limitation by crossing such unadapted germplasm with cultivated varieties, followed by selection and backcrossing to eliminate undesirable traits while retaining the beneficial ones. The main objective of pre-breeding is to broaden the

Anushka Kuntal
Research Scholar, Agriculture University, Kota, Rajasthan

Netram
Farm Manager, College of Agriculture, Fatehpur-Shekhawati, SKNAU, Jobner, Jaipur, Rajasthan

Ganga Ram
Technical Assistant, Krishi Vigyan Kendra, Rajsamand, MPUAT, Udaipur, Rajasthan

Table 1: Difference between pre-breeding and traditional breeding

Basis	Pre-breeding	Traditional Breeding
Definition	Process of transferring useful genes from wild/unadapted germplasm into usable breeding material	Process of developing improved crop varieties using adapted parental lines
Purpose	To broaden the genetic base and introduce new traits	To improve yield, quality, and performance of crops
Genetic Material Used	Wild relatives, landraces, exotic and unadapted germplasm	Well-adapted, cultivated varieties and elite lines
Stage in Breeding	Preliminary/initial stage	Advanced/final stage
Type of Traits	Mainly novel traits (disease resistance, stress tolerance)	Agronomic traits (yield, quality, maturity)
Adaptability	Materials are usually poorly adapted	Materials are well adapted to local conditions
Outcome	Development of intermediate breeding lines	Development of improved varieties/hybrids
Complexity	More complex due to linkage drag and incompatibility	Comparatively simpler
Time Required	Longer duration	Relatively shorter
Example	Transfer of resistance genes from wild species	Development of high-yielding wheat or rice varieties

genetic base of crops and to develop intermediate breeding lines that possess useful traits in a more adapted genetic background. Thus, pre-breeding serves as a vital link between genetic resource conservation and practical plant breeding, ensuring the effective utilization of genetic diversity for sustainable crop improvement.

Objectives of Pre-Breeding

- ✓ Broadening the genetic base of cultivated crops by introducing diverse genes from wild and unadapted sources.
- ✓ Identification and utilization of useful genes such as resistance to diseases, pests, and tolerance to abiotic stresses (drought, salinity, heat, etc.).
- ✓ Transfer of desirable traits from wild relatives or landraces into agronomically acceptable back-grounds.
- ✓ Development of intermediate breeding material (pre-breeding lines) that can be easily used in crop improvement programs.
- ✓ Elimination of undesirable traits (linkage drag) associated with wild germplasm.
- ✓ Enhancement of genetic variability for future breeding work.
- ✓ Conservation and effective use of germplasm resources.

Need for Pre-Breeding

- ✓ Lack of sufficient genetic variability
- ✓ Increased genetic vulnerability for pests and diseases
- ✓ Climate change and global warming
- ✓ Pest and pathogen populations
- ✓ Introducing new nutritional and quality traits
- ✓ Short duration varieties.

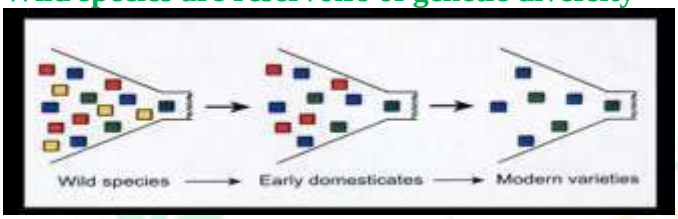
Barriers in wide hybridization

Pre-Fertilization Barriers	Post-Fertilization Barriers
Non-synchronous flowering	Failure of zygote formation
Failure of pollen germination	Failure of zygote development
Lack of stigma receptivity	Failure of seedling development
Failure of pollen tube to reach the ovary	
Failure to obtain sexual hybrids	
Non-synchronous flowering	
Failure of pollen germination	

Table 2: Wild relatives of major cereal crops and their associated stress tolerance traits used in pre-breeding

Crop	Wild Relatives	Traits (Abiotic Stress)	Traits (Biotic Stress)
Rice	*Oryza minuta* *Oryza rufipogon* *Oryza australiensis* *Porteresia coarctata* *Oryza meridionalis* *O. australiensis*	Salt tolerance, heat and cold tolerance & flooding tolerance	Blast resistance, bacterial leaf streak resistance, bacterial blight resistance, fungal diseases resistance.
Barley	*Hordeum spontaneum* *Hordeum chilense*	Drought tolerance, salt tolerance	Fusarium crown rot resistance, scald resistance, powdery mildew/leaf rust resistance.
Wheat	*Triticum dicoccoides* *Triticum aegilops* *Triticum tauschii* *Triticum monococcum* *Agropyron elongatum* *Aegilops species*	Drought tolerance, salt tolerance	Powdery mildew fungus resistance, stem rust resistance, leaf rust resistance

Wild species are reservoirs of genetic diversity



Major Approaches of Pre-Breeding

Introgression: It is the transfer of specific desirable genes from wild or unadapted species into cultivated varieties through repeated backcrossing, while retaining the main genetic background of the cultivated parent.

Incorporation: It involves the introduction and stabilization of useful traits from exotic or wild germplasm into breeding lines without necessarily repeated backcrossing, aiming to develop new usable genetic material.

Wide Crosses: Crossing between distantly related species or genera to introduce novel traits such as disease resistance, stress tolerance or quality improveement. These crosses may require special techniques due to incompatibility.

Genetic Transformation: Direct transfer of specific genes into a plant genome using biotechnological tools (e.g., genetic engineering), enabling the introduction of traits that may not be possible through conventional breeding.

Applications of Pre-Breeding

Development of disease-resistant varieties: Pre-breeding helps in transferring resistance genes from wild relatives to cultivated crops, protecting them from major diseases.

Insect and pest resistance: Useful genes for resistance against insects and pests are introduced into breeding lines.

Abiotic stress tolerance: Improves tolerance to environmental stresses such as drought, salinity, heat, and cold.

Broadening genetic base: Reduces genetic vulnerability by introducing diverse genes into cultivated crops.

Quality improvement: Enhances nutritional quality, oil content, protein content, and other desirable traits.

Yield improvement: Provides new gene combinations that can contribute to higher productivity.

A general scheme of physiological pre-breeding pipeline



Conclusion

RBL112 performed best in field, best in physiology, best in biochemical traits and best at gene expression level. It showed the lowest drought damage and highest production under water stress. RBL112 identified as most drought-tolerant and high-yielding line among all tested genotypes.

Protected Cultivation of Cucumber: Modern Technology for Sustainable and Profitable Farming

Malatesha Kenchikoppa, Mahebub Sheikh and Manjunath Sharanappa Tondihal

Introduction

Cucumber (*Cucumis sativus* L.) is one of the most important vegetable crops cultivated throughout India due to its high consumer demand, short crop duration, and attractive market price. With changing climatic conditions, increasing pest and disease pressure, and the need for year-round vegetable supply, traditional open-field cultivation is becoming more challenging. Consequently, protected cultivation has emerged as an efficient production system that provides a favorable environment for crop growth while ensuring higher productivity and better fruit quality. Protected cultivation involves growing crops under structures such as polyhouses, greenhouses, and insect-proof net houses, where temperature, humidity, irrigation, and nutrient supply can be managed efficiently. This technology enables farmers to produce high-quality cucumbers during both normal and off-seasons, thereby increasing profitability.

Protected Cultivation Structures

Protected structures protect crops from excessive rainfall, strong winds, extreme temperatures and insect vectors while creating a favorable microclimate for continuous growth. Among these, naturally ventilated polyhouses are widely adopted because they require relatively low investment and provide excellent growing conditions.



Figure 1: Protected cultivation structures commonly used for commercial cucumber production.

Why Choose Protected Cultivation?

Protected cultivation offers several advantages over open-field farming.

- ✓ Higher productivity per unit area
- ✓ Better fruit quality and uniformity
- ✓ Off-season production with premium market prices
- ✓ Reduced pest and disease incidence
- ✓ Efficient use of irrigation water and fertilizers
- ✓ Lower pesticide residue on produce
- ✓ Increased income through continuous harvesting

Under proper management, cucumber yield can be two to three times higher than under open-field conditions.

Selecting the Right Hybrid

Malatesha Kenchikoppa
Division of Vegetable Science, ICAR-Indian Agricultural Research Institute, New Delhi
Mahebub Sheikh
Division of Vegetable Crops, ICAR-Indian Institute of Horticultural Research, Bengaluru, Karnataka
Manjunath Sharanappa Tondihal
ICAR Research Complex for NEH Region, Nagaland



Figure 2: High-yielding parthenocarpic cucumber hybrids suitable for protected cultivation.

The success of protected cucumber cultivation largely depends on selecting suitable hybrids. Farmers should prefer hybrids possessing the following characteristics:

- ✓ Parthenocarpic nature (fruit development without pollination)
- ✓ Predominantly female flowering habit
- ✓ Straight, dark-green fruits
- ✓ Tender skin and excellent shelf life
- ✓ High resistance to powdery mildew, downy mildew, and viral diseases
- ✓ Long harvesting duration

These hybrids produce uniform fruits with excellent market acceptance.

Nursery Raising: Healthy seedlings are the foundation of a successful crop. Seeds should be sown in plastic protrays filled with sterilized cocopeat. Seedlings generally become ready for transplanting within 18-22 days after sowing. A healthy seedling should possess:

- ✓ 2-3 true leaves
- ✓ Well-developed roots
- ✓ Thick stem
- ✓ Disease-free appearance

Land Preparation and Planting: Raised beds improve drainage and aeration. Plastic mulch conserves moisture, suppresses weeds, and keeps fruits clean.



Figure 3: Raised beds covered with plastic mulch and drip irrigation.

Raised beds improve drainage and aeration. Plastic mulch conserves moisture, suppresses weeds, and keeps fruits clean.

Recommended spacing

- ✓ Plant-to-plant: 30-45 cm
- ✓ Row-to-row: 60-80 cm

Seedlings should be transplanted during the evening to minimize transplanting shock.

Training and Pruning: Vertical training is an essential practice in protected cultivation. The main vine is tied to a plastic string attached to overhead wires. Side shoots and flowers up to the fifth node are removed to encourage vigorous vegetative growth.



Figure 4: Vertical training of cucumber vines using overhead support

Older leaves should also be removed regul-arly to improve air circulation and reduce disease incidence. Benefits include:

- ✓ Better sunlight interception
- ✓ Improved fruit quality
- ✓ Reduced disease pressure

Table 1: Integrated Pest and Disease Management

Problem	Symptoms	Management
Whiteflies, aphids and thrips	Leaf curling and virus transmission	Install yellow and blue sticky traps, maintain sanitation, adopt need-based insecticide application
Red spider mites	Yellow speckling and webbing	Maintain adequate humidity and apply recommended acaricides when necessary
Powdery mildew	White powdery growth on leaves	Improve ventilation and use recommended fungicides
Downy mildew	Yellow angular lesions	Reduce humidity, remove infected leaves, and follow preventive fungicide sprays
Root diseases	Wilting and poor growth	Soil solarization, bioagents (*Trichoderma* spp.), and good drainage

- ✓ Easy harvesting
- ✓ Efficient use of greenhouse space

Irrigation and Fertigation: Drip irrigation combined with fertigation provides water and nutrients directly to the root zone. During early crop growth, balanced fertilizers promote vegetative development. During flowering and fruiting, potassium-rich fertilizers improve fruit size, firmness, and quality. Advantages include:

- ✓ Water savings of 30-50%
- ✓ Improved nutrient-use efficiency
- ✓ Reduced fertilizer losses
- ✓ Higher yield and fruit quality

Integrated Pest and Disease Management: Although protected cultivation reduces pest incidence, regular monitoring remains essential are given in Table 1.



Figure 5: Important pest and disease management practices under protected cultivation.

Harvesting and Post-Harvest Handling: Harvesting begins approximately 40-45 days after transplanting. Fruits should be harvested every 2-3 days while they are tender, uniformly green, and before seed hardening. Harvesting during the cool morning hours helps maintain freshness. After harvest:

- ✓ Grade fruits based on size and quality.
- ✓ Pack them in clean ventilated plastic crates.
- ✓ Avoid bruising during transport.
- ✓ Store under cool conditions to extend shelf life.



Figure 6: Harvesting and grading of premium-quality cucumbers.

Economics of Protected Cultivation: Although the initial investment for a polyhouse is higher than open-field cultivation, protected cucumber farming offers excellent economic returns. Major sources of income include:

- ✓ Higher yield
- ✓ Premium off-season prices
- ✓ Better fruit quality
- ✓ Continuous harvesting
- ✓ Reduced crop losses

Well-managed crops can produce 100-180 tonnes per hectare annually, and many growers recover their investment within two to three cropping cycles. Government subsidy programmes further encourage adoption.

Future Prospects

Protected cultivation is becoming increasingly important as climate variability, water scarcity, and market demand continue to influence vegetable production. Integration of precision irrigation, fertigation, climate sensors, automation, and digital advisory tools will further enhance productivity and resource-use efficiency. With appropriate hybrid selection and scientific crop management, protected cultivation has the potential to significantly improve farmers' income while ensuring a reliable supply of high-quality vegetables.

Conclusion

Protected cultivation has transformed cucumber production into a highly productive and profitable enterprise. By combining improved hybrids with efficient irrigation, balanced nutrition, vertical training, and integrated pest management, growers can achieve higher yields, better-quality produce, and year-round market opportunities. Wider adoption of this technology, supported by government schemes, technical guidance, and improved infrastructure, will contribute to sustainable vegetable production and enhanced farm income.

Artificial Intelligence in Vegetable Farming: Transforming the Future of Agriculture

Malatesha Kenchikoppa, Mahebub Sheikh and Manjunath Sharanappa Tondihal

Introduction

Vegetable cultivation plays a vital role in ensuring food and nutritional security while providing employment and income to millions of farming families. India is one of the world's leading producers of vegetables; however, growers continue to face challenges such as unpredictable weather, emerging pests and diseases, increasing labour costs, inefficient use of inputs, and fluctuating market prices. These factors often reduce productivity and farm profitability. The rapid advancement of digital technologies has introduced new opportunities to address these challenges.



Figure 1: Integration of Artificial Intelligence with drones, sensors, mobile applications, and precision farming technologies for efficient vegetable production.

Among these, Artificial Intelligence (AI) is gaining importance as a decision-support tool for modern agriculture. Rather than replacing farmers, AI assists them by analyzing field data and providing timely recommendations that improve crop management. Its integration with sensors, drones, satellites and smartphones is gradually transforming vegetable farming into a more precise, efficient and sustainable enterprise.

Understanding Artificial Intelligence in Agriculture: Artificial Intelligence refers to computer systems that can analyze information, identify patterns, learn from previous data, and assist in making informed decisions. In agriculture, AI combines information from weather forecasts, soil sensors, crop images, and farm records to generate practical recommendations for irrigation, nutrient management, pest surveillance, disease diagnosis, and harvesting. Unlike conventional farming practices that depend mainly on experience, AI enables farmers to take data-based decisions, reducing uncertainty and improving management efficiency.

Applications of Artificial Intelligence in Vegetable Production

Crop Monitoring: Regular monitoring is essential for maintaining healthy vegetable crops. AI-powered cameras mounted on drones or smartphones can identify changes in plant colour, growth, and canopy

Malatesha Kenchikoppa
Division of Vegetable Science, ICAR-Indian Agricultural Research Institute, New Delhi
Mahebub Sheikh
Division of Vegetable Crops, ICAR-Indian Institute of Horticultural Research, Bengaluru, Karnataka
Manjunath Sharanappa Tondihal
ICAR Research Complex for NEH Region, Nagaland

development. These observations help farmers detect crop stress at an early stage and take corrective measures before significant yield losses occur.

Early Detection of Pests and Diseases: Timely diagnosis is one of the most valuable contributions of AI in vegetable cultivation. Image recognition technologies can identify symptoms of diseases and insect damage from photographs captured in the field. Early warning systems allow farmers to implement appropriate control measures before the problem spreads across the crop. This approach is particularly useful in vegetables where diseases such as viral infections, bacterial wilt, early blight, powdery mildew, and downy mildew can cause severe economic losses if not managed promptly.



Figure 2: AI systems can detect diseases at an early stage using image recognition, enabling timely management and minimizing crop losses.

Precision Irrigation: Efficient water management has become increasingly important under changing climatic conditions. AI integrates soil moisture data, weather forecasts, and crop growth stages to determine the appropriate timing and quantity of irrigation. Such precision irrigation reduces water wastage, conserves natural resources, and maintains optimum plant growth.



Figure 3: AI-assisted irrigation scheduling based on soil moisture, weather forecasts and crop water requirements helps conserve water while maintaining optimum plant growth

Nutrient Management: Balanced fertilization is essential for achieving high productivity and quality in vegetable crops. AI analyses soil properties and crop nutrient requirements to recommend suitable fertilizer schedules. Site-specific nutrient management minimizes excessive fertilizer application, lowers production costs, and reduces environmental pollution.

Yield Forecasting: Accurate estimation of crop yield supports better planning for harvesting, transportation, storage, and marketing. AI uses historical production data, satellite imagery, weather information, and crop growth models to estimate yield well before harvest, enabling farmers to make informed marketing decisions.

Greenhouse and Protected Cultivation: Protected cultivation requires continuous monitoring of environmental conditions. AI-based systems automatically regulate temperature, humidity, ventilation, irrigation, and fertigation according to crop requirements. Such automation improves resource-use efficiency while ensuring consistent production of high-quality vegetables throughout the year.



Figure 4: Artificial Intelligence automatically regulates environmental conditions such as temperature, humidity, fertigation, and ventilation in protected cultivation systems

Weed Management: Advanced computer vision systems can distinguish weeds from crop plants with high accuracy. This enables selective weed control

through targeted herbicide application or robotic weeding, reducing labour requirements and minimizing unnecessary chemical use.

Benefits of AI in Vegetable Farming

The adoption of AI offers several advantages for vegetable growers:

- ✓ Improves decision-making through real-time information.
- ✓ Detects pest and disease outbreaks at an early stage.
- ✓ Enhances water and fertilizer use efficiency.
- ✓ Reduces production costs by minimizing input wastage.
- ✓ Improves crop quality and marketable yield.
- ✓ Supports climate-resilient production practices.
- ✓ Reduces post-harvest losses through better harvest planning.
- ✓ Increases farm profitability and resource-use efficiency.

Challenges to Adoption: Although AI has significant potential, its adoption remains limited in many regions. High investment costs, limited digital infrastructure, poor internet connectivity, lack of technical awareness and inadequate training continue to restrict widespread use. Small and fragmented landholdings also make it difficult for individual farmers to invest in advanced technologies. Strengthening extension services, improving rural digital infrastructure, and promoting affordable AI-based tools through public-private partnerships will be essential for increasing adoption.

The Road Ahead: Artificial Intelligence is expected to play a greater role in the future of vegetable production. Integration of AI with robotics, remote sensing, the Internet of Things (IoT), and precision agriculture will support more efficient crop management. AI will also contribute to vegetable breeding program-mes by analyzing large datasets to identify desirable traits, accelerating the development of climate-resilient, disease-resistant and high-yielding varieties. As digital technologies become more accessible and affordable, AI-based advisory services are likely to become an integral component of vegetable farming, benefiting both commercial growers and smallholder farmers.



Figure 5: AI, robotics, and autonomous technologies are expected to revolutionize vegetable farming by improving productivity, sustainability and profitability

Conclusion

Artificial Intelligence represents a significant step towards modernizing vegetable cultivation. By enabling timely, data-driven decisions, AI helps farmers optimize the use of water, nutrients, labour, and crop protection measures while improving productivity and profitability. Although several challenges remain, continued investment in digital infrastructure, research, and farmer capacity building will facilitate wider adoption. Harnessing the potential of AI will contribute to sustainable vegetable production, improved livelihoods, and enhanced nutritional security in the years ahead.

Integrated Crop Livestock Farming: Improving Productivity through Sustainable Agriculture and Veterinary Pharmacology

Sivaraman Ramanarayanan, Anuradha Ojha and Aakash Ojha

Abstract

Sustainable agriculture requires farming systems that improve productivity while conserving natural resources and ensuring animal health. Integrated Crop Livestock Farming (ICLF) is one such approach in which crops and livestock complement each other through efficient nutrient recycling, resource utilization, and diversified income generation. Crop residues serve as animal feed, whereas livestock manure enriches soil fertility and reduces dependence on synthetic fertilizers. Simultaneously, responsible veterinary pharmacology including rational use of antimicrobials, vaccination, and preventive healthcare ensures healthy livestock, safe food production, and reduced antimicrobial resistance. The integration of sustainable crop production with scientific livestock health management enhances farm resilience, environmental sustainability, and profitability. This article highlights the importance of integrated farming, recent technological advances, and the role of veterinary pharmacology in building climate-resilient and economically viable farming systems.

Introduction

Indian agriculture is undergoing a major transformation due to increasing pressure on natural resources, climate variability, rising production costs, and the need to produce safe food for a growing population. Intensive monocropping and excessive dependence on chemical fertilizers and pesticides have contributed to soil degradation, biodiversity loss, and environmental pollution. Likewise, irrational use of veterinary medicines has accelerated antimicrobial resistance (AMR), threatening both animal and human health.

Integrated Crop Livestock Farming (ICLF) offers an effective solution by combining crop cultivation and livestock production into a single, mutually beneficial system. Rather than operating as separate enterprises, crops and animals support one another through continuous recycling of nutrients, efficient utilization of farm resources and improved biological productivity. This farming approach aligns well with the One Health concept, recognizing the interconnectedness of human, animal and environmental health.

Crop-Livestock Integration: A Circular Farming

Sivaraman Ramanarayanan
Assistant Professor, Department of Veterinary Pharmacology and Toxicology, College of Veterinary and Animal Sciences, Kishanganj, Bihar

Anuradha Ojha
Research Scholar, Department of Microbiology, Punjab Agricultural University, Ludhiana, Punjab

Aakash Ojha
Research Scholar, Department of Agronomy, CSKHPKV, Palampur, Himachal Pradesh

Model

Integrated farming functions on the principle of a circular economy. Crop residues such as wheat straw, maize stover, rice straw, and fodder crops become valuable feed resources for livestock. In return, cattle dung, urine, and other organic wastes are converted into farmyard manure, compost, vermicompost, or biogas slurry, which replenish soil nutrients and improve soil organic carbon. This recycling process reduces external input requirements, minimizes waste, improves nutrient-use efficiency, and strengthens the sustainability of agricultural production systems. Studies have demonstrated that integrated crop-livestock systems improve overall farm productivity, enhance resilience against climatic stress, and diversify farmers' income sources.

Sustainable Agriculture: Building Healthy Soils and Crops

Healthy soils are the foundation of sustainable agriculture. Continuous application of organic manures enhances soil microbial diversity, improves aggregation, increases water-holding capacity, and promotes nutrient availability. When combined with practices such as crop rotation, conservation agriculture, integrated nutrient management, and integrated pest management (IPM), farmers can reduce dependence on synthetic fertilizers and pesticides while maintaining high crop yields. Beneficial microorganisms, including nitrogen-fixing bacteria, phosphate-solubilizing bacteria, potassium-mobilizing microbes, and plant growth-promoting rhizobacteria (PGPR), further improve nutrient acquisition and suppress several soil-borne pathogens. Such biological approaches reduce production costs and contribute to environmentally friendly agriculture. For maize-based farming systems, integrating livestock with microbial biofertilizers offers significant opportunities to improve productivity while maintaining long-term soil fertility.

Veterinary Pharmacology: Ensuring Healthy Livestock

Livestock contribute substantially to farm profitability through milk, meat, eggs, manure, and draft power. However, diseases remain a major constraint to livestock productivity. Veterinary pharmacology plays a critical role in preventing, controlling, and treating infectious and metabolic diseases. Modern veterinary healthcare emphasizes the judicious use of medicines rather than indiscriminate antibiotic application. Antibiotics should only be administered under veterinary supervision, appropriate dosages should be followed, and withdrawal periods must be observed before marketing milk, meat, or eggs. These practices reduce antimicrobial residues in food products and help combat antimicrobial resistance. Preventive healthcare including vaccination, regular deworming, biosecurity measures, balanced nutrition, and sanitation reduces disease incidence and minimizes the need for therapeutic drug use, thereby lowering production costs and improving animal welfare.

Natural Alternatives to Antibiotics

Growing concerns regarding antimicrobial resistance have accelerated interest in natural alternatives to conventional antibiotics. Herbal preparations containing garlic (*Allium sativum*), turmeric (*Curcuma longa*), neem (*Azadirachta indica*), tulsi (*Ocimum sanctum*), and aloe vera possess antimicrobial, antioxidant and immunomodulatory properties that support animal health. Similarly, probiotics and prebiotics improve intestinal microbial balance, enhance nutrient digestibility, strengthen immunity and improve growth performance in livestock. These eco-friendly approaches complement conventional veterinary medicines and promote sustainable livestock production.

Environmental and Economic Benefits

Integrated Crop Livestock Farming offers several ecological and economic advantages:

- ✓ Efficient recycling of nutrients and organic wastes.
- ✓ Reduced dependence on chemical fertilizers and purchased feed.
- ✓ Improved soil organic carbon and microbial activity.
- ✓ Diversified income from crops, milk, meat, eggs, and manure.
- ✓ Reduced greenhouse gas emissions through improved manure management.
- ✓ Greater resilience against climate variability and market fluctuations.

Biogas production from livestock manure further contributes to renewable energy generation while producing nutrient-rich slurry suitable for crop cultivation. Such circular resource utilization strengthens environmental sustainability and reduces farming costs.

One Health: Connecting Agriculture, Animals and Humans

The One Health framework recognizes that the health of people, animals, plants, and ecosystems is closely interconnected. Sustainable crop production reduces pesticide contamination, while responsible veterinary pharmacology minimizes antimicrobial resistance and drug residues in food products. Together, these practices improve food safety, environmental quality, and public health. Integrated farming therefore contributes not only to agricultural productivity but also to national goals related to food security, climate resilience, and sustainable development.

Future Prospects

Rapid advances in digital agriculture are transforming integrated farming systems. Precision agriculture, artificial intelligence, sensor-based livestock monitoring, drone technology, mobile veterinary advisory services, and climate-smart farming practices are enabling more efficient resource management and early disease detection. Future research should focus on integrating precision livestock management with biofertilizers, precision nutrient management, and disease forecasting systems to maximize productivity while minimizing environmental impacts.

Conclusion

Integrated Crop Livestock Farming represen-

ts one of the most promising pathways toward sustainable agricultural development. By linking crop production with scientific livestock management and responsible veterinary pharmacology, farmers can enhance productivity, reduce production costs, improve soil health, and safeguard animal welfare. Recycling farm resources, adopting biological inputs, and ensuring prudent use of veterinary medicines contribute to resilient farming systems capable of meeting future food demands while protecting the environment. Wider adoption of integrated farming, supported by scientific knowledge and effective extension services, will play a vital role in achieving sustainable agriculture and ensuring long-term livelihood security for farming communities.

References

Food and Agriculture Organization (FAO). *Integrated Crop-Livestock Systems*. FAO, Rome.

Sekaran, U., Lai, L., Ussiri, D. A. N., Kumar, S. aand Clay, S. (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security - A review. *Agronomy*.

Gautam, A. K., Devi, S., Mishra, R. C. and Joshi, V. (2025). Integrated crop-livestock farming systems for sustainable agricultural development in India: A review. *International Journal of Research in Agronomy*, 8(12): 1144-1148.

FAO. Sustainable Crop Production Intensification and Integrated Farming Systems.

World Organisation for Animal Health (WOAH). *Responsible and prudent use of antimicrobial agents in veterinary medicine*.

World Health Organization (WHO). *Antimicrobial resistance: Global action framework*.

Indian Council of Agricultural Research (ICAR). *Indian Farming*.

National Dairy Development Board (NDDB). *Good Dairy Farming Practices*.

Applications of Internet of Things (IoT) in Precision Pest Management

Mukesh and Mahendra

Abstract

The increasing demand for sustainable agriculture and reduced pesticide use has accelerated the adoption of digital technologies in crop protection. Among these technologies, the Internet of Things (IoT) has emerged as a transformative tool for precision pest management by enabling real-time monitoring, early pest detection, automated surveillance and data-driven decision-making. IoT integrates sensors, smart traps, weather stations, wireless communication networks, cloud computing, artificial intelligence (AI), and mobile applications to provide timely pest advisories and optimize pest management interventions. This technology improves the accuracy of pest monitoring, minimizes unnecessary pesticide applications, reduces production costs and supports environmentally sustainable agriculture. This article discusses the principles, components, benefits, challenges and future opportunities of IoT in precision pest management.

Introduction

Agriculture is increasingly challenged by insect pests, climate change, pesticide resistance, and the need for sustainable crop production. Conventional pest management mainly relies on manual field scouting and calendar-based pesticide applications, which are often labor-intensive, time-consuming, and may result in excessive pesticide use, environmental pollution and the development of insecticide resistance (Ahmed *et al.*, 2024; Rameash, 2024). These limitations have created a need for innovative technologies that enable timely and precise pest management. The Internet of Things (IoT) has emerged as a transformative technology in precision agriculture by connecting sensors, smart insect traps, weather stations, cameras, drones, and cloud-based platforms to monitor crop health and pest populations in real time (Singh and Yogi, 2022). IoT systems facilitate continuous data collection, wireless communication, and automated decision-making, allowing farmers to detect pest infestations early and implement site-specific management practices. The integration of artificial intelligence (AI) and machine learning (ML) with IoT further enhances pest identification, population estimation, outbreak forecasting, and advisory services, thereby improving the efficiency of Integrated Pest Management (IPM) (Ahmed *et al.*, 2024; Rameash, 2024). Furthermore, bibliometric analyses indicate a rapid global increase in research on IoT-based pest management, reflecting growing interdisciplinary collaboration among agricultural scientists, engineers, computer

Mukesh
Senior Research Fellow, ICAR-NDRI, Karnal, Haryana
Mahendra
Research Scholar, Department of Entomology, SKRAU, Bikaner, Rajasthan

scientists, and environmental researchers (Sugas *et al.,* 2025). This article aims to summarize recent developments in IoT-based precision pest management, discuss its concept, components, working principles, applications, and challenges, and explore future perspectives on integrating the Internet of Things (IoT) with artificial intelligence (AI) and precision agriculture to achieve sustainable and climate-resilient crop protection.

Internet of Things (IoT): Concept

The Internet of Things refers to a network of interconnected physical devices equipped with sensors, communication modules, processors and software that collect, exchange and analyze data over the internet with minimal human intervention. In agriculture, IoT enables continuous monitoring of crop health, pest populations, environmental conditions and farm operations.

Components of IoT-Based Precision Pest Management

An IoT system generally consists of the following components:

Sensors: Various sensors continuously monitor field conditions, including:

- ✓ Temperature
- ✓ Relative humidity
- ✓ Soil moisture
- ✓ Rainfall
- ✓ Wind speed
- ✓ Light intensity
- ✓ Leaf wetness

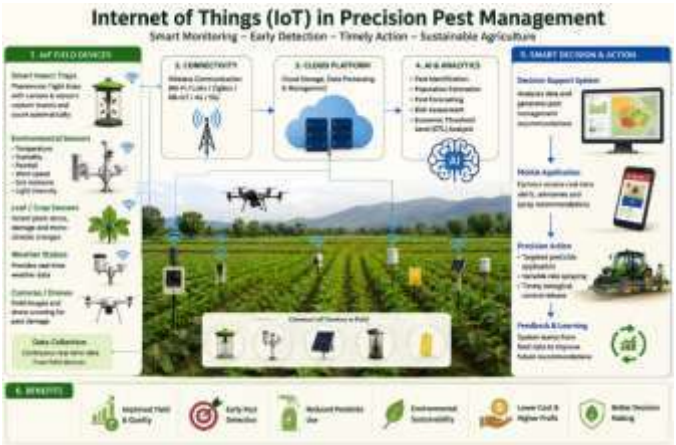
These parameters influence pest development and help predict outbreaks.

Smart Insect Traps: IoT-enabled smart traps combine pheromone or light traps with cameras and sensors to capture insects, automatically count pest populations, identify pest species using artificial intelligence (AI), and transmit real-time data for continuous monitoring and decision-making

Weather Stations: Weather data play a crucial role in forecasting pest development, migration, and its outbreaks.

Wireless Communication: Data are transmitted through wireless communication technologies such as Wi-Fi, Bluetooth, ZigBee, LoRaWAN, Narrowband Internet of Things (NB-IoT), and cellular networks (4G/5G), enabling seamless and real-time transfer of information from field devices to cloud-based platforms or monitoring systems.

Cloud Computing: Cloud platforms store and process large volumes of field data, enabling remote access and long-term analysis.



(Source: Open AI)

Artificial Intelligence: Machine learning and deep learning algorithms analyze sensor and image data to detect pests, estimate pest population density, fore-

cast potential pest outbreaks, and recommend appropriate pest management options for timely and effective crop protection.

Mobile Applications: Farmers receive pest alerts, spray recommendations, weather forecasts and decision-support advisories through smartphones and digital platforms, enabling timely and informed decision-making for effective pest management.

Working Principle

An IoT-based precision pest management system typically follows these steps:

- ✓ Sensors continuously monitor field conditions.
- ✓ Smart traps collect insect data.
- ✓ Images are transmitted to cloud servers.
- ✓ AI algorithms identify pest species and estimate abundance.
- ✓ Weather information is integrated with pest observations.
- ✓ Decision-support systems compare pest density with economic threshold levels (ETLs).
- ✓ Farmers receive real-time advisories for appropriate management actions.

Applications in Precision Pest Management

Real-Time Pest Monitoring: Continuous surveillance provides early warning before pest populations reach damaging levels. Major target pests as follows:

- ✓ Fall armyworm
- ✓ Pink bollworm
- ✓ Rice stem borer
- ✓ Brown plant hopper
- ✓ Whiteflies
- ✓ Fruit flies
- ✓ Diamondback moth
- ✓ *Helicoverpa armigera*

Automated Pest Identification: Deep learning models can identify insect species from trap images with high accuracy, reducing manual labor and improving surveillance.

Pest Forecasting: Combining weather data with historical pest records enables prediction of pest outbreaks several days or weeks in advance.

Site-Specific Pest Management: IoT allows insecticides to be applied only in infested areas, reducing pesticide use and production costs.

Resistance Management: Continuous monitoring helps detect shifts in pest populations and supports insecticide rotation to delay resistance.

Greenhouse Pest Management: IoT systems are increasingly used to monitor whiteflies, aphids, thrips, and spider mites in protected cultivation.

Integration with Integrated Pest Management (IPM)

IoT strengthens Integrated Pest Management by supporting:

- ✓ Pest surveillance
- ✓ Economic threshold-based decisions
- ✓ Biological control timing
- ✓ Pheromone trapping
- ✓ Weather-based forecasting
- ✓ Reduced pesticide applications
- ✓ Resistance management etc.

Advantages of IoT-Based Precision Pest Management

The major advantages are as follows:

- ✓ Real-time monitoring
- ✓ Early pest detection
- ✓ Reduced pesticide use
- ✓ Lower production costs
- ✓ Improved spray timing
- ✓ Accurate pest forecasting
- ✓ Better crop protectionReduced environmental pollution
- ✓ Protection of beneficial insects
- ✓ Improved farm profitability
- ✓ Data-driven decision making

Challenges

Despite its potential, several challenges limit widespread adoption:

- ✓ High initial investment
- ✓ Limited internet connectivity in rural areas
- ✓ Sensor maintenance
- ✓ Battery life constraints
- ✓ Large data management requirements
- ✓ Limited digital literacy among farmers
- ✓ AI model accuracy for diverse pest species
- ✓ Lack of standardization
- ✓ Data privacy and cybersecurity concerns

Future Opportunities

Future developments are expected to include:

- ✓ AI-powered autonomous pest diagnosis
- ✓ Digital twins for crop health simulation
- ✓ Swarm robotics for pest monitoring
- ✓ Ultra-low-power wireless sensor networks
- ✓ Edge computing for real-time analysis
- ✓ 5G-enabled smart agriculture
- ✓ Integration with climate-smart agriculture
- ✓ Farmer-friendly mobile advisory systems
- ✓ Low-cost smart traps for smallholder farmers

Case Studies

Recent studies demonstrate the practical potential of IoT-enabled precision pest management in improving pest surveillance and decision-making. For instance, Ahmed *et al.* (2024) developed an IoT-based smart insect trap integrated with convolutional neural network (CNN) models for the automatic detection of oriental fruit flies, achieving high classification accuracy under field conditions. Similarly, Rameash (2024) highlighted the integration of artificial intelligence (AI), computer vision, wireless sensor networks, unmanned aerial vehicles (UAVs), and cloud computing to enable smart pest monitoring, outbreak forecasting, and timely management interventions. These advanced digital technologies have significantly improved the accuracy and efficiency of pest detection while reducing pesticide use, production costs, and environmental impacts, thereby contributing to sustainable crop protection and enhanced agricultural productivity.

Conclusion

The Internet of Things is revolutionizing precision pest management by enabling continuous pest surveillance, real-time data collection, automated insect identification and evidence-based decision-making. By integrating sensors, smart traps, weather monitoring, artificial intelligence and cloud computing, IoT supports timely and site-specific pest management while reducing pesticide use, production costs and environmental impacts.

Although challenges related to cost, infrastructure, connectivity, and data management remain, rapid advances in digital agriculture, AI, wireless communication, and low-cost sensing technologies are expected to accelerate adoption. IoT-based precision pest management has the potential to become a cornerstone of climate-smart, sustainable and economically viable agriculture.

References

Ahmed, S., Marwat, S. N. K., Ben Brahim, G., Khan, W. U., Khan, S., Al-Fuqaha, A. and Koziel, S. (2024). IoT based intelligent pest management system for precision agriculture *Scientific Reports,* 14: 31917.

Rameash, K. (2024). Smart pest management through IoT and AI interventions. *Indian Journal of Plant Protection,* 52(3): 371-378.

Singh, G. and Yogi, K. K. (2022). Usage of Internet of Things based devices in smart agriculture for monitoring the field and pest control. In *2022 IEEE Delhi Section Conference (DELCON)* (pp. 1-6). IEEE. https://doi.org/10.1109/DELCON54057.2022.9753021

Sugas, P. N., Elaiayabharathi, T., Balaji Kannan, Murugan, M., Srinivasan, T. and Thangamani, C. (2025). IoT applications in pest management: A bibliometric perspective on global trends and One Health implications. TNAU. (Conference/Proceedings paper).

Drone-Based Phenotyping: A New Era in Plant Breeding

Mishasri D., Kavitha Reddy A., Shivani D., Amarnath K. and Rajesh Kumar K.

Introduction

Feeding a growing global population under the scenario of global climate change, depleting natural resources, and emerging pests and diseases requires development of climate resilient crop varieties at a faster pace. Plant breeding has played a crucial role in enhancing agricultural productivity, however, one of the longstanding bottlenecks in plant breeding has been phenotyping, which involves measuring a large number of plant traits. Traditional phenotyping is labour intensive, time consuming, and not always easy or accurate to perform across thousands of breeding lines and in diverse environments. Phenotyping using drones can overcome these barriers by providing information on the performance of a large number of breeding lines at different stages during crop growth, contributing to the selection of the best performing genotypes.

What is Drone-Based Phenotyping?

Drone Phenotyping uses Unmanned Aerial Vehicles (UAVs) equipped with sensors. The UAVs collect crop data from above the plants. The sensors include Red-green-blue (RGB) cameras, Hyperspectral Sensors (HSS), Multispectral Sensors (MSS), Thermal Cameras (TC), and LiDAR which create high-resolution data from crop growth. Using drones in crop phenotyping is beneficial compared to conventional methods because of the accuracy and speed in data collection.

The drone phenotyping process: Drone-based phenotyping starts with the scheduling of UAV flights over breeding trials at specific crop developmental stages. Drones capture extensive field data using cutting-edge imaging and sensing technologies. This information is then integrated with breeding databases and genomic resources, leading to faster, data-driven selection decisions and enhancing the efficacy of modern plant breeding programs.

The Technologies behind Drone Phenotyping

Category	Examples
Drone Platform	DJI Phantom, DJI Matrice
Sensors/Cameras	RGB, Multispectral, Hyperspectral, Thermal, LiDAR
Positioning System	GPS, GNSS, RTK-GPS
Flight Planning Software	Pix4D Capture, DJI Terra, Drone Deploy
Image Processing Software	Pix4D Mapper, Agisoft Metashape
Data Analysis Tools	R, Python, MATLAB
AI/ML Tools	TensorFlow, PyTorch
Cloud Platforms	Google Earth Engine, AWS, Microsoft Azure
Breeding Data Management	BMS, Field Book

Mishasri D., Kavitha Reddy A. and Shivani D.
Department of Genetics & Plant Breeding, School of Agriculture, Kaveri University, Siddipet, Telangana

Amarnath K.
Vignan Institute of Agriculture and Technology, Vignan's Foundation for Science, Technology and Research, Vadlamudi, Guntur, Andhra Pradesh

Rajesh Kumar K.
Kaveri Drone Training Academy, Kaveri University, Siddipet, Telangana

The power of drone phenotyping lies in its combination with Artificial Intelligence (AI). The latter's utilization enables the processing of large amounts of data captured by drones to quickly analyse and interpret the information in order to identify patterns important for breeding. This involves the application of machine learning and deep learning that allows accelerating the process of selection and genetic gain.

Applications of Drone-Based Phenotyping in Plant Breeding

Drone-based phenotyping allows to detect biotic and abiotic stresses at an early stage and high-throughput screening of large breeding populations in different test environments while providing information about the growth, physiological and yield-related traits, predicting the yield, monitoring the crops, studying the response to the water and nutrient supply, and other variables related to crop performance.

Challenges and Future Prospects

Regardless of its great opportunities, the use of drones in phenotyping encounters a number of challenges, including data handling and manage-ment, standardization issues, cost and the integration of phenotypic, genomic and environmental data, among others. Addressing these limitations will undoubtedly accelerate the adaption of drones in br-eeding programs. In future the combination of drones, artificial intelligence and machine learning together will cloud computing platforms and genomic will result in diital breeding. These technologies will promote the development of advanced methods and accelerate crop improvement processes resulting in thee production of climate-resilient and high-yielding crop varieties.

Conclusion

Drones are playing essential role in modern plant breeding by facilitating rapid high-throughput phenotyping of large breeding populations. This new way of collecting plant data together with artificial intelligence and genomic information will result in precision and predictive plant breeding.

References

Aalborg, T., Christiansen, M. T., Romé, H., Chawade, A., Bagge, M. and Nielsen, K. L. (2026). Drone-imaging assisted genome-wide association studies reveal key quantitative trait loci for emergence and late blight resistance in tetraploid potato. *Crop Science*, 66(2): e70261.

Aggarwal, N., Rathore, M., Jan, F., Sharma, D., Kumar, S., Thudi, M., Jighly, A., Varshney, R. K. and Mir, R. R. (2026). Harnessing artificial intelligence in plant breeding: innovations in digital phenotyping and breeding methodologies. *Theoretical and Applied Genetics*, 139(7): 188.

Dharmaraj, D., Murugasridevi, K., Karthikeyan, M. and Perumal, M. S. (2026). AI-Based Genotype-to-Phenotype Prediction in Crop Breeding. In *Plant Genomic Prediction: AI-Enhanced Models for Plant Genomics and Crop Improvement* (pp. 53-67). GB: CABI.

Gano, B., Bhadra, S., Vilbig, J. M., Ahmed, N., Sagan, V. and Shakoor, N. (2024). Drone-based imaging sensors, techniques, and applications in plant phenotyping for crop breeding: A comprehensive review. *The Plant Phenome Journal*, 7(1): e20100.

Ji, L., Wang, X., Hassan, H. and Deng, Z. (2026). A Multi-Sensor UAV Platform: Design, Testing and Application for High-Throughput Plant Phenotyping. *Drones*, 10(5): 372.

Lankada, L. B., Prasanna, G., Wasudeo, N. G., Subhasri, K., Kumar, G. H. and Rahimi, M. (2026). High throughput phenotyping techniques in accelerated plant breeding. *Journal of Crop Science and Biotechnology*, 29(2): 223-236.

Moreta, D. E., Blahut, N., Kaczmar, N., Kolkman, J. M., Bergstrom, G., Smith, M., Gore, M. A. and Nelson, R. (2026). Drone-based phenotyping of maize for multiple disease resistance and yield in breeding field trials. *The Plant Phenome Journal*, 9(1): e70079.

Pandey, K., Casas, J., Buendia, H., Jennifer, W., Mosquera, G. and Selvaraj, M. (2026). AI-Powered Yield Prediction, Bacterial Blight and Crop Health Classification in Common Bean (*Phaseolus vulgaris* L.) Using Drone RGB and Multispectral Imaging.

Wang, T., Tong, R., Xu, T., Li, Y. and Chen, Y. (2026). Artificial intelligence in plant science: From image-based phenotyping to yield and trait prediction. *Frontiers in Plant Science*, 16: 1732979.

Newer Molecule Insecticides for the Management of Emerging Invasive Insect Pests in India

Priyanka K.

Introduction

Invasive insect pests have become one of the major threats to Indian agriculture, causing significant reductions in crop yield, quality and farmers' income. Increased international trade, climate change and the movement of agricultural commodities have accelerated the introduction and establishment of several exotic insect pests in India (Early *et al.*, 2016; Paini *et al.*, 2016). Unlike native pests, invasive species often establish rapidly because they escape their natural enemies and adapt easily to new environments. Recent invasions of fall armyworm (*Spodoptera frugiperda*), tomato pinworm (*Tuta absoluta*), papaya mealybug (*Paracoccus marginatus*), rugose spiralling whitefly (*Aleurodicus rugioperculatus*) and chilli thrips (*Thrips parvispinus*) have caused substantial economic losses in cereals, vegetables, fruits and plantation crops (Sharanabasappa *et al.*, 2018; Deshmukh *et al.*, 2020). Although conventional insecticides have been widely used to manage these pests, their indiscriminate use has resulted in insecticide resistance, pest resurgence and harmful effects on beneficial organisms (Sparks and Nauen, 2015). Consequently, newer molecule insecticides with novel modes of action have emerged as effective and environmentally compatible alternatives for sustainable pest management.

Major Emerging Invasive Insect Pests in India

Fall Armyworm (*Spodoptera frugiperda*): Fall armyworm (FAW) is currently one of the most destructive invasive pests in India. First reported in Karnataka during 2018, it rapidly spread to all major maize-growing states because of its strong migratory ability and high reproductive capacity (Sharanabasappa *et al.*, 2018). The larvae feed on more than 350 host plants, with maize being the preferred crop. Severe infestations cause window-pane feeding, whorl damage and yield losses exceeding 50% under favourable conditions (Day *et al.*, 2017; Sisay *et al.*, 2019).

Tomato Pinworm (*Tuta absoluta*): *Tuta absoluta* is a serious invasive pest of tomato. The larvae mine leaves, stems and fruits, reducing photosynthetic activity and marketable yield. Because they remain protected within plant tissues, control with conventional contact insecticides is often unsatisfactory. Selective diamide insecticides and pheromone-based monitoring have improved its management (Desneux *et al.*, 2010).

Papaya Mealybug (*Paracoccus marginatus*): Papaya mealybug attacks more than 200 host plant species, including papaya, cassava, cotton and vegetables. Heavy infestations cause yellowing, stunted

Priyanka K.
Research Scholar, Department of Entomology, College of Agriculture, Central Agricultural University, Imphal, Manipur

growth and honeydew deposition, leading to black sooty mould. Although biological control has been successful, selective systemic insecticides remain important during severe outbreaks (Muniappan *et al.*, 2011).

Rugose Spiralling Whitefly (*Aleurodicus rugioperculatus*) and Chilli Thrips (*Thrips parvispinus*):

Rugose spiralling whitefly has become an important pest of coconut, banana, guava and ornamental crops, whereas chilli thrips is causing increasing damage in chilli and vegetable production. Both pests multiply rapidly and frequently develop resistance to conventional insecticides. Their effective management now depends on the selective use of insecticides integrated with biological control, crop monitoring, and resistance-management strategies (Selvaraj *et al.*, 2017). The rapid spread of these invasive pests demonstrates that traditional pest management strategies alone are no longer sufficient. Sustainable crop protection requires insecticides that are highly effective, selective and compatible with Integrated Pest Management programmes.

Why Conventional Insecticides are no longer enough

Conventional insecticides, including organophosphates, carbamates and synthetic pyrethroids, have been widely used for insect pest management for several decades. However, repeated and indiscriminate application of these insecticides has accelerated the development of insecticide resistance in many invasive pests, particularly fall armyworm, tomato pinworm and whiteflies (Gutierrez-Moreno *et al.*, 2019). Excessive pesticide use has also resulted in pest resurgence, destruction of natural enemies, contamination of soil and water, and increased pesticide residues in agricultural produce (Desneux *et al.*, 2007). These limitations have created an urgent need for insecticides with novel modes of action that are more selective, effective and environmentally safer.

Newer Molecule Insecticides: A New Era in Crop Protection

Newer molecule insecticides are designed to target specific physiological processes in insects, providing effective control at comparatively lower doses. Their unique modes of action reduce cross-resistance and improve compatibility with Integrated Pest Management (IPM) programmes. Many of these insecticides also cause rapid feeding cessation, thereby minimizing crop damage before insect mortality occurs (Sparks and Nauen, 2015) (Table 1). Among the available molecules, chlorantraniliprole has become one of the most widely recommended insecticides for managing fall armyworm and tomato pinworm. It belongs to IRAC Group 28 and acts by activating insect ryanodine receptors, leading to muscle paralysis and rapid cessation of feeding (Lahm *et al.*, 2009). Field studies have demonstrated excellent suppression of fall armyworm populations and significant yield improvement in maize (Sharanabasappa *et al.*, 2018).

Another important diamide insecticide is cyantraniliprole, which belongs to IRAC Group 28 and acts on insect ryanodine receptors.

Besides lepidopteran pests, it is also useful against some sucking pests, making it valuable in vegetable pest-management programmes (IRAC, 2024; Sparks and Nauen, 2015). Broflanilide, a recently introduced meta-diamide insecticide (IRAC Group 30), acts on γ-aminobutyric acid (GABA)-gated chloride channels and has shown excellent activity against fall armyworm, cutworms and armyworms. Its unique mode of action makes it valuable for insecticide rotation and resistance management (Nakao *et al.,* 2013). Similarly, tetraniliprole, another diamide insecticide, provides prolonged residual activity and effective suppression of lepidopteran pests at relatively low application rates. As a Group 28 diamide, it acts on insect ryanodine receptors and can be included in rotation programmes for managing invasive caterpillar pests such as fall armyworm (Richardson *et al.,* 2020; IRAC, 2024). For piercing-sucking pests, flupyradifurone (IRAC Group 4D) and sulfoxaflor (IRAC Group 4C) are useful systemic insecticides. Flupyradifurone has shown strong activity against sap-feeding insects such as whiteflies, aphids and psyllids (Nauen *et al.,* 2015), while both molecules should be rotated with other IRAC groups to delay resistance development (IRAC, 2024). Another important molecule is spinetoram, a semi-synthetic derivative of naturally occurring spinosyns. It provides rapid control of thrips, caterpillars and leaf miners and is widely used in vegetable ecosystems because of its favourable compatibility with biological control agents (Sparks *et al.,* 2008).

Advantages of Newer Molecule Insecticides

Compared with conventional insecticides, newer molecules offer several advantages that contribute to sustainable crop protection. Their novel modes of action reduce the risk of cross-resistance and improve efficacy against resistant pest populations (Sparks and Nauen, 2015). Most are effective at lower application rates, reducing pesticide load in the environment and minimizing residue levels on harvested produce. Several compounds, including chlorantraniliprole and spinetoram, are relatively selective towards beneficial insects when used according to label recommendations, making them more compatible with Integrated Pest Management (Biondi *et al.,* 2012). Another important characteristic is rapid feeding cessation. Diamide insecticides stop insect feeding soon after exposure, preventing further crop damage even before insect mortality occurs (Lahm *et al.,* 2009). In addition, newer molecules can be integrated with biological control agents, pheromone traps and cultural practices, reducing dependence on repeated pesticide applications.

Future Prospects

The future of invasive pest management lies in integrating newer insecticide molecules with precision agriculture and ecological pest management. Technologies such as drone-assisted pesticide application, artificial intelligence (AI)-based pest surveillance and RNA interference (RNAi)-based insecticides are expected to improve application efficiency while reducing environmental impacts.

Table 1: Important newer molecule insecticides for invasive pest management

Insecticide	IRAC Group	Major target pests	Key advantage
Chlorantraniliprole	28	Fall armyworm, *Tuta absoluta*	Rapid feeding cessation
Cyantraniliprole	28	Whiteflies, aphids, thrips	Broad-spectrum activity
Broflanilide	30	Armyworms, cutworms	Novel mode of action
Tetraniliprole	28	Fall armyworm	Long residual activity
Flupyradifurone	4D	Whiteflies, mealybugs	Excellent systemic action
Sulfoxaflor	4C	Aphids, thrips	Effective against resistant sucking pests
Spinetoram	5	Thrips, caterpillars	IPM compatible and rapid knockdown

Source: Adapted from Insecticide Resistance Action Committee (IRAC, 2024); Sparks and Nauen (2015)

Continuous monitoring of insecticide resistance and rotation among different IRAC mode-of-action groups will be essential to preserve the effectiveness of these valuable chemistries (IRAC, 2024). Greater emphasis on farmer awareness, pest surveillance and conservation of natural enemies will further strengthen sustainable pest management programmes.

Conclusion

The rapid spread of invasive insect pests poses a significant challenge to Indian agriculture, threatening crop productivity and food security. Conventional insecticides alone are no longer sufficient because of resistance development, environmental concerns and their adverse effects on beneficial organisms. Newer molecule insecticides, including chlorantraniliprole, cyantraniliprole, broflanilide, tetraniliprole, flupyradifurone, sulfoxaflor and spinetoram, have transformed modern pest management through their novel modes of action, higher efficacy and compatibility with Integrated Pest Management. However, their long-term effectiveness depends on responsible use, including rotation among different IRAC groups, application at recommended doses and integration with biological and cultural control methods. Adoption of these modern insecticides within an IPM framework will help safeguard Indian agriculture against emerging invasive pests while promoting sustainable crop production.

References

Biondi, A., Mommaerts, V., Smagghe, G., Viñuela, E., Zappalà, L. and Desneux, N. (2012). The non-target impact of spinosyns on beneficial arthropods. *Pest Management Science*, 68 (12): 1523-1536.

Day, R., Abrahams, P., Bateman, M., Beale, T., Clottey, V., Cock, M., Colmenarez, Y., Corniani, N., Early, R., Godwin, J., Gomez, J., Moreno, P. G., Murphy, S., Oppong-Mensah, B., Phiri, N., Pratt, C., Silvestri, S. and Witt, A. (2017). Fall armyworm: Impacts and implications for Africa. *Outlooks on Pest Management*, 28(5): 196-201.

Richardson, E. B., Troczka, B. J., Gutbrod, O., Davies, T. G. E. and Nauen, R. (2020). Diamide resistance: 10 years of lessons from lepidopteran pests. *Journal of Pest Science*, 93: 911-928.

Desneux, N., Decourtye, A. and Delpuech, J. M. (2007). The sublethal effects of pesticides on beneficial arthropods. *Annual Review of Entomology*, 52: 81-106.

Deshmukh, S., Pavithra, H. B., Kalleshwaraswamy, C. M., Shivanna, B. K., Maruthi, M. S. and Mota-Sanchez, D. (2020). First report of invasive chilli thrips, *Thrips parvispinus* (Karny) (Thysanoptera: Thripidae) in India. *Journal of Asia-Pacific Entomology*, 23(3): 714-720.

Desneux, N., Wajnberg, E., Wyckhuys, K. A. G., Burgio, G., Arpaia, S., Narváez-Vasquez, C. A., González-Cabrera, J., Catalán Ruescas, D., Tabone, E., Frandon, J., Pizzol, J., Poncet, C. and Cabello, T. (2010). Biological invasion of European tomato crops by *Tuta absoluta*: Ecology, geographic expansion and prospects for biological control. *Journal of Pest Science*, 83: 197-215.

Early, R., Bradley, B. A., Dukes, J. S., Lawler, J. J., Olden, J. D., Blumenthal, D. M., Gonzalez, P., Grosholz, E. D., Ibañez, I., Miller, L. P., Sorte, C. J. B. and Tatem, A. J. (2016). Global threats from invasive alien species in the twenty-first century and national response capacities. *Nature Communications*, 7: 12485.

Sparks, T. C. and Nauen, R. (2015). IRAC: Mode of action classification and insecticide resistance management. *Pesticide Biochemistry and Physiology*, 121: 122-128.

Nakao, T., Banba, S., Nomura, M. and Hirase, K. (2013). Broflanilide: A novel meta-diamide insecticide acting on GABA receptors. *Pest Management Science*, 69: 1081-1088.

Gutierrez-Moreno, R., Mota-Sanchez, D., Blanco, C. A., Whalon, M. E., Terán-Santofimio, H., Rodriguez-Maciel, J. C. and DiFonzo, C. D. (2019). Field-evolved resistance of the fall armyworm (*Spodoptera frugiperda*) to synthetic insecticides. *Journal of Economic Entomology*, 112(2): 792-802.

Lahm, G. P., Selby, T. P., Freudenberger, J. H., Stevenson, T. M., Myers, B. J., Seburyamo, G., Smith, B. K., Flexner, L., Clark, C. E. and Cordova, D. (2009). Insecticidal anthranilic diamides: A new class of potent ryanodine receptor activators. *Bioorganic & Medicinal Chemistry Letters*, 19(18): 5555-5559.

Muniappan, R., Shepard, B. M., Watson, G. W., Carner, G. R., Sartiami, D., Rauf, A. and Hammig, M. D. (2011). First report of the papaya mealybug, *Paracoccus marginatus*, in Indonesia and India and its successful biological control. *Florida Entomologist*, 94(4): 809-815.

Nauen, R., Jeschke, P., Velten, R., Beck, M. E., Ebbinghaus-Kintscher, U., Thielert, W., Wölfel, K., Haas, M., Kunz, K. and Raupach, G. (2015). Flupyradifurone: A brief profile of a new butenolide insecticide. *Pest Management Science*, 71(6): 850-862.

Paini, D. R., Sheppard, A. W., Cook, D. C., De Barro, P. J., Worner, S. P. and Thomas, M. B. (2016). Global threat to agriculture from invasive species. *Proceedings of the National Academy of Sciences*, 113(27): 7575-7579.

Insecticide Resistance Action Committee. (2024). *IRAC mode of action classification scheme*. https://irac-online.org

Selvaraj, K., Sundararaj, R., Venkatesan, T., Ballal, C. R., Jalali, S. K., Gupta, A., Mridula, H. K. and Lalitha, Y. (2017). Occurrence and management of rugose spiralling whitefly in India. *Current Science,* 112(8): 1594-1595.

Sharanabasappa, D., Kalleshwaraswamy, C. M., Maruthi, M. S. and Pavithra, H. B. (2018). First report of the fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), an alien invasive pest on maize in India. *Pest Management in Horticultural Ecosystems,* 24(1): 23-29.

Sisay, B., Simiyu, J., Mendesil, E., Likhayo, P., Ayalew, G., Mohamed, S., Subramanian, S. and Tefera, T. (2019). First report of the fall armyworm in Asia: Implications for integrated pest management. *Journal of Integrative Agriculture,* 18(1): 2-10.

Sparks, T. C., Dripps, J. E., Watson, G. B. and Paroonagian, D. (2008). Resistance and mode of action of spinosyn insecticides. *Pesticide Biochemistry and Physiology,* 102: 1-10.

Smart Irrigation System Using Sensors

Joy Patel, Purvi Kalal and Prempal Yadav

Introduction

Agriculture plays a vital role in ensuring food security and supporting the economy, especially in developing countries like India, where a significant portion of the population depends on farming. However, the increasing water demand, coupled with climate change and population growth, has led to serious concerns regarding water scarcity. Inefficient irrigation practices further worsen this issue, making sustainable water management a critical challenge in modern agriculture. Traditional irrigation techniques, such as flood irrigation and manual watering, are still widely used due to their simplicity and low cost. However, these methods are inefficient as they do not consider real-time soil and environmental conditions. As a result, they often lead to excessive water consumption, nutrient leaching, soil degradation and reduced crop productivity. These limitations highlight the need for more precise and efficient irrigation systems. In recent years, technological advancements have led to the development of smart irrigation systems that utilize sensors, automation, and communication technologies. These systems monitor key parameters such as soil moisture, temperature, and humidity in real time and make irrigation decisions based on predefined conditions. By supplying water only when required, they significantly improve water use efficiency and prevent over-irrigation. Smart irrigation systems are an essential component of precision agriculture, which focuses on data-driven farming practices to enhance productivity and resource efficiency. The integration of microcontrollers and IoT platforms enables remote monitoring and control, allowing farmers to manage irrigation effectively with minimal manual effort. In addition to conserving water, these systems improve crop growth and reduce operational costs. In conclusion, sensor-based smart irrigation systems offer an efficient and sustainable solution to the challenges of water scarcity and inefficient irrigation. Their adoption can play a crucial role in improving agricultural productivity while ensuring optimal utilization of water resources.

System Overview

A smart irrigation system is an automated irrigation technique that uses sensors, microcontrollers, and communication technologies to manage water supply efficiently. The system continuously collects data from the field and makes

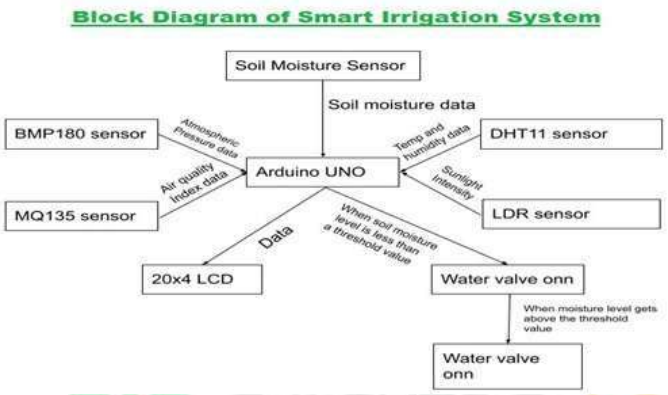
Joy Patel
B.Sc. (Hons.) Agriculture Student, Rai School of Agriculture, Rai University, Ahmedabad, Gujarat
Purvi Kalal
Assistant Professor, Department of Agronomy, Rai School of Agriculture, Ahmedabad, Gujarat
Prempal Yadav
Assistant Professor, Department of Plant Pathology, Rai School of Agriculture, Ahmedabad, Gujarat

decisions based on predefined conditions. It eliminates guesswork and ensures optimal irrigation scheduling.

Objectives

- ✓ Efficient utilization of water resources.
- ✓ Reduction in human intervention.
- ✓ Enhancement of crop yield.
- ✓ Real-time monitoring and control.

Smart Irrigation System



Components of Smart Irrigation System

Soil Moisture Sensor: Measures the volumetric water content in soil and determines irrigation need.

Temperature and Humidity Sensor: Monitors atmospheric conditions affecting evapotranspiration rate.

Microcontroller (Arduino/nodemcu): Acts as the brain of the system and processes sensor data.

Relay Module: Controls switching of the water pump.

Water Pump: Supplies water to crops automatically.

IoT Platform: Enables remote monitoring via mobile or web interface.

Working Principle

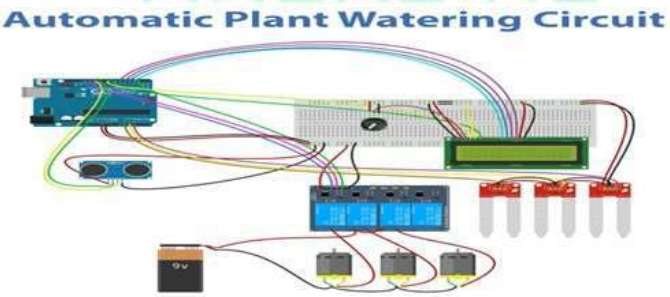
The system operates on a simple feedback control mechanism. Soil moisture is continuously monitored and compared with a predefined threshold value. When the moisture level falls below the threshold, the system activates the pump; otherwise, it remains off. This ensures that plants receive water only when necessary, avoiding over-irrigation and under-irrigation.

Working Mechanism

Methodology: The development of the smart irrigation system involves the following steps:

- ✓ Selection and calibration of sensors.
- ✓ Integration with microcontroller.
- ✓ Programming threshold conditions.
- ✓ Connecting pump via relay module.
- ✓ Testing under different soil conditions.
- ✓ Data monitoring using IoT platform.

Field testing can be conducted on different crops to analyze performance under real conditions.



Working Process

Additionally, the integration of IoT allows farmers to monitor their fields remotely, making it easier to manage large agricultural areas. The system also provides real-time alerts, improving responsiveness and decision-making.

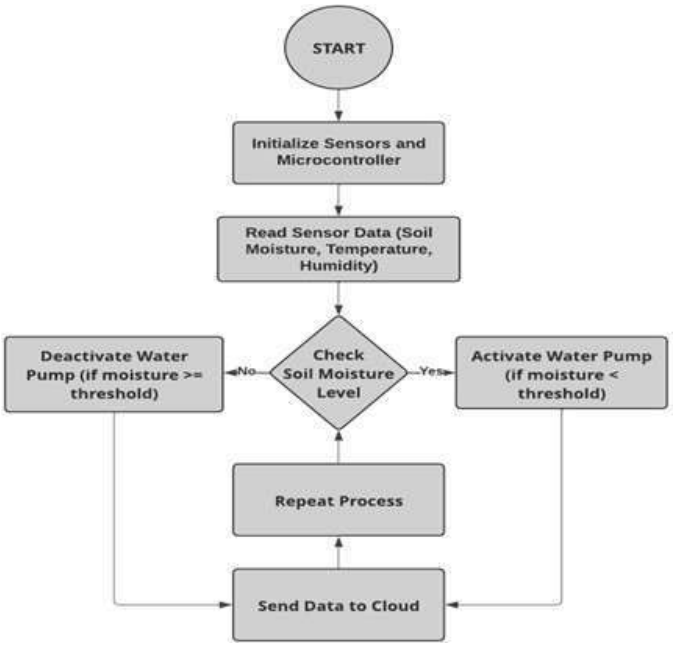
Advantages

- ✓ Maintains water Efficiency by minimizing wastage.

- ✓ Improved Crop Health by maintaining optimal soil moisture.
- ✓ Automation reduces manual intervention.
- ✓ Suitable for small and large farms.
- ✓ Enables monitoring via smartphones.

Limitations

- ✓ High initial installation cost.
- ✓ Dependence on power supply.
- ✓ Sensor degradation over time.
- ✓ Internet dependency for cloud-based systems.



Conclusion

The implementation of smart irrigation systems has shown significant improvements in water efficiency and crop productivity. Studies indicate that such systems can reduce water consumption by approximately 30-50% compared to traditional methods. The automated system ensures that irrigation is carried out based on actual soil requirements rather than fixed schedules. This prevents both water stress and waterlogging conditions, which can negatively impact plant growth.

References

Food and Agriculture Organization of the United Nations. (2021). The State of the World's Land and Water Resources for Food and Agriculture - Systems at Breaking Point. Rome: FAO.

Evans, R. G. and Sadler, E. J. (2008). Methods and technologies to improve efficiency of water use. *Water Resources Research*, 44(7): W00E04.

Ojha, T., Misra, S. and Raghuwanshi, N. S. (2015). Wireless sensor networks for agriculture: The state-of-the-art in practice and future challenges. *Computers and Electronics in Agriculture*, 118: 66-84.

Food and Agriculture Organization of the United Nations. (2017). *Water for Sustainable Food and Agriculture*. Rome: FAO.

Non-Thermal Preservation Technologies in Vegetable Science

Vignesh M., Adithya B., Aditya Yadav and Sara Kumar K.

Abstract

Fresh vegetables are highly perishable commodities that undergo rapid deterioration due to microbial growth, enzymatic activity, moisture loss, and physiological changes after harvest. Conventional thermal preservation methods effectively control spoilage microorganisms but may adversely affect nutritional quality, flavor, texture, and color. Non-thermal preservation technologies have emerged as innovative alternatives that enhance food safety and extend shelf life while maintaining fresh-like characteristics. Technologies such as high-pressure processing (HPP), pulsed electric fields (PEF), cold plasma, ultraviolet (UV-C) radiation, irradiation, ozone treatment, and ultrasound processing are increasingly being applied in vegetable preservation. These methods reduce microbial contamination, delay spoilage, and retain nutritional and sensory qualities. This article discusses the principles, applications, advantages, challenges, and future prospects of non-thermal preservation technologies in vegetable science.

Introduction

Vegetables are important sources of vitamins, minerals, antioxidants, and dietary fiber. However, their high moisture content and metabolic activity make them highly susceptible to spoilage. Traditional preservation methods such as blanching, pasteurization, and sterilization involve heat treatment, which may negatively affect nutritional and sensory properties. Consumer demand for minimally processed, fresh-like, and safe vegetables has stimulated the development of non-thermal preservation technologies. These innovative methods inactivate microorganisms and enzymes without exposing products to high temperatures. Consequently, they help maintain quality while extending shelf life. Non-thermal preservation has become an important area of research and commercial application in vegetable science.

Need for Non-Thermal preservation Technologies

Increasing consumer preference for fresh and nutritious foods has highlighted the limitations of conventional thermal processing. Heat treatments often result in loss of vitamins, pigments, flavor compounds, and textural quality. Fresh vegetables require preservation methods that ensure microbial safety while retaining nutritional value. Non-thermal technologies offer effective microbial control with minimal quality degradation. These methods support

Vignesh M.
Research Scholar, Department of Vegetable Science, Horticultural College and Research Institute, Coimbatore, Tamil Nadu
Adithya B., Aditya Yadav and Sara Kumar K.
M.Sc. Scholar, Department of Postharvest Management, Horticultural College and Research Institute, TNAU, Coimbatore, Tamil Nadu

the production of minimally processed vegetables with extended shelf life. They also reduce energy consumption and improve processing efficiency. Therefore, non-thermal preservation technologies are gaining widespread acceptance in the food industry.

High-Pressure Processing (HPP): High-pressure processing is one of the most widely adopted non-thermal preservation methods. It involves subjecting vegetables to pressures ranging from 100 to 600 MPa for a specified duration. High pressure disrupts microbial cell membranes and inactivates spoilage organisms without significant heating. HPP effectively extends shelf life while preserving texture, color, and nutritional quality. It is particularly useful for fresh-cut vegetables and vegetable-based products. The technology ensures food safety without the use of chemical preservatives. High-pressure processing is increasingly used in commercial food processing industries.

Pulsed Electric Field (PEF) Technology: Pulsed electric field technology uses short bursts of high-voltage electrical pulses to inactivate micro-organisms. The electric field causes permeabilization of microbial cell membranes, leading to cell death. PEF treatment preserves sensory and nutritional attributes because it generates minimal heat. It is especially suitable for liquid vegetable products such as juices and purees. PEF can also improve extraction efficiency of bioactive compounds from vegetables. The technology offers rapid processing and low energy requirements. Its application is expanding in modern vegetable processing indus-tries.

Cold Plasma Technology: Cold plasma is an emerging non-thermal technology that generates reactive oxygen and nitrogen species capable of destroying microorganisms. It effectively reduces bacterial, fungal, and viral contamination on vegetable surfaces. Cold plasma treatment leaves no chemical residues and causes minimal changes to product quality. It can be applied directly to fresh vegetables or packaging materials. This technology improves food safety and extends shelf life. Research has demonstrated its effectiveness against a wide range of postharvest pathogens. Cold plasma represents a promising tool for sustainable vegetable preservation.

Ultraviolet (UV-C) Radiation Treatment: Ultra-violet-C radiation is widely used for surface decontamination of fresh vegetables. UV-C light damages microbial DNA, preventing replication and growth. In addition to reducing microbial populations, UV-C treatment can stimulate natural defense mechanisms in vegetables. This process helps delay spoilage and improve storage stability. UV-C technology is simple, environmentally friendly, and chemical-free. It is commonly used for leafy vegetables, tomatoes, cucumbers, and other fresh produce. Proper dose optimization is necessary to maximize effectiveness without affecting product quality.

Ozone Treatment for Vegetable Preservation: Ozone is a powerful oxidizing agent used for micro-

bial control in fresh vegetables. It effectively destroys bacteria, fungi, viruses, and spoilage organisms. Ozone treatment can be applied in gaseous or aqueous form during washing and storage operations. It leaves no harmful residues because it rapidly decomposes into oxygen. Ozone also reduces ethylene accumulation, thereby slowing ripening and senescence. This technology enhances food safety and extends shelf life. Its eco-friendly nature makes it attractive for sustainable preservation systems.

Food Irradiation Technology: Food irradiation involves exposing vegetables to controlled doses of ionizing radiation such as gamma rays, electron beams, or X-rays. The radiation disrupts microbial DNA and inhibits pest development. Irradiation effectively reduces spoilage organisms and extends storage life. It can also delay sprouting and ripening in certain vegetables. The technology is approved in many countries and is considered safe when properly applied. Food irradiation contributes significantly to reducing postharvest losses. It remains an important non-thermal preservation method for fresh produce.

Ultrasound Processing in Vegetable Preservation: Ultrasound technology utilizes high-frequency sound waves to inactivate microorganisms and enhance preservation processes. The formation of microscopic bubbles generates mechanical and chemical effects that damage microbial cells. Ultrasound treatment can improve washing efficiency and reduce surface contamination. It is often combined with other preservation technologies to enhance effectiveness. The process preserves nutritional quality and requires relatively low energy inputs. Ultrasound has shown considerable potential for preserving minimally processed vegetables.

Advantages of Non-Thermal Preservation Technologies: Non-thermal technologies offer numerous benefits compared to conventional thermal methods. They maintain nutritional quality, color, flavor, and texture more effectively. These technologies provide efficient microbial control without extensive heat exposure. They support consumer demand for minimally processed and fresh-like products. Energy consumption is often lower than traditional thermal processing methods. Many non-thermal technologies reduce the need for chemical preservatives. Their adoption contributes to improved food safety, reduced waste, and enhanced product quality.

Challenges and Limitations: Despite their advantages, non-thermal technologies face several challenges. High equipment costs may limit adoption by small-scale processors. Some technologies require specialized infrastructure and technical expertise. Regulatory approvals and consumer acceptance vary among countries. Uniform treatment of complex vegetable surfaces can be difficult. Large-scale commercial implementation remains limited for certain technologies. Continued research is necessary to improve efficiency, reduce costs, and enhance industrial applicability. Addressing these challenges will accelerate wider adoption.

Future Prospects: Future developments in non-thermal preservation are expected to focus on integr-

ated and multifunctional technologies. Combining multiple preservation methods may enhance microbial control and shelf-life extension. Advances in automation, artificial intelligence, and sensor technologies will improve process monitoring and optimization. Research into novel plasma systems, nanotechnology-assisted preservation, and smart packaging will expand opportunities for innovation. Sustainable and energy-efficient preser-vation systems will become increasingly important. Non-thermal technologies are expected to play a major role in future vegetable preservation and food safety strategies.

Conclusion

Non-thermal preservation technologies represent a revolutionary advancement in vegetable science. Methods such as high-pressure processing, pulsed electric fields, cold plasma, UV-C radiation, ozone treatment, irradiation, and ultrasound provide effective microbial control while preserving product quality. These technologies address consumer demand for safe, nutritious, and minimally processed vegetables. Although challenges related to cost and commercialization remain, ongoing technological innovations continue to improve their feasibility and effectiveness. Non-thermal preservation will play a crucial role in reducing postharvest losses and promoting sustainable vegetable supply chains.

References

Barbosa-Cánovas, G. V. and Zhang, H. Q. (2023). Nonthermal Preservation Technologies in Food Processing. CRC Press.

FAO. (2024). Innovative Postharvest Technologies for Fresh Produce Preservation. Food and Agriculture Organization of the United Nations.

Kumar, R., Sharma, P. and Singh, A. (2024). Advances in non-thermal preservation technologies for horticultural crops. *Scientia Horticulturae*, 332: 113087.

Li, X., Wang, H. and Zhang, Y. (2024). Cold plasma applications in postharvest disease manage-ment and food preservation. *Food Control*, 163: 110532.

Meena, R. S. and Yadav, P. (2023). Emerging non-thermal technologies for fresh vegetable preservation. *Agricultural Reviews*, 44(4):, 380-396.

Singh, V., Kaur, G. and Gill, R. (2024). High-pressure processing and pulsed electric field technologies in vegetable science. *Frontiers in Sustainable Food Systems*, 8: 1365987.

Verma, N., Patel, R. and Kumar, S. (2024). Ozone and UV-C technologies for postharvest management of vegetables. *Journal of Food Science and Technology*, 61(7): 2845-2860.

Doctors Treat Disease. Farmers Prevent It: Agriculture as the Foundation of Preventive Healthcare

Navdeep Singh, Jyoti Verma, Babanjeet and Dilpreet Talwar

When we think of healthcare, images of hospitals, doctors, medicines, and diagnostic laboratories usually come to mind. These institutions play an indispensable role in treating illness and saving lives. Yet, long before a patient visits a clinic, another profession quietly shapes the health of every individual the farmer. The simple statement, "Doctors treat disease. Farmers prevent it," captures a reality that is often overlooked: good health begins not with medicine, but with food. Every meal we eat is the outcome of months of effort in the field. Farmers cultivate crops that provide carbohydrates, proteins, vitamins, minerals, and countless other nutrients essential for human growth and immunity. Without a reliable supply of safe and nutritious food, even the most advanced healthcare systems would struggle to keep populations healthy. Prevention, after all, starts on the farm.

From Traditional Farming to Modern Agriculture

Agriculture has undergone remarkable transformation over thousands of years. Early farming systems relied on crop diversity, livestock integration, natural manures, and seasonal crop rotations to maintain soil fertility. These practices created balanced agroecosystems where soil, plants, animals, and people supported one another. The agricultural revolution of the twentieth century dramatically changed this relationship. Mechanization, improved crop varieties, irrigation, and synthetic fertilizers enabled farmers to produce unprecedented quantities of food. Machines replaced much of the manual labour, and productivity increased significantly. At the same time, the cultivation of a few highly profitable crops such as wheat, rice, potato, maize, and soybean expanded rapidly, giving rise to large-scale monocropping. While this transformation greatly improved food availability, it also introduced new challenges. Continuous cultivation of the same crop reduced biodiversity, depleted soil nutrients, and increased dependence on chemical fertilizers and pesticides. Natural practices such as crop rotation, mixed farming, and the recycling of organic manure gradually declined in many farming systems.

Healthy Soil is the First Prescription: The foundation of human health lies beneath our feet. Healthy soil is much more than a medium that supports plants. It is a living ecosystem inhabited by billions of microorganisms that recycle nutrients, improve

Navdeep Singh
Department of Agriculture, Sri Guru Granth Sahib World University, Fatehgarh Sahib, Punjab
Jyoti Verma, Babanjeet and Dilpreet Talwar
Department of Vegetable Science, Punjab Agricultural University, Ludhiana, Punjab

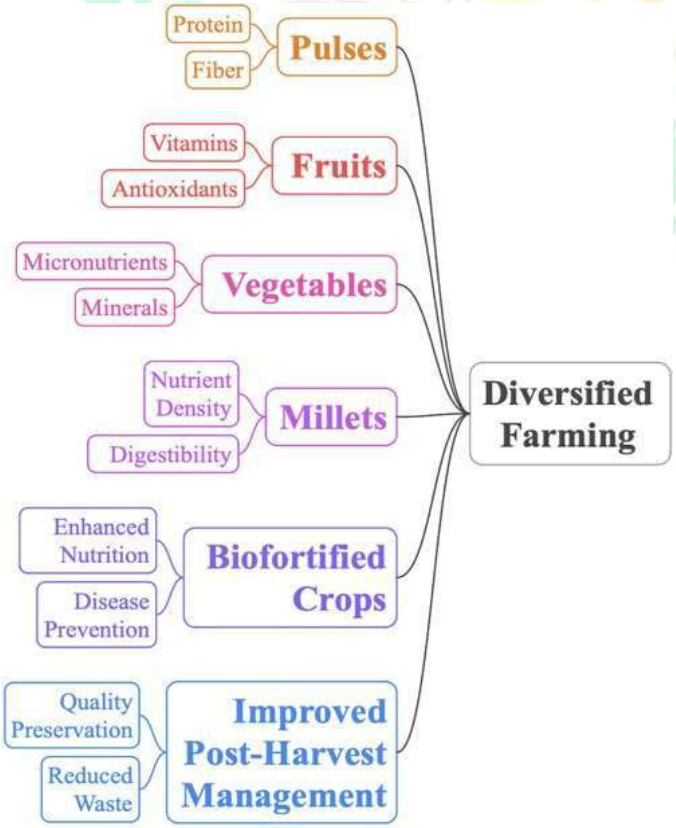
soil structure, retain water, and support vigorous crop growth. When soils are rich in organic matter and biological activity, crops are better able to absorb essential nutrients, resulting in healthier and more nutritious food. Conversely, degraded soils often produce lower yields and may compromise the nutritional value of agricultural produce. Restoring soil health has therefore become one of the most important investments in preventive healthcare. Practices such as crop rotation, conservation agriculture, integrated nutrient management, green manuring, compost application, cover cropping, and balanced fertilization help rebuild soil fertility while reducing environmental degradation. Protecting soil today means protecting public health tomorrow.

Safe Food Requires Responsible Farming: Modern agriculture has also highlighted the importance of food safety. Since the middle of the twentieth century, the use of synthetic pesticides and herbicides has expanded worldwide to protect crops from insects, weeds, and diseases. These chemicals have undoubtedly contributed to higher agricultural productivity by reducing crop losses and ensuring stable food supplies. However, excessive or indiscriminate use of pesticides can leave harmful residues in food, contaminate soil and water resources and pose risks to both farmers and consumers. Recognizing these concerns, governments and international organizations have established strict regulations governing pesticide registration, residue limits and food safety standards. Scientific evaluation, responsible product use, and continuous monitoring have become essential components of modern agriculture. Today, farmers are increasingly encouraged to adopt Integrated Pest Management (IPM), which combines biological control, cultural practices, resistant crop varieties, and judicious pesticide application. This balanced approach minimizes environmental risks while ensuring that crops remain healthy and productive. Producing food is no longer only about quantity; it is equally about safety, quality, and sustainability.

Farmers: Partners in Public Health: The role of farmers extends far beyond growing crops. Every decision made on the farm influences public health. Selecting suitable crop varieties, maintaining soil fertility, using fertilizers responsibly, conserving water, managing pests carefully, and harvesting produce at the correct stage all determine the quality of food that eventually reaches consumers. In this sense, farmers serve as the first guardians of preventive healthcare. A nutrient-rich diet reduces the likelihood of malnutrition, anaemia, obesity, diabetes, cardiovascular diseases, and several other lifestyle disorders. While doctors diagnose and manage these illnesses, farmers contri-bute by ensuring that nutritious food is available before disease develops. Their contribution becomes even more valuable during natural disasters, pandemics, or economic crises, when uninterrupted food production is critical for maintaining national health and food security.

Food Security and Human Well-being: Food security is often measured by the availability of

sufficient food, but true food security extends much further. It also requires that food be nutritious, affordable, accessible, and safe. Millions of people continue to suffer from hidden hunger caused by deficiencies of essential micronutrients despite consuming enough calories. Addressing this challenge requires agricultural systems that emphasize nutritional quality alongside productivity. Diversified farming, cultivation of pulses, fruits, vegetables, millets, biofortified crops, and improved post-harvest management all contribute to healthier diets. Such approaches not only reduce nutritional deficiencies but also lessen the burden on healthcare systems by preventing disease before medical intervention becomes necessary.



Agriculture and Healthcare must work together

For decades, agriculture and healthcare have often functioned as separate sectors despite pursuing the same objective (human well-being). A stronger partnership between farmers, agricultural scientists, nutritionists, physicians, environmental experts, and policymakers can transform preventive healthcare. Policies that encourage soil conservation, judicious pesticide use, farmer education and training, climate-resilient agriculture, nutritional security, and sustainable farming practices benefit not only agriculture but society as a whole. Investments in agricultural research and extension are, in many respects, investments in public health. As climate change, population growth, and resource scarcity place increasing pressure on food systems, this collaboration will become even more important.

Conclusion

Doctors and farmers perform different but equally essential roles. Doctors restore health when illness occurs, while farmers work tirelessly to ensure that illness is less likely to occur in the first place. Every fertile field, every healthy crop, and every nutritious meal contributes to stronger immune systems, healthier communities. Modern agriculture has achieved remarkable success in increasing food production, but the future depends on producing food that is not only abundant but also safe, nutritious, and environmentally sustainable. Protecting soil health, promoting responsible use of agricultural inputs, preserving biodiversity, and supporting farmers are all investments in preventive medicine. Doctors heal the sick, but farmers help keep societies healthy. The first step toward a healthier future is not taken inside

a hospital it begins in the soil, with the hands that grow our food.

References

Adams, J., Cotton, J. and Brumby, S. (2020). Agricultural health and medicine education Engaging rural professionals to make a difference to farmers' lives. *Australian Journal of Rural Health*, 28(4) 366-375.

Chambers, R. (1982). Health, agriculture, and rural poverty: why seasons matter. *The Journal of Development Studies*, 18(2): 217-238.

Donham, K. J. andd Thelin, A. (2016). *Agricultural medicine: Rural occupational and environmental health, safety, and prevention*. John Wiley & Sons.

Singh, N., Verma, J., Babanjeet and Talwar, D. (2026). Healthy soils, healthy future: The hidden foundation of global food security, climate resilience and sustainable agriculture. *Agri Magazine*, 3(6): 480-483.

Nursery Management of Medicinal and Aromatic Plants

Amit Kumar Tiwari, R. K. Upadhyay, Sonveer Singh, Dipender Kumar, R. C. Padalia and Amit Chauhan

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 trans-planting 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 vegetat-ively 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:

- ✓ Producing uniform & vigorous planting material

Amit Kumar Tiwari, R. K. Upadhyay, Sonveer Singh, Dipender Kumar, R. C. Padalia and Amit Chauhan
CSIR-Central Institute of Medicinal and Aromatic Plant, Research Centre Pantnagar, Uttarakhand

- ✓ 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 man-

ures, 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.

References

Atal, C. K. and Kapoor, B. M. (1989). *Cultivation and Utilization of Medicinal Plants*. Regional Research Laboratory (CSIR), Jammu, India.

Chadha, K. L. (Ed.) (2015). *Handbook of Agriculture* (6th Ed.). Indian Council of Agricultural Research (ICAR), New Delhi.

Farooqi, A. A. and Sreeramu, B. S. (2004). *Cultivation of Medicinal and Aromatic Crops*. Universities Press (India) Pvt. Ltd., Hyderabad.

Gupta, R., Sharma, S. and Singh, R. (2018). Nursery techniques for medicinal plants. *Indian Journal of Agricultural Sciences*, 88(3): 321-328.

Applications of Remote Sensing in Soil Science: Enhancing Soil Assessment and Sustainable Management

Ankit Singh, Krisanu Golui, Yogesh Rajrana and Pardeep Phogat

Abstract

Remote sensing technology has revolutionized soil science by providing scalable, non-invasive and precise methods for assessing various soil properties, including soil moisture, erosion, organic carbon content and nutrient levels. This article explores the diverse applications of remote sensing in soil science, highlighting its role in soil moisture monitoring using satellites like Sentinel-1, erosion assessment through digital elevation models and soil organic carbon estimation using hyperspectral sensors. Additionally, it delves into nutrient mapping and soil texture analysis using multispectral and radar data, which support precision agriculture practices. Remote sensing further contributes to sustainable land management by tracking degraded soil like salinity, waterlogging and drought conditions, offering crucial insights for climate change adaptation. The integration of advanced sensors and machine learning algorithms enhances the accuracy and efficiency of soil management, ensuring sustainable agricultural productivity.

Introduction

Remote sensing refers to the science and technology of acquiring information about objects or areas from a distance, typically using aircraft or satellites. It involves detecting and monitoring physical characteristics of an area by measuring its reflected and emitted radiation. This data is then used to analyse and interpret various properties of the Earth's surface, such as land cover, vegetation health, soil moisture and temperature. This technology is widely used in fields like agriculture, forestry, geology, environmental science and climate change monitoring (Abdulraheem *et al.*, 2023).



Fig. 1: Basic remote sensing process

In soil science, remote sensing applications include mapping soil properties, monitoring erosion, assessing moisture levels and tracking land degradation, contributing to sustainable land management (Fig. 1). With advancements in sensors and data processing, remote sensing provides precise, scalable and non-invasive methods to assess various soil

Ankit Singh and Krisanu Golui
Research Scholar, Department of Soil Science, CCSHAU, Hisar, Haryana
Yogesh Rajrana
Research Scholar, Department of Agricultural Meteorology, CCSHAU, Hisar, Haryana
Pardeep Phogat
Research Scholar, Division of Soil and Crop Management, ICAR-CSSRI, Karnal, Haryana

characteristics, contributing to more sustainable land and agricultural management practices (Li *et al*., 2022).

Applications

Soil moisture monitoring: One of the most critical applications of remote sensing in soil science is soil moisture monitoring. Soil moisture is a key factor in hydrological, meteorological and agricultural processes. Remote sensing technologies, such as microwave radiometry, have revolutionized this by providing large-scale and real-time soil moisture data. The Sentinel-1 and SMAP (Soil Moisture Active Passive) satellites, for instance, have enabled detailed mapping of global soil moisture patterns, facilitating better irrigation planning and drought management (Das *et al*., 2023). Recent advancements in microwave remote sensing have improved the spatial and temporal resolution of soil moisture data. For instance, passive and active microwave sensors combined with bistatic radar systems like Tandem-L are being developed to decouple soil moisture signals from other factors like surface roughness, enhancing accuracy. Moreover, advanced algorithms are being employed to extract deeper soil moisture profiles, which is essential for understanding root-zone moisture and water availability for crops.

Soil erosion and degradation assessment: Soil erosion is a major threat to agricultural productivity and environmental health. Remote sensing has been instrumental in assessing soil erosion over large areas. High-resolution satellite imagery, coupled with digital elevation models (DEMs), can detect changes in terrain that indicate erosion. Techniques like Synthetic Aperture Radar (SAR) and optical remote sensing have been widely used for this purpose. For example, multispectral sensors from Landsat and Sentinel-2 satellites provide vital data on vegetation cover, which serves as an indicator of erosion risk, while DEMs help quantify soil loss due to surface runoff (Li *et al*., 2022). In addition, the integration of remote sensing data with machine learning and digital soil mapping techniques has enabled the prediction of erosion hotspots, aiding in soil conservation efforts. Such approaches have proven effective in mapping soil erosion under different land use practices, thereby facilitating more targeted interventions (Koradia and Patel, 2024).

Soil organic carbon estimation: Soil organic carbon (SOC) is a vital component of soil fertility, impacting crop productivity and carbon sequestration. Traditional SOC measurement involves soil sampling and laboratory analysis, which are expensive and labour-intensive. Remote sensing offers an alternative by using hyperspectral and multispectral sensors to estimate SOC content across large landscapes. Hyperspectral imaging, for example, captures detailed spectral signatures of soils, which are then correlated with SOC levels. Advances in satellite platforms like the Environmental Mapping and Analysis Program (EnMAP) and the upcoming hyperspectral missions aim to improve the accuracy of SOC estimation by providing high-resolution data across the electromagnetic

spectrum. These technologies allow for the creation of SOC maps, which are essential for soil management and climate change mitigation strategies (Radocaj *et al*., 2024).

Soil classification and mapping: Soil classification, which involves categorizing soils based on their physical, chemical and biological properties, is essential for effective land management and agricultural planning. Traditional soil surveys are time-consuming and costly, but remote sensing offers an efficient alternative for large-scale soil mapping (Choudhury *et al*., 2023). Spectral reflectance data from multispectral and hyperspectral sensors can be used to identify soil types based on their unique spectral signatures. For example, hyperspectral sensors like Hyperion provide high-resolution data that can capture subtle variations in soil composition, such as organic matter content, mineralogy and moisture levels (Zhao *et al*., 2024). Machine learning algorithms have significantly improved the accuracy of soil classification from remote sensing data. Techniques such as Random Forest, Support Vector Machines (SVM) and deep learning models are now widely used to automate the classification process. These models are trained on spectral data from satellite imagery, combined with ground-truth observations, to create detailed soil maps (Pokhariyal *et al*., 2023).

Soil texture and structure analysis: Soil texture, which refers to the proportion of sand, silt and clay particles in the soil, significantly influences its physical properties, such as water retention, permeability and aeration. Remote sensing, particularly through radar and optical imagery, provides valuable data on surface roughness, which is closely related to soil texture. LIDAR (Light Detection and Ranging) and SAR sensors are being used to assess soil structure and compaction, helping to identify areas susceptible to degradation. In particular, spaceborne radar missions like TerraSAR-X and Sentinel-1 have been employed to study soil surface roughness and texture at different scales. This information is critical for modelling soil water infiltration rates and designing irrigation systems (Jena *et al*., 2023).

Precision agriculture and soil health monitoring: The advent of precision agriculture has further expanded the use of remote sensing in soil science. Precision agriculture involves managing crops at a site-specific level, optimizing inputs like water, fertilizers and pesticides based on the unique needs of different parts of a field. Remote sensing provides the necessary data to make informed decisions about soil management, enhancing both productivity and sustainability. By monitoring soil properties such as moisture content, organic matter and nutrient levels, remote sensing enables farmers to apply the right amount of water and nutrients at the right time. This not only improves crop yields but also reduces environmental impacts, such as nutrient runoff or over-irrigation. Remote sensing also supports soil health monitoring by detecting changes in soil organic carbon (SOC) levels, which are a key indicator of soil fertility and carbon sequestration potential. By combining remote sensing data with

field measurements, scientists can track SOC dynamics over time, informing efforts to improve soil health and mitigate climate change through carbon management (Pouladi *et al*., 2023).

Climate change and sustainable agriculture: With the growing concerns about climate change, remote sensing in soil science is being utilized to monitor how changing weather patterns impact soil properties. The integration of remote sensing data with climate models helps predict the effects of extreme weather events, such as droughts and floods, on soil conditions. For example, long-term soil moisture datasets derived from remote sensing can be used to study the impact of climate variability on water availability and crop production. In the context of sustainable agriculture, remote sensing helps in adopting practices that reduce the carbon footprint of farming activities. For instance, monitoring soil organic carbon and nitrogen levels via remote sensing enables more efficient nutrient management, reducing the need for chemical fertilizers. Furthermore, it assists in tracking the effectiveness of carbon sequestration efforts, which are crucial for mitigating climate change (Roy *et al*., 2023).

Conclusion

Remote sensing has emerged as a powerful tool in soil science, offering non-invasive, scalable and cost-effective methods for assessing soil properties, monitoring soil health and supporting sustainable land management practices. With continuous advancements in sensor technology and data processing techniques, remote sensing is likely to play an even more significant role in addressing global challenges such as food security, climate change and land degradation. Future research and developments, particularly in the integration of AI and machine learning with remote sensing, promise further improvements in the precision and application of this technology in soil science.

References

Abdulraheem, M. I., Zhang, W., Li, S., Moshayedi, A. J., Farooque, A. A. and Hu, J. (2023). Advancement of remote sensing for soil measurements and applications: A comprehensive review. *Sustainability*, 15(21): 1544

Koradia, A. and Patel, J. N. (2024). Erosion Risk Assessment for Prioritization of Soil and Water Conservation Measures in the Semi-Arid Region: A Remote Sensing and GIS-Based Approach. *Journal of the Indian Society of Remote Sensing*, 1-13.

Das, B., Rathore, P., Roy, D., Chakraborty, D., Bhattacharya, B. K., Mandal, D. and Kumar, P. (2023). Ensemble surface soil moisture estimates at farm-scale combining satellite-based optical-thermal-microwave remote sensing observations. *Agricultural and Forest Meteorology*, 339: 109567.

Jena, R. K., Moharana, P. C., Dharumarajan, S., Sharma, G. K., Ray, P., Deb Roy, P. and Hossain, A. (2023). Spatial prediction of soil particle-size fractions using digital soil mapping in the North Eastern Region of India. *Land*, 12(7): 1295.

Choudhury, B. U., Divyanth, L. G. and Chakraborty, S. (2023). Land use/land cover classification using hyperspectral soil reflectance features in the Eastern Himalayas, India. *Catena*, 229: 107200.

Li, T., Mu, T., Liu, G., Yang, X., Zhu, G. and Shang, C. (2022). A method of soil moisture content estimation at various soil organic matter conditions based on soil reflectance. *Remote Sensing*, 14(10): 2411.

Pokhariyal, S., Patel, N. R. and Govind, A. (2023). Machine Learning-Driven Remote Sensing Applications for Agriculture in India-A Systematic Review. *Agronomy*, 13(9): 2302.

Pouladi, N., Gholizadeh, A., Khosravi, V. and Boruvka, L. (2023). Digital mapping of soil organic carbon using remote sensing data: A systematic review. *Catena*, 232: 107409.

Radocaj, D., Gasparovic, M. and Jurisic, M. (2024). Open remote sensing data in digital soil organic carbon mapping: a review. *Agriculture*, 14(7): 1005.

Roy, A., Murtugudde, R., Narvekar, P., Sahai, A. K. and Ghosh, S. (2023). Remote sensing and climate services improve irrigation water management at farm scale in Western-Central India. *Science of The Total Environment*, 879: 163003.

Zhao, J., Du, D., Chen, L., Liang, X., Chen, H. and Jin, Y. (2024). HA-Net for Bare Soil Extraction Using Optical Remote Sensing Images. *Remote Sensing*, 16(16): 3088.

Enhancing Productivity through Smart and Sustainable Agriculture

Sudhir Kumar and Sujeet Kumar

Abstract

Smart and sustainable agriculture integrates digital technologies with ecological farming practices to increase productivity, reduce input costs, and strengthen climate resilience. This paper synthesizes core concepts, principles, and technological innovations such as precision agriculture, IoT, remote sensing, and digital advisory platforms and illustrates how their integration with sustainable practices (soil health management, crop rotation, integrated pest management, and renewable energy) can deliver measurable benefits for Indian agriculture. Case examples and policy-oriented recommendations are provided to guide researchers, extension professionals, and policymakers seeking to scale inclusive, data-driven agricultural systems.

Introduction

Agriculture is the most important sector for food, income, and employment. Agriculture and allied sector employ 42.3% workforce and contribute 18.2% in GDP. But today, the sector faces many challenges such as decreasing soil fertility, irregular rainfall, climate change, rising input costs, and post-harvest losses. To overcome these problems and increase production, we need a new approach. This approach is called smart and sustainable agriculture. It combines modern technology with eco-friendly farming practices to produce more food while protecting the environment.

Understanding Smart Agriculture

Smart agriculture refers to application of emerging technologies like AI, IoT sensors, drones, mobile apps, and robotics directly at the farm level. These tools allow farmers to make precise, data driven decision that improve yield, enhance productivity, reduce resource waste, and mitigation climate vulnerabilities. Digital infrastructure around farms includes satellite-based crop monitoring, blockchain enabled supply chains for traceability, digital marketplaces, and geotagging assets. These systems empower farmers indirectly by enhancing transparency, access to markets, and credit services. Smart agriculture increases the yield 10% to 30% or more in specific crops and regions.

Principles of Sustainable Agriculture

Sustainable agriculture focuses on long-term protection of natural resources like soil, water, and air. It encourages farmers to use organic manures, crop rotation, mulching, and natural pest control methods. These practices can improve soil health by

Sudhir Kumar
B.Sc. (Hons) Agriculture Student, Baba Raghav Das Post Graduate College, Deoria, Uttar Pradesh

Sujeet Kumar
B.Sc. (Hons) Agriculture Student, The School of Advanced Agriculture Sciences and Technology, Chhatrapati Shahu Ji Maharaj University, Kanpur, Uttar Pradesh

Integrated Approach of smart agriculture and Sustainability

Aspect	Smart Agriculture Approach	Sustainable Agriculture	Integrated Outcome
Core Principle	Optimizing efficiency and productivity through technology and data analytics.	Emphasizing ecological balance, resource conservation, and long-term soil health.	Data-driven optimization of resource use leads to enhanced efficiency while conserving natural resources.
Resource Management	Uses IoT sensors and data for precise application of water and fertilizers (Precision Farming).	Aims to minimize water waste, reduce chemical runoff, and improve soil moisture retention.	Significant reduction in water (e.g., 25% reduction in a case study) and fertilizer consumption (e.g., 30% reduction), minimizing environmental pollution.
Pest/Disease Control	Uses drones and AI for early detection and targeted intervention.	Focuses on Integrated Pest Management (IPM), using natural methods and minimizing chemical pesticides.	Reduced pesticide use, leading to healthier ecosystems and safer food, while ensuring effective crop protection.
Environmental Impact	Reduces greenhouse gas emissions by optimizing machinery usage and preventing waste.	Promotes practices like agroforestry, crop rotation, and soil conservation to sequester carbon and avoid deforestation.	Lower carbon footprint and enhanced farm resilience to climate change through data-optimized, eco-friendly practices.
Decision Making	Uses real-time data from sensors and predictive analytics to inform management decisions.	Employs traditional knowledge and holistic system understanding for long-term viability.	Empowers farmers with informed, data-driven decisions that align with long-term ecological and economic sustainability goals.
Economic Viability	Aims to increase yields and reduce operational costs through efficiency.	Seeks to ensure sustained agricultural production and improved livelihoods for farmers.	Increased profitability for farmers due to higher yields and lower input costs, making sustainability financially attractive.

increasing soil organic carbon up to 19.10% in 6-20 years, maintain biodiversity, and reduce pollution. It also promotes the use of renewable energy. Rainwater harvesting and farm ponds are useful techniques that helps to store water for irrigation during dry periods. Solar pumps, biogas plants, and solar dryers are eco-friendly alternatives that reduce greenhouse gas emissions and lower dependence on fossil fuels.

Technological Innovations Driving Productivity

E-agriculture involves the conceptualization, design, development, evaluation and application of innovative ways to use information and communication technologies (ICTs) in the rural domain, with a primary focus on agriculture. e-Soil Health card Program, Department of Agriculture, Government of India, is one of the ambitious programs which aims to analyze the soil of all the villages of the state & proposes to provide online guidance to farmers on their soil health condition, fertilizer usage and alternative cropping pattern. Precision agriculture uses tools like GPS, sensors, drones, and satellite imagery to monitor fields with high accuracy. These technologies help farmers apply the right amount of water, fertilizer, and pesticides exactly where they are needed. This reduces input costs and minimizes environmental impact. Smart irrigation systems such as drip irrigation, automated sprinklers, and IoT-based moisture monitoring help optimize water use. These systems ensure that crops receive adequate moisture without wastage.

When smart and sustainable practices are integrated, they form a strong, efficient and environment-friendly farming system. For example, using a

weather app can help farmers plan irrigation and fertilizer application based on rainfall predictions. Similarly, organic farming can be made more efficient by using modern tools and machinery. This combination not only increases yield but also preserves natural resources for future generations. Smart and sustainable agriculture is increasing income of farmers by increasing productivity.

Case Studies and Success Stories

Projects like Microsoft's AI-infused farm vibes initiative in Baramati, Maharashtra, have demonstrated the potential of AI-driven solutions achieving up to a 40 percent increase in crop yields, with 25 percent reduction in fertilizer use, and 50 percent savings in water consumption. Government initiatives like FASAL (Forecasting Agricultural Output Using Space, Agro-meteorology, and Land based observation), in collaboration with ISRO, have significantly improved the accuracy of crop forecasting and drought early warning systems. Agri-tech platforms such as Cropin and Syngenta are leveraging satellite and remote sensing data to help farmers optimize sowing schedules, irrigation, and input usage.

Platforms like Kisan Suvidha, m-Kisan empowers farmers by providing timely information on weather forecast, farm inputs, market trends, insurance, and other essential services it reaches over 8.93crore farm families, delivering customized advisories in local languages.

Under Namo Drone Didi Yojna, 15,000 women led SHGs are being empowered with Agri drones enabling smart spraying, Higher productivity and stronger rural livelihoods.

Conclusion

Indian agriculture is witnessing a profound transformation-from age-old traditional methods to a modern, data-driven ecosystem. With the Integration of technologies such as Artificial Intelligence, the Internet of Things, drones, satellite imaging, and blockchain, farming is becoming more precise, sustainable, and profitable. These innovations are enhancing productivity, reducing input costs, and empowering farmers with timely information and better market access. With continued investment in digital infrastructure, localized training, and inclusive policy support, India can ensure that the benefits of digital agriculture reach every corner of the country.

Artificial Intelligence: The New Guardian of Soil Health for Sustainable Agriculture

Supriya M. E., Nayana H. N. and Shruthi G. S.

Introduction

Soil is one of the most valuable natural resources on Earth. It not only supports plant growth but also stores water, recycles nutrients, sustains billions of microorganisms, regulates the carbon cycle and maintains environmental balance. Nearly all the food consumed by humans depends directly or indirectly on healthy soil, making soil conservation essential for sustainable agriculture and global food security (Schweng *et al.,* 2026 and Kopittke *et al*., 2019). Today, however, soils across the world are facing serious threats due to erosion, nutrient depletion, salinity, acidification, contamination, organic matter loss and climate change. These problems reduce soil productivity, increase cultivation costs and threaten long-term agricultural sustainability. Conventional soil testing remains an important tool for assessing soil fertility, but laboratory analyses are often time-consuming, costly and unable to capture the large variability that exists within individual fields (Kikis and Antoniadis, 2026; Rahman and Das, 2025). The rapid development of Artificial Intelligence (AI) is opening a new era in soil science. AI enables computers to learn from large datasets, recognize complex relationships, predict future conditions and assist farmers in making better management decisions (Schweng *et al.,* 2026). Instead of replacing soil scientists or farmers, AI functions as an intelligent decision-support system that combines information from soil tests, satellite images, drones, sensors, weather stations and crop records to provide accurate and timely recommendations (Minasny *et al.*, 2026).

Why does soil science need artificial intelligence?

Agricultural soils are highly dynamic. Soil moisture changes daily, nutrient availability varies with crop growth and microbial activity and environmental conditions continuously influence soil fertility. Managing such a complex system through periodic laboratory testing alone has become increasingly difficult (Abdulrahee *et al.,* 2023). Modern agriculture also generates enormous amounts of information from satellites, drones, sensors, weather stations and digital farm records. Analysing these large datasets manually is practically impossible. Artificial Intelligence overcomes this challen-

Supriya M. E.
Assistant Professor, Department of Soil Science and Agricultural Chemistry, GPS Institute of Agricultural Management, Peenya, Bangalore, Karnataka
Nayana H. N.
Research Scholar, Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bengaluru, Karnataka
Shruthi G. S.
Senior Research Fellow, Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bengaluru, Karnataka

ge by processing vast amounts of information within seconds and converting them into practical recommendations for nutrient management, irrigation, crop planning and soil conservation (Rahman and Das, 2025).

AI helps answer questions such as:

- ✓ Which part of the field requires more fertilizer?
- ✓ When should irrigation be applied?
- ✓ Which soil is becoming saline?
- ✓ Where is soil organic carbon declining?
- ✓ Which crop is most suitable for a particular field?

Thus, AI transforms soil testing from a diagnostic practice into a predictive and decision-support system capable of improving both productivity and sustainability (Schweng *et al.*, 2026).

Artificial Intelligence Technologies Used in Soil Science

Artificial Intelligence is supported by several modern technologies that work together to understand soil conditions more efficiently than conventional methods.

Machine Learning: Machine Learning (ML) is the most widely used branch of AI in soil science. It learns from historical soil data and identifies relationships between soil properties, climate, crop performance and management practices (Wadoux *et al.*, 2020). Algorithms such as Random Forest, Support Vector Machine and Artificial Neural Networks are commonly used to predict soil organic carbon, pH, nutrient availability, soil moisture, texture and crop productivity. Among these, Random Forest has emerged as one of the most reliable algorithms because of its high prediction accuracy (Schweng *et al.*, 2026; Kikis and Antoniadis, 2026).

Remote Sensing and GIS: Remote sensing allows scientists to monitor soil and crop conditions using satellite imagery. Geographic Information Systems (GIS) combine these images with climate, topography and soil data to generate highly detailed soil maps. AI analyses these datasets to identify nutrient-deficient areas, soil erosion, moisture stress and land degradation over large agricultural regions (Rahman and Das, 2025).

Drone Technology: Unmanned Aerial Vehicles (UAVs), commonly known as drones, capture high-resolution images of agricultural fields. AI analyses these images to detect soil variability, crop stress, nutrient deficiencies, poor drainage and early signs of pest or disease attack. Drone-based monitoring enables farmers to identify problems quickly and manage fields more precisely (Gowda *et al*., 2025).

Internet of Things (IoT) and Soil Sensors: IoT-enabled soil sensors continuously monitor soil moisture, temperature, pH, electrical conductivity and nutrient status (Ullo et al., 2021). The collected data are transmitted to cloud-based platforms, where AI analyses the information and provides recommendations for irrigation and fertilizer application. Real-time monitoring allows farmers to respond immediately to changing soil conditions, improving both resource use efficiency and crop productivity (Barath Gowda *et al*., 2025).

Applications of Artificial Intelligence in Soil Science

Digital Soil Mapping: Traditional soil surveys require extensive field sampling and years of laboratory work. Artificial Intelligence has transformed this process through Digital Soil Mapping (DSM), where machine learning combines satellite images, terrain information, climate data and existing soil observations to generate highly detailed maps of soil properties. These maps assist farmers and planners in identifying soil constraints and selecting suitable crops for different locations (Adeniyi *et al.*, 2024; Schweng *et al.*, 2026).

Precision Nutrient Management: One of the greatest advantages of AI is its ability to recommend site-specific nutrient management. Instead of applying the same fertilizer dose across an entire field, AI identifies nutrient-deficient zones and recommends the right fertilizer source, dose, timing and placement. This improves fertilizer use efficiency, reduces production costs and minimizes nutrient losses to the environment (Rahman and Das, 2025).

Soil Moisture and Irrigation Management: Water is becoming an increasingly scarce resource in agriculture. AI integrates weather forecasts, soil texture, evapotranspiration and sensor data to predict soil moisture and schedule irrigation efficiently. Such systems reduce water wastage, conserve groundwater and improve crop productivity, especially in drought-prone regions (Kikis and Antoniadis, 2026).

Monitoring Soil Organic Carbon: Soil Organic Carbon (SOC) plays a crucial role in maintaining soil fertility and mitigating climate change. AI analyses satellite observations, land-use history and field measurements to estimate SOC stocks and monitor changes over time. These assessments support carbon sequestration programmes, climate-smart agriculture and sustainable land management (Schweng *et al.*, 2026).

Detection of Soil Degradation and Contamination : Artificial Intelligence also assists in identifying soil degradation caused by salinity, erosion, heavy metal contamination and poor land management. Early detection enables timely corrective measures, helping protect soil productivity, environmental quality and human health (Kikis and Antoniadis, 2026).

Benefits, Challenges, Future Prospects and Conclusion

Benefits of Artificial Intelligence in Soil Science

Artificial Intelligence is transforming soil science from a descriptive discipline into a predictive and decision-support science. By integrating information from laboratory analyses, remote sensing, drones, IoT sensors and weather databases, AI helps farmers and researchers make faster, more accurate and economically beneficial decisions. Unlike conventional soil management, AI continuously analyses new data and provides real-time recommendations, making agriculture more efficient and sustainable (Schweng *et al.*, 2026; Kikis and Antoniadis, 2026). Some of the major advantages of AI in soil science include:

Rapid soil assessment: AI analyses large datasets within minutes, considerably reducing the time

required for conventional laboratory interpretation (Rahman and Das, 2025).

Precision nutrient management: Site-specific fertilizer recommendations improve nutrient use efficiency, reduce fertilizer costs and minimize environmental pollution (Schweng *et al.*, 2026).

Efficient irrigation management: AI-based soil moisture prediction supports scientific irrigation scheduling, helping conserve water and improve crop productivity (Kikis and Antoniadis, 2026).

Digital soil mapping: Machine learning creates accurate soil maps that support crop planning, land capability assessment and sustainable land-use decisions (Schweng *et al*., 2026).

Climate-smart agriculture: AI assists in monitoring soil organic carbon, carbon sequestration, greenhouse gas mitigation and climate-resilient farming (Schweng et al., 2026).

Improved decision-making: AI provides timely recommendations for fertilizer application, irrigation scheduling, soil conservation and crop selection, thereby reducing production risks (Rahman and Das, 2025).

Overall, AI enables farmers to apply the right input, at the right place, at the right time and in the right quantity, which is the foundation of precision agriculture.

Challenges in Adopting Artificial Intelligence

Despite its enormous potential, several factors limit the large-scale adoption of AI in soil science.

Availability of quality data: AI models require large, accurate and representative datasets for reliable predictions. In many regions, particularly in developing countries, soil information is still limited or inconsistent (Schweng *et al*., 2026).

Regional variability: Models developed using data from Europe or North America may not perform equally well under tropical soils because of differences in climate, parent material and management practices (Schweng *et al.*, 2026).

Black-box nature of AI: Advanced machine learning models often generate highly accurate predictions without clearly explaining how decisions are made. This reduces user confidence and highlights the need for Explainable Artificial Intelligence (XAI) (Kikis and Antoniadis, 2026).

Infrastructure and cost: Adoption of AI requires reliable internet connectivity, digital infrastructure, sensors, drones and computing facilities, which may not always be affordable for smallholder farmers (Rahman and Das, 2025).

Need for skilled manpower: Effective implementation of AI requires collaboration among soil scientists, agronomists, computer scientists, engineers and extension personnel (Minasny *et al.*, 2026).

Future Prospects

Artificial Intelligence is evolving rapidly beyond simple prediction models toward intelligent systems capable of scientific reasoning and autonomous decision support. One promising development is the Digital Soil Twin, a virtual representation of real soil that continuously receives information from sensors, satellites, weather stations and labora-

tory analyses. Such systems allow farmers and scientists to simulate fertilizer strategies, irrigation schedules and crop rotations before implementing them in the field, thereby reducing risk and improving resource-use efficiency (Minasny *et al.*, 2026). Another emerging technology is Generative Artificial Intelligence, where Large Language Models (LLMs) assist farmers by interpreting soil test reports, answering technical questions, preparing advisory notes and generating educational materials. However, these systems should complement rather than replace scientific expertise because recommendations must always be validated by domain experts (Kikis and Antoniadis, 2026).

The latest advancement is Multi-Agent Artificial Intelligence, in which multiple intelligent software agents work together to analyse field data, interpret remote sensing information, generate research hypotheses, design experiments and support scientific discovery. These systems are expected to accelerate soil research and improve interdisciplinary collaboration while maintaining human oversight (Minasny *et al.*, 2026).

Artificial Intelligence in Indian Agriculture

India's agriculture is characterized by diverse soils, climates and cropping systems. Such variability makes AI particularly valuable for improving soil and crop management. AI can strengthen existing programmes such as the Soil Health Card Scheme, Digital Agriculture Mission, precision farming initiatives and climate-smart agriculture by providing site-specific fertilizer recommendations, irrigation scheduling, digital soil mapping, soil degradation monitoring and carbon management. With increasing access to smartphones, cloud computing, satellite services and digital advisory platforms, AI has the potential to improve fertilizer use efficiency, conserve water, enhance soil health and increase farm profitability across both small and large farms.

Conclusion

Artificial Intelligence is redefining the future of soil science by integrating digital technologies with traditional soil knowledge. Machine learning, remote sensing, drones, IoT, digital soil mapping and intelligent decision-support systems enable faster soil assessment, precise nutrient management, efficient water use and improved monitoring of soil health. Although challenges such as data availability, infrastructure, model transparency and digital literacy remain, continuous advances in AI are making these technologies increasingly accessible and reliable. The future of soil science will depend not only on healthy soils but also on intelligent technologies that support sustainable land management. Importantly, AI should be viewed as an assistant rather than a replacement for soil scientists and farmers. The combination of scientific expertise, field experience and Artificial Intelligence offers the best opportunity to conserve soil resources, improve agricultural productivity and ensure food security for future generations (Minasny *et al.*, 2026).

References

Abdulraheem, M. I., Zhang, W., Li, S., Moshayedi,

A. J., Farooque, A. A. and Hu, J. (2023). Advancement of remote sensing for soil measurements and applications: A comprehensive review. *Sustainability*, 15(21): 15444.

Barath Gowda, H., Divya, D. and Kumar, A. (2025). Artificial intelligence in soil analysis. Agriculture Forum for Technical Education of Farming Society, Kota, Rajasthan.

Kopittke, P. M., Menzies, N. W., Wang, P., Mckenna, B. A. and Lombi, E. (2019). Soil and the intensification of agriculture for global food security. *Environment International*, 132: 105078.

Minasny, B., Mcbratney, A., Demattê, J. A. M., Román Dobarco, M. and Smith, P. (2026). Enhancing soil science research with multi-agent artificial intelligence systems. *Fronties in Science*, 4: Article 1721295.

Rahman, R. and Das, K. N. (2025). Artificial intelligence and machine learning in soil analysis for precision agriculture: A review. *Journal of Experimental Agriculture International*, 47(5): 511-524.

Ullo, S. L. and Sinha, G. R. (2021). Advances in IoT and smart sensors for remote sensing and agriculture applications. *Remote Sensing*, 13 (13): 2585.

Wadoux, A. M., Minasny, B. and Mcbratney, A. B. (2020). Machine learning for digital soil mapping: Applications, challenges and suggested solutions. *Earth-Science Reviews*, 210: 103359.

Adeniyi, O. D., Bature, H. and Mearker, M. (2024). A systematic review on digital soil mapping approaches in lowland areas. *Land*, 13: 379.

Schweng, S., Bernardini, L., Keiblinger, K., Kaul, H.-P., Fister Jr., I., Lukač, N., Del Ser, J. and Holzinger, A. (2026). What can artificial intelligence do for soil health in agriculture? *Computer Science Reviews*, 59: 100832.

Kikis, C. and Antoniadis, V. (2026). Benefits and challenges of artificial intelligence in soil science-A review. *Land*, 15(2): Article 331.

Biofortification: Genetic Enhancement of Iron and Zinc in Millets

Hetvi Butani, Devangi Kachot, Janvi Patoliya and Dhruvi Nariya

Abstract

Micronutrient deficiencies, particularly iron and zinc, affect billions worldwide and contribute to anemia, stunting, and poor immunity. Biofortification - genetic enhancement of crops, offers a sustainable solution by enriching staple foods with essential nutrients. Millets such as pearl millet (*Pennisetum glaucum*) and finger millet (*Eleusine coracana*) are ideal candidates due to their resilience and natural nutrient richness. Genetic studies reveal high heritability and positive correlation between iron and zinc traits, enabling simultaneous improvement through QTL mapping, marker-assisted selection, and hybrid breeding. Successful varieties like *Dhanashakti* demonstrate the potential of biofortification to improve nutrition without yield penalties. Despite challenges of bioavailability and farmer awareness, biofortification remains a cost-effective, farmer-friendly, and climate-resilient strategy to combat hidden hunger and strengthen food security.

Introduction

Definition: Biofortification is the process of increasing the nutritional value of crops through genetic improvement, focusing on essential micronutrients like iron and zinc.

Why Millets?

Millets (pearl millet, finger millet, foxtail millet, *etc*.) are staple foods in semi-arid regions. They are naturally rich in micronutrients and resilient to drought, making them ideal candidates for biofortification.

Biofortification is a sustainable approach to improve the nutritional quality of food crops by enhancing micronutrient content through breeding. Millets, especially pearl millet (*Pennisetum glaucum*) and finger millet (*Eleusine coracana*), are ideal candidates because they are naturally nutrient-rich and resilient to drought. Enhancing their iron (Fe) and zinc (Zn) content addresses hidden hunger, particularly anemia and zinc deficiency, which affect millions in India and Africa (Saltzman *et al*., 2013).

Genetic Basis

Iron and zinc traits in millets are polygenic with high heritability (>80-90%), making them amenable to selection (Kumar *et al*., 2016). Studies show a strong positive correlation ($r \approx 0.8$) between Fe and Zn, allowing simultaneous improvement (Kanatti *et al.*, 2016).

QTL Mapping: Quantitative trait loci (QTLs) for Fe and Zn have been identified in pearl millet, especially on chromosomes 4, 5, and 7 (Kumar *et al.*, 2016).

Candidate Genes: Genes related to metal ion binding, transporters, and Myb transcription factors

Hetvi Butani, Devangi Kachot, Janvi Patoliya and Dhruvi Nariya
M.Sc. Scholar, Department of Genetics and Plant Breeding, JAU, Junagadh, Gujarat

are implicated in micronutrient accumulation (Govindaraj *et al*., 2014).

Breeding Approaches

Conventional Breeding: Selecting naturally nutrient-rich genotypes (Govindaraj *et al*., 2014).

Marker-Assisted Selection (MAS): Using DNA markers linked to Fe/Zn QTLs for faster improvement (Kumar *et al*., 2016).

Genomic Selection (GS): Predicting nutrient content using genome-wide markers (Kanatti *et al*., 2016).

Hybrid Breeding: Exploiting non-additive gene action to combine yield with micronutrient density (Kanatti *et al*., 2016).

Biotechnology (CRISPR-Cas): Future potential for precise editing of micronutrient pathways (Saltzman *et al*., 2013).

Key Findings

Pearl Millet (Dhanashakti): Developed by ICRISAT, contains ~70 ppm Fe and ~40 ppm Zn, compared to ~45 ppm Fe and ~25 ppm Zn in conventional varieties (Govindaraj *et al.*, 2014).

Finger Millet: Naturally high in calcium, also enriched with Fe and Zn through breeding programs in India (Saltzman *et al*., 2013).

Recent GWAS Studies: Identified SNPs associated with Fe (32-120 mg kg^{-1}) and Zn (19-87 mg kg^{-1}), confirming strong genetic control (Kumar *et al.*, 2016).

Farmer & Public Health Impact

Biofortified millets reduce anemia and improve immunity, especially in women and children (Saltzman *et al.*, 2013). Seeds provide nutrition directly through diets, unlike supplements. Millets thrive in drought-prone areas, ensuring food and nutrition security under climate stress. Adoption examples include:

Pearl millet: "Dhanashakti" promoted in Maharashtra and Gujarat (Govindaraj *et al*., 2014).

Finger millet: Used in tribal nutrition programs (Saltzman *et al*., 2013).

Main Advantages of Biofortification

Addresses Hidden Hunger

- ✓ Micronutrient malnutrition (iron, zinc, vitamin A deficiency) affects over 2 billion people worldwide.
- ✓ Biofortified crops directly reduce anemia, stunted growth, and immune deficiencies by providing nutrients through daily diets (Tiwari, 2026; WHO, 2020).

Cost-Effective and Sustainable

- ✓ Unlike supplementation or industrial fortification, biofortification requires no recurring costs once seeds are developed.
- ✓ Farmers can save and replant seeds, ensuring long-term nutritional benefits (Weber, 2025).

Farmer-Friendly and Scalable

- ✓ Biofortified varieties are bred to maintain yield stability and agronomic performance.
- ✓ Farmers benefit from nutrient-rich crops without yield penalties, making adoption easier (Govindaraj *et al.*, 2014).

Climate Resilience

- ✓ Millets are naturally drought-tolerant; biofortifi-

cation enhances their role in climate-smart agriculture.

- ✓ Improves nutrient use efficiency and crop productivity under stress conditions (Tiwari, 2026).

Public Health Impact

- ✓ Documented improvements in iron status among women and children consuming iron-biofortified beans, and enhanced zinc status in populations consuming zinc-biofortified wheat (Weber, 2025).
- ✓ Reduces healthcare costs by preventing long-term deficiencies.

Integration with Other Strategies

- ✓ Works synergistically with dietary diversification and supplementation.
- ✓ Provides a long-term base solution, while other interventions address immediate needs (Weber, 2025).

Challenges

Yield vs. Nutrition Trade-off: Breeding must balance micronutrient density with grain yield (Kanatti *et al.*, 2016).

Bioavailability: Anti-nutritional factors (phytates) reduce absorption; breeding must address this (Saltzman *et al*., 2013).

Farmer Awareness: Outreach programs are essential for adoption (Govindaraj *et al.*, 2014).

References

Weber, J. (2025). Biofortification: Enhancing crops for global health. *Vitamins & Minerals*, 14 (6) 399.

Govindaraj, M., Rai, K. N., Shanmugasundaram, P., Dwivedi, S. L., Sahrawat, K. L. and Pfeiffer, W. H. (2014). Breeding biofortified pearl millet varieties and hybrids to enhance grain iron and zinc concentrations. *Frontiers in Plant Science*, 5(570): 1-9.

Kanatti, A., Rai, K. N., Govindaraj, M., Kumar, S. and Rao, A. S. (2016). Grain iron and zinc density in pearl millet: Combining ability, heterosis and association with grain yield and grain size. *Frontiers in Plant Science*, 7(1636): 1-10.

Kumar, S., Hash, C. T., Nepolean, T., Mahendrakar, M. D., Satyavathi, C. T., Singh, G. and Yadav, R. S. (2016). Mapping quantitative trait loci controlling high iron and zinc content in self and open pollinated grains of pearl millet. *Frontiers in Plant Science*, 7 (1634): 1-12.

Saltzman, A., Birol, E., Bouis, H. E., Boy, E., De Moura, F. F., Islam, Y. and Pfeiffer, W. H. (2013). Biofortification: Progress toward a more nourishing future. *Global Food Security*, 2(1): 9-17.

Tiwari, C. (2026). Importance of biofortification in crops. *International Journal of Advanced Biochemistry Research*, 10(1): 464-470.

World Health Organization. (2020). *Micronutrient deficiencies: Iron deficiency anemia*. Geneva : WHO. Retrieved from https://www.who.int/health-topics/anaemia

The Living Library: The Crucial Role of Biodiversity Hotspots in Germplasm Conservation

Shridevi S., Vengatesh M. and Nivetha A. L.

Introduction: Nature's Greatest Library has no Walls

Imagine a library where every book contains a solution to a future problem. One book may hold the secret to developing drought-resistant rice, another the key to combating devastating wheat diseases, while yet another contains genes that can help crops survive rising temperatures. Unlike ordinary libraries filled with printed pages, this remarkable library is alive. Its books are seeds, wild plants, trees, grasses, and microbes, each carrying millions of years of evolutionary wisdom.



These living libraries are known as biodiversity hotspots regions of extraordinary biological richness that safeguard countless species found nowhere else on Earth. Hidden within their forests, mountains, grasslands and wetlands lies an invaluable collection of genetic resources, or germplasm, that forms the foundation of global food security. As climate change intensifies, new pests emerge and agricultural lands face increasing pressure, these hotspots have become far more than ecological wonders. They are nature's insurance policy for the future of agriculture.

What is Germplasm? The Blueprint of Life

Every seed tells a story. Inside it lies a unique combination of genes that determines how a plant grows, flowers, resists diseases, tolerates drought, or produces nutritious grains and fruits. This hereditary material is known as germplasm.

Germplasm includes:

- ✓ Traditional crop varieties cultivated by farmers for centuries
- ✓ Modern improved cultivars
- ✓ Wild relatives of cultivated crops
- ✓ Landraces adapted to local environments
- ✓ Breeding lines and genetic stocks

Plant breeders depend on germplasm to develop superior crop varieties. Whenever agriculture encounters a new challenge whether it is a deadly disease, prolonged drought, salinity, or heat

Shridevi S.
Research Scholar, Departmennt of Crop Improvement, NCA, Trichy, Tamil Nadu
Vengatesh M.
Senior Assistant Professor (PBG) Department of Crop Improvement, NCA, Trichy, Tamil Nadu
Nivetha A. L.
Research Scholar, Departent of Genetics and Plant Breeding, KAU, Kerala

stress the search for solutions often begins with diverse genetic resources preserved in nature.

Biodiversity Hotspots: Earth's Living Gene Banks

A biodiversity hotspot is not simply a region rich in plants and animals. It is an area containing exceptional numbers of unique species that are found nowhere else, while simultaneously facing serious threats from habitat destruction. Although biodiversity hotspots occupy only a small fraction of Earth's land surface, they support an astonishing proportion of the world's plant diversity. These ecosystems have evolved over millions of years, allowing countless species to adapt naturally to different environmental conditions. For agriculture, this diversity represents an irreplaceable reservoir of useful genes. Wild rice growing in flooded forests may possess genes for flood tolerance. Wild wheat surviving in rocky mountains may carry resistance to devastating rust diseases. Wild relatives of tomatoes, potatoes, bananas, and pulses often harbour natural immunity against pests and pathogens that threaten cultivated crops. These naturally evolved traits become invaluable resources for plant breeding programmes.

Why Biodiversity Matters to Agriculture

Modern agriculture relies heavily on genetic diversity. Yet, many cultivated crops today originate from a relatively narrow genetic base. As farmers increasingly cultivate uniform, high-yielding varieties, valuable traditional varieties and their unique genetic traits are gradually disappearing. This phenomenon, known as genetic erosion, makes crops more vulnerable to diseases, pests, and climate extremes. Biodiversity hotspots help counter this risk by preserving wild relatives and traditional genetic resources that can replenish the genetic diversity of cultivated crops. Every time plant breeders develop a new disease-resistant variety or climate-resilient crop, they often draw upon genes that originated from wild species conserved in natural ecosystems.

Nature's Insurance Policy against Climate Change

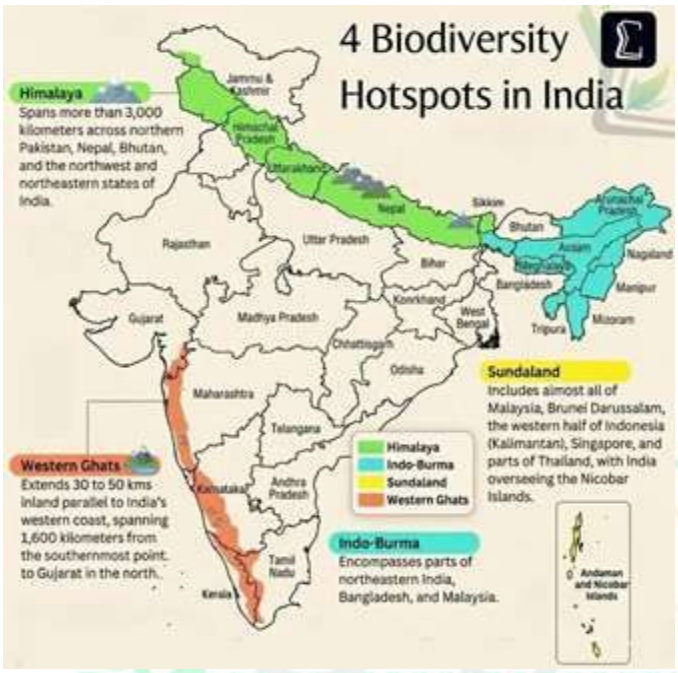
Climate change is rapidly transforming agriculture across the globe. Rising temperatures, erratic rainfall, prolonged droughts, floods, and emerging pests are challenging crop production like never before. Fortunately, nature has already been conducting its own breeding programme for millions of years. Plants growing in deserts have naturally evolved drought tolerance. Species inhabiting saline coastal regions have developed salt tolerance. Mountain plants survive freezing temperatures, while tropical species withstand high humidity and intense pest pressure. These adaptations are encoded within their genes. Scientists can identify these valuable traits and introduce them into cultivated crops through conventional breeding or advanced molecular techniques. Thus, biodiversity hotspots provide the raw genetic material needed to build climate-resilient agriculture.

India: A Treasure House of Biodiversity

India is recognized as one of the world's megadiverse countries and is home to four globally

recognized biodiversity hotspots:

- ✓ The Himalaya
- ✓ The Indo-Burma Region
- ✓ The Western Ghats-Sri Lanka
- ✓ Sundaland (Nicobar Islands)



These regions harbour an extraordinary diversity of crop wild relatives and economically important plant species. The Western Ghats alone contain wild relatives of rice, black pepper, cardamom, mango, jackfruit, banana, citrus, nutmeg, turmeric, and numerous medicinal plants. Similarly, the Himalayan region preserves unique genetic diversity in barley, buckwheat, apples, walnuts, and several temperate fruits. Protecting these ecosystems directly contributes to safeguarding India's agricultural future.

The Silent Threats

Despite their immense value, biodiversity hotspots are under unprecedented pressure.

Major threats include:

- ✓ Deforestation
- ✓ Urban expansion
- ✓ Mining activities
- ✓ Infrastructure development
- ✓ Habitat fragmentation
- ✓ Invasive species
- ✓ Pollution
- ✓ Climate change
- ✓ Unsustainable harvesting

When habitats disappear, the unique species they support vanish forever. Unlike buildings or infrastructure, extinct species cannot be recreated. Every lost species represents a lost opportunity for future crop improvement.

Conserving the Living Library

Scientists use two complementary approaches to conserve germplasm.

***In situ* Conservation:** This involves protecting plants within their natural habitats. National parks, wildlife sanctuaries, biosphere reserves and community-managed forests allow species to continue evolving under natural environmental conditions. This dynamic conservation preserves ongoing evolutionary processes.

***Ex situ* Conservation:** Here, genetic resources are conserved outside their natural habitats through:

- ✓ Seed banks
- ✓ Field gene banks
- ✓ Botanical gardens
- ✓ Tissue culture repositories
- ✓ Cryopreservation facilities

Institutions around the world preserve mill-

ions of germplasm accessions that serve as valuable resources for research and crop improvement. Both approaches complement each other. Seed banks provide secure storage, while biodiversity hotspots allow nature to continue generating new genetic diversity.

Communities: The Unsung Guardians

For centuries, indigenous communities and traditional farmers have protected biodiversity through sustainable agricultural practices. Their cultivation of local landraces, traditional knowledge of medicinal plants and community-based conservation efforts have helped preserve countless valuable genetic resources. Recognizing and supporting these custodians of biodiversity is essential for successful conservation.



A Future Rooted in Diversity

The challenges facing global agriculture continue to grow. Feeding an increasing population while coping with climate change requires crops that are more resilient, nutritious, and productive. The answers to many of these challenges may already exist within the forests, mountains, and grasslands of biodiversity hotspots. Every conserved species expands humanity's genetic toolbox. Every protected habitat strengthens food security. Every seed saved today may become tomorrow's breakthrough variety. Conserving biodiversity hotspots is therefore not merely about protecting wildlife it is about safeguarding the future of agriculture, nutrition, and human survival.

Conclusion

Biodiversity hotspots truly are Nature's Living Libraries repositories of irreplaceable genetic wealth that sustain agriculture and life on Earth. As climate uncertainties grow and food demands increase, conserving these natural reservoirs becomes an investment in humanity's future. By protecting biodiversity today, we preserve the genetic resources that will enable scientists, farmers, and future generations to cultivate resilient crops, restore ecosystems, and ensure global food security. The seeds of tomorrow's solutions are already growing in nature; our responsibility is to ensure that this living library remains open for generations to come.

The Ripple Effect: How Ecological Imbalance is threatening Global Crop Production

Vengatesh M., Nivetha A. L. and Shridevi S.

Nature thrives on harmony. Within a healthy agricultural ecosystem, soil microbes break down organic matter, predatory insects keep crop-destroying pests in check, and predictable weather patterns guide the seasonal growth cycles of plants. However, as human activities push natural systems past their breaking points, this intricate balance is fracturing. Ecological imbalance defined as a major disruption to the stable relationships within an ecosystem is no longer just an environmental talking point. It has emerged as one of the most pressing threats to global food security. When we disrupt the environmental foundations supporting agriculture, our farm fields bear the immediate brunt, resulting in stagnating crop yields, depleted soils, and vulnerable food supply chains.

The Broken Cycle of Soil Degradation

Healthy agricultural production relies on an unspoken ecological agreement: nutrients drawn from the ground must eventually return to it. In unmanaged ecosystems, nutrients naturally cycle through plants, animals, and microbes, staying largely in place. However, modern intensive agriculture disrupts this cycle by exporting massive volumes of biomass in the form of grain, forage, and vegetables every harvest season (How Pop Ecology Misleads Agriculture, 2026). When farmers attempt to bypass natural soil-building processes entirely through the excessive use of synthetic inputs, the underlying ecological systems begin to decay. Over-reliance on heavy tillage and chemical fertilizers strips the soil of its organic matter, altering its physical and biological architecture.

Accelerated Soil Erosion: Without the structural support of diverse root systems and organic matter, soil loses its resilience against the elements. Globally, the rate of agricultural soil erosion vastly outpaces natural soil formation. While nature takes centuries to weather parent rock and build a mere fraction of a millimeter of topsoil, conventional farming practices expose dry, loose landscapes to severe wind and sheet water erosion (Environmental Effects of the U.S. Food System, 2015). This net resource depletion reduces the land's water-holding capacity and fertility, leading directly to lower crop yields.

Acidification and Salinization: Irrational agricult-ural management practices carry hidden ecological

Vengatesh M.
Senior Assistant Professor (PBG) Department of Crop Improvement, NCA, Trichy, Tamil Nadu
Nivetha A. L.
Research Scholar, Departent of Genetics and Plant Breeding, KAU, Kerala
Shridevi S.
Research Scholar, Departmennt of Crop Improvement, NCA, Trichy, Tamil Nadu

costs. Intensive chemical fertilization particularly the excessive application of nitrogen fuels widespread soil acidification and groundwater eutrophication (He *et al.*, 2024). Furthermore, poorly managed irrigation infrastructure and over-extraction of minerals can raise water tables, causing waterlogging and heavy accumulations of water-soluble salts (Causes and Consequences of Ecological Imbalances in India, 2022). Once a soil becomes severely salinized or acidified, its biological fertility plummets, making it toxic to standard food crops.

Climate Instability and the Crop Physiology Crisis

Ecological imbalance acts as both a driver and an amplifier of global climate change. Deforestation, land conversion, and greenhouse gas emissions break the atmospheric feedback loops that once provided reliable seasonal weather patterns. Agriculture is uniquely exposed to these shifting baselines, as altered temperature and precipitation cycles directly impair the physiological limits of plants (Yuan *et al.*, 2024).

[Deforestation & Emissions] ➔ [Atmospheric Disruption] ➔ [Extreme Weather & Heat Stress] ➔ [Crop Physiological Failure]

The Threat of Composite Extreme Events: Rather than dealing with single, isolated anomalies, modern farmers increasingly face "composite extreme events" simultaneous or back-to-back occurrences of droughts, heatwaves, frosts, and waterlogging (Yuan *et al.*, 2024). For instance, an extreme drought followed immediately by intense rain does not cure a water deficit; instead, it washes away weakened topsoil and destroys vulnerable root networks. Major agricultural regions worldwide are experiencing noticeable yield shocks or complete crop failures due to these erratic, hard-to-predict climate swings.

Disrupted Crop Growth Cycles: Even outside of sudden disasters, rising average baseline temperatures present a constant challenge to plant biology. Unprecedented temperature fluctuations during critical reproductive phases such as the flowering and grain-filling stages of wheat and rice can drastically reduce final harvest volumes (Alotaibi, 2023). Warmer winters also eliminate the natural thermal resets that ecosystems historically relied on, allowing crop diseases and destructive insects to survive the cold months, multiply their generations, and expand into entirely new geographic territories.

The Collapse of Biodiversity and Natural Pest Control: An agricultural field is not an isolated factory; it is a living ecosystem that depends heavily on biodiversity to function properly. When natural landscapes are aggressively cleared to create vast, single-crop monocultures, the local biodiversity collapses. This loss of ecological variation removes the natural checks and balances that historically protected crops from ruin.

The Predator-Prey Imbalance: In a balanced environment, populations of herbivorous insects are naturally restricted by predatory insects, birds, and frogs. When wide-spectrum chemical pesticides are applied indiscri-minately to save a crop, they frequently wipe out these beneficial predator species

along with the pests. Because pest populations typically reproduce and develop chemical resistance much faster than their natural predators, this creates an ecological vacuum. The result is a cycle of secondary pest outbreaks that require even heavier, costlier chemical interventions.

The Pollinator Deficit: A significant portion of global crop varieties including many high-value fruits, vegetables, and oilseeds rely directly on animal pollinators to set fruit and seeds. Habitat destruction, industrial land clearing, and chemical pollution have caused a severe decline in wild bee and insect populations. Without sufficient pollinators, crops suffer from poor fertilization, leading to misshapen fruit, low seed counts, and reduced overall market yields.

Economic and Systemic Strains on Global Food Supply

The consequences of ecological imbalances quickly ripple outward from farm fields into global economic systems. When an ecosystem fractures, farmers are forced to spend more money on artificial fixes to maintain their baseline productivity.

Skyrocketing Input Costs: To offset degraded soil and aggressive pest mutations, growers must invest heavily in synthetic fertilizers, advanced chemical pesticides, and artificial irrigation infrastructure.

Strain on Smallholders: Small-scale farmers suffer the most from these changes. Sudden crop losses from severe weather or pest invasions can dry up local credit options and force reliance on government farm subsidies (Yuan *et al.*, 2024).

Supply Chain Disruption: Because international food markets are tightly interconnected, a sudden drop in production in one major agricultural region quickly triggers global price spikes, export restrictions and regional food insecurity issues.

Restoring Balance through Sustainable Agro-ecosystems: To protect global food production from long-term decline, agricultural management must shift away from fighting nature and focus instead on rebuilding ecological health. Modern agroecological frameworks show that evaluating a farm's productivity should involve assessing its "Ecosystem Fit" matching specific crop choices directly to local soil profiles and climate realities rather than forcing a uniform framework onto a degraded landscape (Klock *et al.*, 2024).

Sustainable Practice	Ecological Mechanism	Agricultural Benefit
Legume-Based Intercropping	Fixes atmospheric nitrogen naturally and improves canopy structure (Bilalis *et al.*, 2024).	Reduces synthetic fertilizer reliance and lowers soil water evaporation.
Minimum / No-Tillage	Keeps soil structure intact and preserves organic root pathways.	Drastically reduces soil erosion and enhances water retention.
Cover Cropping	Protects bare soil between main seasons and recycles deep nutrients.	Suppresses weeds naturally and builds long-term topsoil fertility.
Integrated Pest Management (IPM)	Preserves native predatory insects and uses targeted biological controls.	Lowers chemical input costs and prevents pest resistance mutations.

By transitioning toward climate-resilient crop varieties and smarter, eco-friendly soil management, we can begin to mend the ecological

rifts threatening our fields (Alotaibi, 2023). Restoring balance to our agricultural ecosystems is no longer an optional conservation goal it is a foundational requirement to sustain global food production for generations to come.

References

Alotaibi, M. (2023). Climate change, its impact on crop production, challenges, and possible solutions. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 51(1): 13020.

Bilalis, D., Roussis, I. and Kakabouki, I. (2024). Enhancing Crop Yield and Adaptability through Sustainable Soil Management: Effective and Eco-Friendly Practices. *Plants*, 13(19): 2789.

Environmental Effects of the U.S. Food System. (2015). *National Center for Biotechnology Information (NCBI)*.

He, Y., Li, M., Zhang, W., Chen, X., Zhao, Z. and Yao, Z. (2024). Environmental impacts of crop production systems in subtropical plateau regions: case study of Yunnan, China. *Scientific Reports*, 14: 11618347.

How Pop Ecology Misleads Agriculture. (2026). *Washington State University Center for Sustaining Agriculture and Natural Resources*.

Klock, A. M., Banerjee, A., Vogt, K. Q., Mafune, K. K., Vogt, D. J. annd Gordon, J. C. (2024). An ecological framework to index crop yields using productivity and Ecosystem Fit: A case study from India. *PLOS Sustainability and Transformation*, 3(3): e0000122.

Causes and Consequences of Ecological Imbalances in India: A Review. (2022). *CABI Digital Library*.

Yuan, X., Li, S., Chen, J., Yu, H., Yang, T., Wang, C., Huang, S., Chen, H. and Ao, X. (2024). Impacts of Global Climate Change on Agricultural Production: A Comprehensive Review. *Agronomy*, 14(7): 1360.

Environmental Conservation and New Measures for Environment Protection

Suraj Singh, Neeraj Kumar, Vikash Sharma, Deepak Kumar and Rajendra Prasad

Introduction

The environment is the fundamental basis of human life. It consists of air, water, land, forests, flora, fauna, and various natural resources that support human existence and determine the overall quality of life. With the progress of human civilization, dependence on natural resources has increased significantly, along with human intervention in natural systems. Industrialization, urbanization, population growth, and modern lifestyles have improved living standards, but they have also placed enormous pressure on the environment. At present, air pollution, water pollution, degradation of soil fertility, climate change, global warming, and loss of biodiversity have become serious global concerns. These problems pose threats not only to natural ecosystems but also to human health, agriculture and economic stability. Under such conditions, environmental conservation has become an essential requirement. Environmental conservation refers to the rational use of natural resources, control of pollution, and maintenance of ecological balance. Its purpose is to meet present needs while ensuring environmental safety and sustainability for future generations. Uncontrolled deforestation, excessive exploitation of water resources and increasing pollution levels may create severe environmental and social challenges in the future. Traditionally, measures such as tree plantation, water conservation, sanitation, energy conservation, and recycling of waste have been adopted to protect the environment. While these measures remain relevant, growing environmental challenges require the adoption of new and modern approaches supported by science and technology. Through these approaches, a balance between development and environmental protection can be achieved. The use of renewable energy sources such as solar, wind, and bio-energy has gained importance as pollution-free alternatives to fossil fuels. Similarly, electric vehicles, green technology, smart city planning, advanced waste management systems, and digital monitoring techniques are contributing to environmental protection. Innovations such as waste-to-energy technologies, alternatives to plastic, and modern water conservation methods further strengthen conservation efforts. Public awareness and participation are also critical factors, as environmen-

Suraj Singh and Rajendra Prasad
Research Scholar, Department of Entomology, CSAUAT, Kanpur, Uttar Pradesh
Neeraj Kumar
Research Scholar, Department of Seed Science, CSAUAT, Kanpur, Uttar Pradesh
Vikash Sharma and Deepak Kumar
Research Scholar, Department of Entomology, CSJMU, Kanpur, Uttar Pradesh

tal policies and laws are effective only when supported by society. Therefore, environmental conservation and new protective measures are vital for sustainable development and long-term environmental stability.

Importance of Environment

The environment forms the foundation of life on Earth. The survival of humans and all other living organisms depends entirely on environmental resources. Clean air is essential for respiration and overall health, while polluted air leads to respiratory and cardiovascular diseases. Water is another vital component of life, required not only for drinking but also for agriculture, industry, sanitation, and energy production. Contamination of water sources can result in health hazards, water scarcity, and reduced agricultural productivity. Land and soil fertility are equally important for food production and economic stability. Fertile soil supports agriculture, which is the backbone of food security. Soil degradation caused by pollution and excessive chemical use may result in reduced crop yields and economic challenges. Forests regulate climate, conserve biodiversity, and maintain the water cycle. Disturbance in environmental balance directly affects human health, agricultural output, economic development, and social well-being. Therefore, environmental conserveation is both a social and ethical responsibility.

Major Causes of Environmental Pollution

Industrial Pollution: Emission of smoke, chemicals and industrial waste.

Excessive use of Vehicles: Fossil fuel-based transportation increases air pollution.

Deforestation: Caused by urban expansion and industrial development.

Excessive Use of Plastic: Non-biodegradable plastic pollutes land and water bodies.

Agricultural Chemicals: Fertilizers and pesticides contaminate soil and groundwater.

Need for Environmental Conservation

- ✓ Protection of natural resources for future availability
- ✓ Maintenance of ecological balance
- ✓ Foundation of sustainable development
- ✓ Protection of human health
- ✓ Reduction of climate change impacts
- ✓ Conservation of biodiversity
- ✓ Mitigation of natural disasters
- ✓ Agricultural productivity and food security
- ✓ Social and economic development

Traditional Measures for Environmental Conservation

- ✓ Tree plantation and forest conservation
- ✓ Water conservation and rainwater harvesting
- ✓ Energy conservation
- ✓ Reuse and recycling of waste
- ✓ Implementation of environmental laws

New and Modern Measures for Environmental Conservation

Expansion of Renewable Energy: Solar, wind, hydro, and bio-energy reduce dependence on fossil fuels and lower pollution levels.

Green Technology: Electric vehicles, energy-efficient appliances, and green buildings reduce

environmental impact.

Smart Cities and Sustainable Urban Development : Efficient energy use, improved waste management, green spaces, and public transportation help control urban pollution.

Innovations in Waste Management: Waste-to-energy technologies, composting, and scientific management of e-waste support environmental protection.

Digital and Technological Solutions: Satellite monitoring, digital data systems, and artificial intelligence help track deforestation, pollution, and climate trends.

Public Awareness and Participation: Education, media, and community programs enhance awareness and support environmental initiatives.

Environmental Conservation Efforts in India

Swachh Bharat Abhiyan: Focuses on sanitation and waste management.

National Solar Mission: Promotes solar energy use.

Namami Gange Programme: Aims at cleaning and rejuvenating the Ganga River.

Plastic Ban Laws: Reduce plastic pollution.

Environment Protection Act, 1986: Provides a legal framework for environmental safety.

Afforestation and Forest Conservation Programmes

National Water Policy and Water Conservation Schemes

Role of Youth in Environmental Conservation

- ✓ Participation in tree plantation activities
- ✓ Involvement in cleanliness drives
- ✓ Promotion of energy conservation
- ✓ Dissemination of environmental awareness
- ✓ Reduction in plastic use
- ✓ Support for water conservation practices
- ✓ Adoption of eco-friendly lifestyles
- ✓ Support for government and social initiatives
- ✓ Engagement in environmental education and research
- ✓ Leadership through responsible practices

Conclusion: Environmental conservation has become a critical global issue affecting natural ecosystems, human health and economic development. Rapid industrialization, urban expansion and resource intensive lifestyles have contributed to environmental degradation on a large scale. Increa-sing pollution levels, climate change, global warming and loss of biodiversity indicate the need for systematic and sustained conservation measures. Environmental protection cannot be addressed solely through policies and regulations. Long-term environ-mental stability depends on the integration of conservation principles with development planning, scientific innovation & social participation. Efficient resource utilization, adoption of renewable energy, technological advancements and effective waste management systems are essential components of sustainable environmental management. Ensuring clean air, safe water, fertile soil, and ecological balance is fundamental for human well-being and sustainable progress. A comprehensive approach that combines traditional conservation practices with modern scientific solutions is necessary to maintain environmental integrity and support future development.

Alliviation of Cold Stress in Vegetable Crops

Pankaj Kumar, M. L. Meena, Anjali, Suraj Pasawan, Animesh Kumar Singh, Rahul, Pradeep Kumar and Vishal Singh

Abstract

At the same time, cold stress, which includes chilling and freezing damage, also impacts the production of horticultural crops. Although the effects of cold stress might not be visible immediately, there are various strategies to lessen these impacts, though none completely prevent damage. The effectiveness of these methods varies depending on the type of crop and the length of exposure. These methods include heat treatment, periodic warming, packaging, waxing, growth regulators, natural antioxidants (such as methyl jasmonate and polyamines), rootstocks (which offer limited protection against cold), controlled atmosphere, location selection, mulching, irrigation, soil banking, nutrient management (like potassium for better water intake), row covers, and wind machines. Each method helps reduce cold injury in different ways, such as by stabilizing plant membranes, acting as antioxidants, or improving water uptake.

Introduction

Among all types of environmental stresses, cold stress is one of the oldest challenges faced in horticulture. It poses difficulties for both scientists and growers, affecting crop production and yield. Cold stress, which includes chilling and freezing injuries, occurs when temperatures drop below 20°C.

Chilling and freezing injury	
Chilling injury	**Freezing injury**
It occurs temperature drop below 10-15°C	It occurs below ^{o}C.
Main site is plasma membrane.	It occurs first in cell wall, then in intercellular spaces.
Main symptoms surface pitting.	Main symptoms water-soaked appearance.

The severity of cold stress depends on the temperature range and the type of plant. Chilling temperatures, which are below 20°C, or freezing temperatures, which are below 0°C, can lead to the formation of ice crystals within plant tissues. This results in the dehydration and damage of plant cells.

Effect of Cold Stress on Different Horticultural Crops

- ✓ Pollen development is negatively impacted.
- ✓ The process of converting starch to sugar is disrupted.
- ✓ The rate of carbon dioxide release is reduced.
- ✓ Photosynthesis is altered.
- ✓ Development is delayed, and the growing season is extended.
- ✓ Germination is slowed and less consistent, affecting seedling energy and causing delays in plant development, which can result in significant loss of crop yield.
- ✓ Growth of plants sensitive to chilling is slowed.

Pankaj Kumar, M. L. Meena, Anjali, Suraj Pasawan, Animesh Kumar Singh, Rahul, Pradeep Kumar and Vishal Singh
Department of Horticulture, School of Agricultural Sciences and Technology, BBAU, Lucknow, Uttar Pradesh

- ✓ Loss of vitality is observed, such as when potatoes lose their ability to sprout if exposed to cold.

Methods to Alleviate Cold Stress

Heat Treatment: Heat treatment has been found to delay or prevent the occurrence of chilling injury in various cases. For instance, treating tomatoes with heat at 40°C for 7 minutes before storing at 2.5°C resulted in good quality and better ripening scores after storage. Vapor heat treatment has also been found to reduce the susceptibility of tomatoes to cold stress.

How Heat Treatment Works?

Heat treatment helps in reducing the damage caused by cold stress by improving the plant's ability to withstand it.

Packaging: Using plastic packaging materials to wrap vegetables helps maintain high levels of relative humidity and modifies the surrounding atmosphere's composition of oxygen and carbon dioxide. Packaging with low-density polyethylene film has been found to reduce chilling injury in cucumber. Similarly, tomato fruits are protected from chilling injury at 2°C by the accumulation of CO_2 in polyethylene bags.

Waxing: Applying different types of waxes to the surface of fruits and vegetables is commonly used to improve their quality, as it helps retain moisture and acts as a semi-permeable barrier, reducing the risk of cold injury.

Growth Regulators and Chemicals: Among the plant growth regulators, cytokinins and abscisic acid (ABA) have shown the most effectiveness. Non-hormonal growth regulators, such as paclobutrazol, chlorocholin chloride, mefluided, uniconazole, and other triazoles, are also used to enhance the chilling resistance of plants. The use of brassinosteroids (BRs) has been found to significantly improve plant resilience against chilling stress in various aspects, including growth, photosynthesis, and the cell defense system in tomato plants.

Controlled Atmosphere: Controlled atmosphere (CA) storage has been found to influence respiration, ethylene production and activity, protein synthesis and movement, the maturation process and senescence of various agricultural products.

Mulching: Mulching involves applying materials, either organic or non-organic, over the plants to protect them from extreme temperatures, including cold. The primary purpose of mulch is to reduce water evaporation, control soil erosion, and help conserve moisture. Organic mulches are effective in moderating the temperature fluctuations of the soil throughout the day. Using plastic mulch can effectively increase soil temperature, conserve moisture, and control weeds. Mulching functions as an insulator, aiding in warming the soil under cool conditions.

Surface Irrigation: Surface irrigation methods such as flooding or furrowing can protect plants from frost injury. This is achieved by converting latent heat into sensible heat through the cooling water. It is important to start irrigation in a timely manner to ensure that water reaches the end of the field before

the ambient temperature drops below the threshold for damage.

Nutrient Management: Nutrient uptake, including nitrogen (N), phosphorus (P), and potassium (K), is reported to be reduced during chilling stress due to poor root function in plants. Proper nutrient application is needed for the recovery from injury. The photosynthesis rate under temperature stress can be increased by using magnesium. Applying a dose of nitrogen fertilizer to potatoes before frost has been found to make them more resistant to injury.

Conclusion

Similarly, cold stress damages cell membranes and disrupts metabolic processes, leading to yield loss. Plants naturally cope with cold stress through acclimation, stabilizing membranes, and activating stress-responsive genes. The external application of plant growth regulators like abscisic acid and salicylic acid offers potential, although the optimal dosage is still under study. Advances in molecular breeding, including the identification of cold-regulated genes and transcription factors, provide additional tools. Combining plant growth regulators with genetic engineering can further strengthen vegetable crops against chilling injury. Together, these integrated approaches will help sustain productivity and ensure food quality under climate stress.

References

Saltveit, M. E. and Morris, L. L. (1990). Overview on chilling injury of horticultural crops. p. 3.

Rolland, E., Vaultier, M. N., Zachowski, A. and Hurry, V. (2009). Cold signalling and cold acclimation in plants. *Advances in Botanical Research*, 49: 35-150.

Sayyari, M., Babalar, M., Kalantari, S., Serrano, M. and Valero, D. (2009). Effect of salicyclic acid treatment on reducing chilling injury in stored pomegranates. *Postharvest Biology and Technology*, 53(3): 152-154.

Upreti, K. K. and Sharma, M. (2016). Role of plant growth regulators in abiotic stress tolerance. In *Abiotic Stress Physiology of Horticultural Crops*. Springer, New Delhi, pp. 19-46.

Recent Technology for Post-Harvest Management of Fruit Crops

M. Shamini, Ghirisan B., Saranya R. and Niranjan R.

Introduction

Fruits are highly perishable commodities, and it is estimated that 20-40% of harvested fruits are lost between harvest and consumption due to physio-logical deterioration, microbial spoilage, mechanical injury, and improper handling. These post-harvest losses not only cause economic damage to growers and traders but also undermine food security and nutritional availability, especially in developing countries where cold chain infrastructure is limited. Post-harvest management, refers to the scientific handling of fruits after harvest, covering cleaning, sorting, grading, packaging, storage, transportation, and ripening control to extend shelf life, preserve nutritional and sensory quality, and minimizing wastage. In recent years, rapid advances in food science, engineering, and digital technology have transformed traditional post-harvest practices into precision-based, technology-driven systems. These innovations aim not only to slow down senescence and decay but also to ensure traceability, safety, and quality assurance across the supply chain.

Smart and Edible Coatings: Instead of wax rubbed onto apples the old-fashioned way, scientists have developed edible coatings made from chitosan (from shellfish shells), aloe vera gel, plant waxes, and even whey protein. These invisible films slow down water loss and oxygen exchange, which means fruit stays firm and fresh for longer without any chemical residue. Some coatings now come infused with natural antimicrobial compounds, essential oils, nanoparticles of silver or zinc oxide that fight fungal decay directly on the fruit's surface. Mango, guava, banana, and citrus growers are increasingly using these to extend shelf life by several days to a couple of weeks.

Scientists have developed edible coatings made from chitosan (derived from scallop shells), aloe vera gel, plant waxes, and even whey protein, as an alternative to the traditional method of rubbing wax on apples. Fruit remains firm and fresh for longer periods without chemical residue because these invisible layers slow water loss and oxygen exchange. Today, some coatings include natural antibacterial compounds such as essential oils and silver or zinc oxide nanoparticles that directly prevent fungal rot on the fruit's surface. Growers of citrus, bananas, mangoes, and guavas are increas-ingly using these coatings to extend shelf life by a few days to several weeks.

Nanotechnology in Packaging: Nanotechnology has moved from the lab into fruit crates. Nano-sized particles embedded in packaging films can absorb ethylene gas (the hormone that makes fruit ripen and rot faster), block UV light, or release tiny amounts of antimicrobial agents over time. This is called “active

M. Shamini, Ghirisan B., Saranya R. and Niranjan R.
SRM College of Agriculture Sciences, SRMIST, Baburayanpettai, Chengalpattu, Tamil Nadu

packaging", and it's especially useful for climacteric fruits like bananas, mangoes, and papayas that keep ripening rapidly after picking. Fruit crates now house nanotechnology instead of labs. The hormone that causes fruit to ripen and rot more quickly, ethylene gas, can be absorbed by nanoparticles incorporated in packaging films, which can also filter UV rays or gradually release minute amounts of antimicrobial chemicals. This is known as "active packaging", and it works particularly well for climacteric fruits that continue to ripen quickly after being picked, such as bananas, mangoes, and papayas.

Controlled and Modified Atmosphere Storage: On its own, cold storage is outdated. More recent techniques for precisely adjusting the oxygen, carbon dioxide, and nitrogen mixture inside storage rooms or even inside individual packaging are called Controlled Atmosphere (CA) and Modified Atmosphere Packaging (MAP). Fruit respiration and ripening are significantly slowed by depriving it of excess oxygen and regulating CO_2 accumulation. Apples can have a longer shelf life if they are stored this way. By limiting extra oxygen and controlling CO_2 accumulation, fruit respiration and ripening are considerably slowed. Apples may be stored in this way for over a year without losing much of their quality, and the same idea is now being used for long sea voyages carrying berries, pomegranates, and grapes.

Smarter Ethylene Management: Ethylene gas is a double-edged sword: useful for ripening fruit on demand, dangerous when it triggers premature spoilage. New catalytic ethylene generators allow exporters to ripen bananas, mangoes, and tomatoes on a precise schedule right before they hit the retail shelf, so fruit arrives at the "just ripe" stage instead of overripe or rock-hard. On the flip side, ethylene scrubbers and absorbent sachets placed in storage rooms and trucks remove excess ethylene to keep fruit firm longer. Fruit can be ripened on demand with ethylene gas, but it can also cause premature spoiling. Fruit arrives at the "just ripe" stage rather than overripe or rock-hard thanks to new catalytic ethylene generators that enable exporters to ripen bananas, mangoes, and tomatoes on a precise schedule just before they hit the retail shelf. Conversely, to keep fruit firm for longer, excess ethylene is removed using ethylene scrubbers and absorbent sachets that are stored in trucks and storage rooms.

Non-Thermal Preservation: Cold Plasma, Ozone and UV

Heat treatments can damage delicate fruit, so researchers have turned to non-thermal methods:

- ✓ Cold plasma uses ionized gas to kill surface bacteria and fungal spores without heating the fruit at all.
- ✓ Ozone treatment is being used in cold rooms and wash-water systems to sanitize fruit and destroy mould spores, extending shelf life while leaving no chemical residue.
- ✓ UV light treatments disinfect the fruit surface and can even trigger natural defence responses in the fruit's skin that slow decay.

AI, Sensors and the "Smart" Cold Chain: Perhaps the biggest shift is digital. Small wireless sensors can now travel inside a shipment of fruit, continuously tracking temperature, humidity, and even ethylene levels, and sending alerts if anything drifts out of range. Combined with the Internet of Things (IoT), this means a shipment of mangoes leaving a farm can be monitored in real time all the way to a distant port. Digital is arguably the largest change. Now, tiny wireless sensors can move throughout a fruit shipment, monitoring temperature, humidity, and even ethylene levels continuously and sending out alarms if anything moves out of range. When combined with the Internet of Things (IoT), this allows real-time tracking of a shipment of mangoes from a farm to a far-off port. Layered on top of this is artificial intelligence. Machine-learning models are now trained to:

- ✓ Predict how many days of shelf life a batch of fruit has left, based on sensor and image data.
- ✓ Detect early bruising, fungal spots, or internal defects using computer vision cameras that "see" what the human eye might miss.
- ✓ Sort and grade fruit automatically on packing lines using hyperspectral imaging, which scans light wavelengths invisible to us to detect ripeness, sugar content, or hidden damage in a fraction of a second.

This lets packhouses divert fruit heading for slow decay into faster, closer markets, instead of finding out too late.

- ✓ Using sensor and picture data, estimate how many days a batch of fruit has left on its shelf.
- ✓ Use computer vision cameras that see what the human eye would miss to find early bruises, fungus patches, or internal flaws.
- ✓ Using hyperspectral imaging, which examines invisible light wavelengths to identify ripeness, sugar content, or hidden damage in a split second, fruit is automatically sorted and graded on packaging lines.

This prevents packhouses from learning too late by rerouting fruit destined for gradual degradation into closer, quicker markets.

Robotics and Automated Sorting: Robotic arms guided by AI vision are increasingly used to gently pick, sort, and pack delicate fruits like strawberries, peaches, and table grapes, reducing the bruising and micro-injuries that often start the spoilage clock early. This is particularly valuable for fruits where human handling used to cause a large share of post-harvest losses. Increasingly, delicate fruits like strawberries, peaches, and table grapes are picked, sorted, and packed by robotic arms that are guided by AI vision. This reduces the bruising and micro-injuries that frequently cause the spoiling clock to start early. This is especially beneficial for fruits, where a significant portion of post-harvest losses were previously caused by human handling.

Blockchain for Traceability: Fruit exporters are using blockchain-based tracking systems to record every step, harvest date, cold storage entry, transport temperature and border crossing into an impenetr-able digital ledger, even though these systems are not

preservation technologies. This increases buyer confidence, aids in identifying specific areas where a batch may have been improperly handled, and has a growing impact on premium fruit export pricing.

Solar-Powered Cold Storage for Smallholders: One of the most promising developments for small farmers, especially in regions with unreliable electricity, is compact solar-powered cold storage units and evaporative cooling chambers. These low-cost systems can bring the temperature of a storage room down significantly using minimal or no grid power, helping smallholders reduce losses without needing expensive industrial refrigeration.

References

Asrey, R., Sharma, S., Barman, K., Prajapati, U., Negi, N. and Meena, N. K. (2023). Biological and postharvest interventions to manage ethylene in fruit: A review. *Sustainable Food Technology,* 1: 803-826.

Moradinezhad, F. and Ranjbar, A. (2023). Advances in postharvest diseases management of fruits and vegetables: A review. *Horticulturae*, 9(10): 1099.

Wahab, W. A. and Hussain, A. I. (2022). Advances in edible coatings for postharvest preservation of fruits and vegetables. *Comprehensive Reviews in Food Science and Food Safety*, 21(1): 157-180.

Wu, J., Tang, R. and Fan, K. (2023). Recent advances in postharvest technologies for reducing chilling injury symptoms of fruits and vegetables: A review. *Food Chemistry X*, 21: 101080.

Zhang, S., Wang, X. and Yao, H. (2022). Recent progress in smart packaging for extending shelf life and ensuring quality of fruits and vegetables: A review. *Critical Reviews in Food Science and Nutrition,* 62(1): 180-193.

Integrated Permaculture Aquaculture Systems: A Climate-Resilient Approach for Sustainable Fish, Crop and Livestock Production

Chamundeshwari Bitli, Md Ibran Ansari, Madhavi K. and Neha P.

Abstract

The growing challenges of climate change, water scarcity, soil degradation and increasing production costs have highlighted the need for sustainable farming systems that maximize productivity while conserving natural resources. Integrated Permaculture Aquaculture Systems (IPAS) combine fish culture, crop production, livestock, trees and efficient water management into a self-sustaining ecosystem where the outputs of one component become inputs for another. This integrated approach enhances nutrient recycling, improves soil fertility, increases water-use efficiency, promotes biodiversity and reduces dependence on external inputs. Fish ponds serve as multifunctional units for water storage, irrigation and nutrient cycling, while livestock and crops contribute to efficient resource utilization. Integration with aquaponics, rainwater harvesting and renewable energy further strengthens climate resilience and farm sustainability. By diversifying farm enterprises, IPAS enhances income generation, resource conservation and farmer well-being, making it a promising model for sustainable and resilient agriculture in India.

Introduction

Agriculture today faces major challenges, including climate change, water scarcity, soil degradation, biodiversity loss and rising production costs. Conventional farming systems, which rely heavily on synthetic fertilizer s and pesticides, often degrade natural resources and threaten long-term sustainability. These challenges have increased the need for farming practices that enhance productivity while conserving the environment. Permaculture, developed by Bill Mollison and David Holmgren in the 1970s, is a regenerative farming approach that integrates crops, livestock, trees, fish and water resources into a self-sustaining ecosystem. When combined with aquaculture, fish ponds function as water reservoirs, nutrient recycling units and bio-diversity hubs, supporting multiple farm enterprises. Integrated Permaculture Aquaculture Systems (IPAS) improve resource-use efficiency, diversify farm income and enhance climate resilience, making them a promising sustainable farming model for small and marginal farmers in India.

Principles of Integrated Permaculture Aqua-culture

Ethics and Ecological Design: Integrated perma-culture is founded on the ethics of Earth Care, People

Chamundeshwari Bitli, Madhavi K. and Neha P.
College of Fishery Science, Narasapuram, Andhra Pradesh
Md Ibran Ansari
Indian Grameen Services, Chhattisgarh

Care and Fair Share, which encourage sustainable resource management and equitable utilization of natural resources. Unlike conventional farming, where each enterprise functions independently, permaculture emphasizes integration so that every component supports several others. Fish ponds store rainwater, livestock provide manure, trees reduce soil erosion, crop residues become compost, and aquatic plants improve water quality. Such interactions create a resilient farming ecosystem capable of maintaining productivity with minimal external inputs.

Designing an Integrated Farm Ecosystem: A successful integrated permaculture farm begins with careful planning based on land slope, water availability, soil characteristics and local climatic conditions. The fish pond is generally located at the lowest point of the farm to facilitate rainwater harvesting and gravity-based irrigation. Productive pond margins are planted with aquatic vegetables and medicinal plants that stabilize pond banks while utilizing excess nutrients. Fruit trees and multipurpose tree species are planted around the pond to create a food forest that moderates temperature, enhances biodiversity and provides additional farm income. Crop fields are positioned nearby so that nutrient-rich pond water can be used for irrigation, thereby reducing fertilizer require-ments. Livestock sheds are strategically located to enable efficient recycling of manure through composting or biogas production before application to ponds and fields.

Land Requirements for Sustainable Operations

Household level: 500-2,000 m^{-2} (0.05-0.2 ha).

Semi-commercial farm: 0.5-2 ha with 10-30% area under water bodies for optimal balance.

Initial investment remains affordable with phased implementation and use of local materials.

Estimated Budget (INR, approx. for 2025-26)

Small backyard system (1,000 m^{-2}): 1,25,000 lakh - 5,00,000 Lakh (including pond construction, basic pumps, and initial stocking).

Medium farm (1 ha): 8,00,000 Lakh-30,00,000 Lakh.

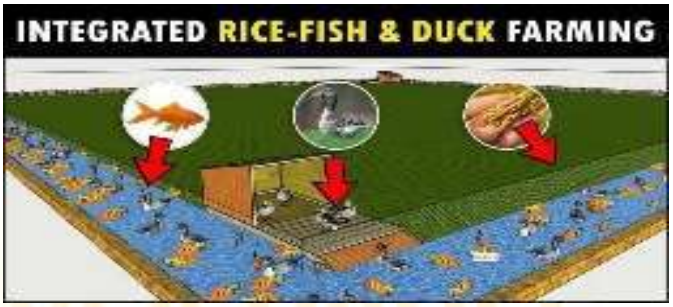


Fig. 1: Schematic layout of an integrated permaculture aquaculture farm.

Integration of Fish, Crops and Livestock: One of the greatest strengths of integrated permaculture lies in nutrient recycling. Fish convert feed into protein while simultaneously producing nutrient-rich wastes that stimulate natural productivity within ponds. Water containing dissolved nutrients is diverted to vegetable fields or aquaponics units, where plants absorb nitrogen and phosphorus before the cleaned water is returned to the fish pond. Ducks, poultry and other livestock contribute manure that enhances pond fertility, stimulates plankton production and reduces dependence on commercial fertilizers. Crop residues are converted into compost or vermi compost, which improves soil structure and moisture

retention. Through this continuous recycling process, farm productivity increases while waste generation is minimized.

Water Conservation and Climate Resilience: Water is the foundation of integrated farming systems. Permaculture employs numerous techniques, including farm ponds, contour bunds, swales, mulching, rainwater harvesting and drip irrigation to maximize water-use efficiency. These practices increase groundwater recharge, reduce runoff and minimize evaporation losses. During prolonged dry periods, stored pond water provides a reliable source of irrigation for crops and maintains fish production, thereby enhancing resilience against climate variability. Recent advances such as solar-powered pumps, automated irrigation systems and water-quality monitoring sensors further improve resource efficiency while reducing operational costs.



Fig. 2: Rainwater harvesting and nutrient recycling within an integrated permaculture system.

Biodiversity and Soil Health: Healthy soils and diverse biological communities are essential for sustainable farming. Integrated permaculture encourages the cultivation of multiple crop species, fruit trees, fodder grasses, aquatic vegetation and beneficial microorganisms. Organic matter from compost, green manure and livestock manure improves soil fertility, enhances microbial activity and increases water-holding capacity. Diverse habitats created by ponds, hedgerows and flowering plants attract pollinators, birds, frogs and predatory insects that naturally suppress pests. Such ecological interactions reduce the need for synthetic pesticides and contribute to long-term environmental sustainability.

Economic Benefits and Livelihood Diversification : Integrated Permaculture Aquaculture Systems provide farmers with multiple sources of income through fish production, vegetables, fruits, eggs, milk and value-added products. Diversification reduces production risks because the failure of one enterprise can be compensated for by returns from others. Although the initial investment may be slightly higher than conventional farming due to pond construction and infrastructure development, operational costs decrease considerably over time because nutrients, water and organic matter are recycled within the system. Government initiatives such as the Pradhan Mantri Matsya Sampada Yojana (PMMSY), National Mission on Natural Farming and various NABARD-supported programs further encourage adoption through financial assistance and technical guidance.

Table 1: Comparative performance of integrated permaculture and conventional farming systems

Parameter	**Integrated Permaculture**	**Conventional Monoculture**
Water Use Efficiency	High (up to 90% savings)	Low
Annual Protein Yield	2–5 t ha^{-1}	1–2 t ha^{-1}
Biodiversity Index	High	Low

Emerging Technologies for Smart Permaculture: Modern technologies are increasingly complementing traditional permaculture principles. Geographic Information System (GIS)-based land suitability mapping assists farmers in planning pond locations and water harvesting structures. Internet of Things (IoT)-based sensors continuously monitor water quality, dissolved oxygen and temperature, enabling timely management interventions. Artificial Intelligence (AI) supports disease prediction and feeding management, while drones facilitate crop health monitoring and precision agriculture. Integration of renewable energy technologies, particularly solar aerators and photovoltaic irrigation systems, further improves the sustainability and economic viability of integrated farming systems.

Mental Health and Wellness Benefits for Farmers : Modern farming is stressful. Permaculture systems address this by incorporating therapeutic elements such as pond-side meditation spaces, sensory gardens, and nature immersion zones. Water features provide calming soundscapes, while daily interaction with thriving ecosystems reduces stress and improves mental resilience. Community-based permaculture projects have shown notable improvements in farmer well-being across rural India.

Conclusion

Integrated Permaculture Aquaculture Systems represent a holistic farming approach that simultaneously addresses food security, environmental conservation and rural livelihood improvement. By integrating fish culture, crop production, livestock, trees and efficient water management, these systems maximize resource utilization while minimizing waste and dependence on external inputs. Their ability to improve soil fertility, conserve water, enhance biodiversity and diversify farm income makes them particularly suitable for climate-resilient agriculture in India. With increasing policy support, technological advancements and farmer awareness, integrated permaculture aquaculture has immense potential to transform smallholder farming into a profitable, sustainable and environmentally responsible enterprise. Continued research, demonstration farms and extension programs will further accelerate its adoption and contribute significantly to achieving sustainable agricultural development.

References

Mollison, B. (1988). Permaculture: A Designer's Manual. Tagari Publications.

Holmgren, D. (2002). Permaculture: Principles and Pathways beyond Sustainability.

FAO. (Various). Aquaculture and Integrated Farming Guidelines.

ICAR-CIFE. Aquaculture Engineering Manuals.

Boyd, C.E. (1995). Pond Bottom Soil and Water Quality Management.

Recent reports on regenerative agriculture from Indian institutions (2024-2026).

Natural Farming: A Sustainable Way to Grow Vegetables

Saranya R., R. Niranjan and T. Ilakiya

Introduction

Vegetable crops constitute a critical component of human nutrition, supplying vitamins, minerals, and dietary fibre essential for health. However, the production systems underpinning vegetable cultivation face mounting agronomic and ecological pressures. Decades of intensive chemical-input agriculture have contributed to soil organic matter depletion, declining groundwater availability, and escalating input costs relative to farm incomes. In this context, natural farming has emerged as a low-cost, ecologically oriented alternative for sustainable vegetable production. Grounded in traditional agricultural knowledge and increasingly supported by empirical research, natural farming offers a framework for reconciling productivity with long-term resource conservation.

Concept and Principles of Natural Farming

Natural farming is a chemical-free method of agriculture that relies entirely on on-farm resources and natural processes rather than synthetic fertilisers and pesticides. Popularised in India as Zero Budget Natural Farming (ZBNF), the approach was built on the idea that nature itself provides everything a crop needs, if farmers work with biological cycles instead of against them. It differs from organic farming in an important way: rather than substituting chemical inputs with purchased organic ones, natural farming minimises external inputs almost entirely, using preparations made from native cow dung, urine, and locally available plant material. The system rests on four widely recognised pillars: Beejamrutha, a seed treatment made from cow dung and urine that protects young roots from soil-borne pathogens; Jeevamrutha, a fermented microbial culture applied to soil to boost beneficial microorganisms and nutrient availability; Mulching, which conserves soil moisture, moderates temperature, and suppresses weeds; and Whapasa, the practice of maintaining an optimal balance of air and moisture in the soil rather than saturating it with irrigation.

Rationale for Adoption in Vegetable Production

Vegetable crops are comparatively input-intensive under conventional cultivation. Species such as tomato, brinjal, and cucurbits typically require substantial fertiliser application and frequent pesticide use, both of which elevate production costs and pose residue-related risks to producers and consumers. Natural farming addresses several of these constraints concurrently, as summarised below.

Reduced cost of cultivation: On-farm preparation of inputs from cow dung, urine, jaggery, and pulse flour substantially lowers dependence on purchased fertilisers and pesticides, thereby improving net returns even where yields remain comparable to conventional systems.

Saranya R., R. Niranjan and T. Ilakiya
Department of Vegetable Science, SRM College of Agricultural Sciences, Baburayanpettai, Chengalpattu, Tamil Nadu

Enhanced soil health: Regular application of Jeevamrutha promotes populations of beneficial soil microorganisms, improves soil structural stability, and restores organic carbon levels that conventional systems tend to deplete progressively.

Improved water-use efficiency: Mulching and adherence to the Whapasa principle reduce evaporative losses and assist shallow-rooted, moisture-sensitive vegetable crops in withstanding irregular rainfall patterns.

Reduced residue burden: The absence of synthetic pesticide application lowers the likelihood of chemical residues in harvested produce, a consideration of increasing relevance to consumer health and export compliance.

Climate resilience: Soils with higher organic matter content and microbial activity demonstrate improved buffering capacity against heat and moisture stress, a factor of growing significance under increasingly erratic weather conditions in tropical vegetable-growing regions.

Research Evidence on Soil Health, Yield and Sustainability

The claims made for natural farming are no longer only anecdotal. Recent studies have documented measurable ecological and economic benefits. Research on cow-based liquid formulations such as Panchagavya has shown their value as a lever for improving vegetable crop growth and yield while reducing dependence on synthetic fertiliser (Behera *et al.*, 2024). Broader assessments of natural farming systems have linked the practice to improved soil organic carbon, higher microbial activity, and better delivery of ecosystem services compared with conventional plots, while also emphasising the role of mulching in conserving soil moisture and building humus (Sarma *et al*., 2023). Traditional, low-input agricultural techniques of this kind, developed largely through farmer experience over generations, are now being re-examined and validated using contemporary scientific methods (Kumar *et al.*, 2023). Economic sustainability has also drawn research attention. Studies note that natural farming is only viable in the long run if it remains financially rewarding for farmers, and that reduced input costs combined with crop diversification can help cushion growers against market and weather-related risks (Das *et al.*, 2023). Policy-level transitions offer supporting evidence at scale: an analysis of Sikkim's state-wide shift to organic and natural farming practices found that government-led support systems could improve farmer welfare during the transition period, even as yields adjusted downward temporarily before recovering (Bhatt and John, 2023).

Constraints and Limitations in Adoption

Natural farming is not without limitations, and prospective adopters should approach the transition with realistic expectations. A temporary decline in yield is commonly observed during the first one to three cropping seasons, attributable to the time required for soil biological activity to re-establish following prolonged chemical input use. Adequate preparation of Jeevamrutha and Beejamrutha further requires consistent access to cattle

resources, a constraint for landless and resource-poor farmers. Pest and disease management also tends to be less predictable during the early transition period, as natural farming relies on preventive and biologically mediated control mechanisms rather than the rapid-acting efficacy of synthetic pesticides. Accordingly, a gradual, field-by-field transition, accompanied by systematic monitoring of soil and crop parameters, is generally recommended over an abrupt farm-wide conversion.

Strategies for Field-Level Implementation

Conversion to natural farming for vegetable cultivation need not proceed across an entire holding simultaneously. A phased approach is generally advisable, beginning with a limited plot under a single vegetable crop and expanding coverage as familiarity with Jeevamrutha and Beejamrutha preparation, and confidence in interpreting soil and crop response, increases. Sustained access to at least one native cattle breed is a prerequisite, given the dependence of natural farming inputs on cow dung and urine. Mulching material, whether crop residue, dried leaves, or straw, should be applied prior to sowing rather than afterward, as its principal function is to protect the soil surface from the earliest irrigation or rainfall event. Systematic observation of soil moisture, root development, and pest incidence during the transition period enables farmers to calibrate the frequency of Jeevamrutha application, which permits considerably greater flexibility than the fixed schedules associated with chemical fertiliser regimes. Institutional and extension support constitutes an additional determinant of successful adoption. Farmers who have transitioned successfully frequently attribute this to peer learning networks, farmer field schools, and state-level promotional programmes that provided guidance through the initial, more difficult seasons. As the shift to natural farming entails a change in both technical skill and management approach, access to trained extension personnel and demonstration plots can meaningfully reduce the associated learning curve.

Conclusion

Natural farming presents a viable intermediate pathway between the high input costs associated with conventional chemical agriculture and the certification requirements of formal organic production systems. By utilising inputs already available on most farms, the approach maintains low cultivation costs while progressively building soil health, with cumulative benefits realised across multiple cropping cycles rather than within a single season. Given increasing climate variability and its implications for vegetable production stability, agronomic practices that enhance intrinsic soil resilience are likely to assume greater importance. While natural farming does not eliminate every production constraint, the available evidence indicates that it constitutes a scientifically supported and practically viable strategy for sustainable vegetable cultivation.

References

Sarma, P., *et al*. (2023). Soil cover, mulching, and

humus formation in natural farming systems. As cited in: Assessing the role of natural farming in enhancing ecosystem services and sustainable agriculture. *Frontiers in Agronomy*, 2026.

Behera, S. R., Pandey, R., Golui, K., Sahoo, S., Jakhwal, R. and Pal, R. (2024). Application of Panchagavya, a cow-based liquid formulation, as a lever for sustainable and enhanced vegetable crop production: A review. *International Journal of Environment and Climate Change*, 14(5): 214-232.

Bhatt, A. and John, J. (2023). Including farmers' welfare in a government-led sector transition: The case of Sikkim's shift to organic agriculture. *Journal of Cleaner Production*, 411: 137207.

Das, S., *et al.* (2023). Economic sustainability and biotechnology-assisted natural farming. As cited in: Synergizing biotechnology and natural farming: Pioneering agricultural sustainability through innovative interventions. *Frontiers in Plant Science*, 15, 1280846.

Kumar, A., *et al.* (2023). Traditional agricultural systems and on-farm techniques: A knowledge review. As cited in: Assessing the role of natural farming in enhancing ecosystem services and sustainable agriculture. *Frontiers in Agronomy*, 2026.

Blockchain Technology: Integrated Seed Supply Chain System

Logapriya S., S. Sandhiya, G. Hemalatha, T. Ramanadane, K. Manojkumar and V. Vasanth

Abstract

Seeds are the foundation of agricultural productivity and ensuring their quality, purity, and authenticity is essential for achieving sustainable agriculture and global food security. However, conventional seed supply chains face several challenges, including poor traceability, record manipulation, dependence on intermediaries, quality deterioration, and lack of transparency. Blockchain technology offers a promising solution by providing a decentralized, transparent, immutable, and traceable digital ledger that securely records every transaction across the seed supply chain. This paper discusses the working principles of blockchain, its major types, and its key characteristics with emphasis on their role in strengthening seed quality assurance. The article also highlights the implementation of a blockchain-based seed distribution system in Jharkhand, the first Indian state to adopt this technology for transparent subsidized seed distribution and farmer authentication. Overall, blockchain-enabled seed supply systems represent an innovative pathway toward a secure, reliable, and transparent agricultural ecosystem that strengthens food security and promotes sustainable agricultural development.

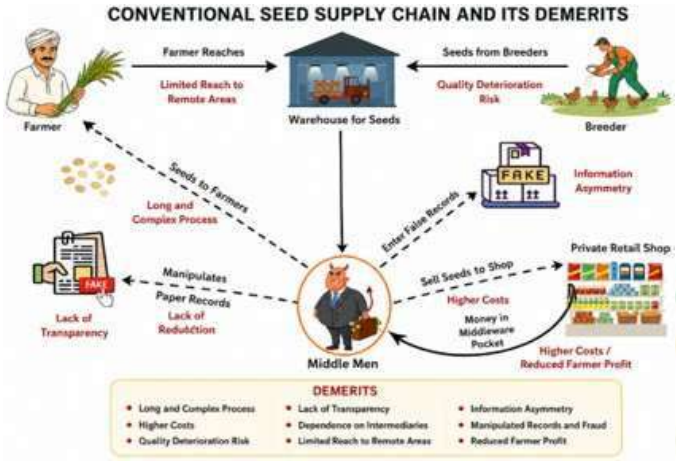
Introduction

Every harvest begins with a seed, and the future of food security depends on its quality, purity, and authenticity. In an era where sustainable agriculture has become a global priority, the United Nations introduced the 17 Sustainable Development Goals (SDGs) to build a hunger-free and sustainable world by 2030. Among these, SDG 2 - Zero Hunger promotes food security and sustainable agriculture, while SDG 9 -Industry, Innovation and Infrastructure encourages the adoption of advanced technologies for sustainable development (United Nations in India). Seeds are the foundation of agricultural productivity, carrying the genetic potential that determines crop yield, quality and resilience.

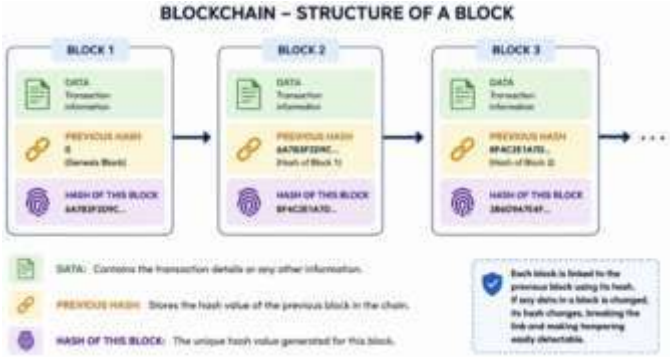
Although seed certification systems are designed to maintain varietal purity and ensure quality standards, conventional methods often face challenges such as limited traceability, lack of transparency, and risks of data manipulation. In this digital age, blockchain technology is emerging as a revolutionary solution for strengthening seed quality assurance. With its decentralized, transparent, and tamper-proof nature, blockchain enables secure tracking of every stage in the seed supply chain from production and certification to storage and distribution. By enhancing trust, traceability, and accountability, blockchain-enabled seed quality assurance offers a smarter and more reliable pathway toward sustainable agriculture and global food security.

Logapriya S., S. Sandhiya, G. Hemalatha, T. Ramanadane, K. Manojkumar and V. Vasanth
Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal, Puducherry

Conventional Seed Supply Chain: The conventional seed supply chain works accordingly. This system of seed supply has a lot of demerits such as quality deterioration risk, manipulation of records, dependence on inter-mediaries, higher costs and information asymmetry which can be overcome by the inclusion of block-chain technology in this supply system.

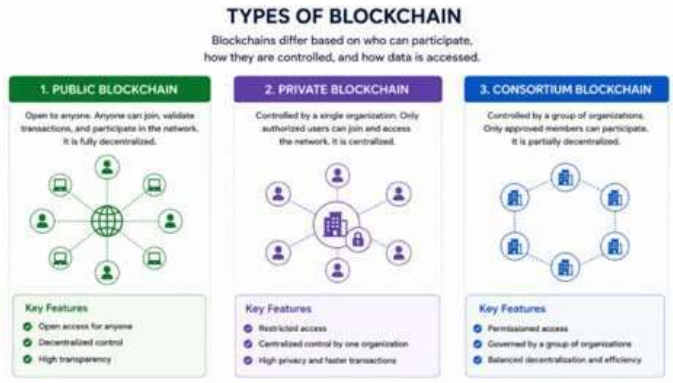


Blockchain Technology: Blockchain is a distributed ledger maintaining a continuously growing list of data records that are confirmed by all of the participating nodes. The data is recorded in this public ledger in a form of blocks of valid transactions, and this public ledger is shared and available to all nodes (Raikwar *et al.*, 2019). A blockchain block consists of three major components. The data stored within the block, the hash value of the previous block, and its own unique hash value, which together create a secure and interconnected chain structure (Lightwala *et al.*, 2022). GeeksforGeeks (2025) explained that a hash function is a mathematical function that converts input data of any size into a fixed-length output value known as a hash value or hash code.



Types of Blockchain

There are three major types of blockchain. They are public blockchain, private blockchain and consortium blockchain (FAO and ITU, 2019).



Characteristics of the Blockchain Technology

The important characteristics of the block-chain technology are decentralization, traceability, immutability and transparency (Li, 2025).

Decentralization: Contemporarily, the centre gathers and controls flow of information in a system. This system is not only costly but also highly susceptible to security breaches and information loss. When supplier records become unavailable or lost farmers as end users are unable to link seed related information with the agricultural commodity supply chain, which ultimately leads to break in upstream traceability. As a result, it reduces market demand and credibility. Blockchain technology solves this issue through a decentralized framework in which

data is shared across multiple network participants. Within blockchain the information are no longer dependent on a single participant in supply chain. Even if one participant lost the data, identical records remain securely with other participants.

Traceability: Traceability refers to the capability of blockchain technology to track the origin and movement of data through its linked chain structure while permanently storing historical records from the genesis block onward. The traceability feature of blockchain enables consumers to obtain accurate information regarding the production location, cultivation period, and history of a product, thereby improving product reliability and consumer confidence.

Immutability: Immutability refers to the characteristic of blockchain in which stored records cannot be modified once they are verified and added to the network through consensus among participating nodes. Cryptographic techniques securely link each block, making unauthorized modifications highly difficult, complex, and costly. Even a minor modification in the input data produces a completely different hash output. Because each hash value is uniquely linked to its original data, any alteration can be easily detected. Thereby greatly improving data reliability and trustworthiness in the seed supply chain.

Transparency: Blockchain technology records each transaction using asymmetric encryption enabling all participants in the network to view and verify transaction details. This creates a highly transparent and accessible system of data management. In the event of disputes or inconsistencies, relevant information can be retrieved quickly and efficiently by authorized participants. Since every transaction is permanently recorded and can be monitored at any stage, blockchain establishes a strong framework of accountability and trust among users involved in the network.

Implementation of Blockchain Technology

Jharkhand became the first Indian state to implement a production-grade blockchain-based seed distribution system to improve transparency and efficiency in agriculture. The system registers farmers using Aadhaar and mobile numbers, and seed distribution is authenticated through OTP verification. Blockchain enables real-time monitoring of seed distribution, including crop varieties, quantities distributed, and farmer purchase records. The initiative supports transparent delivery of subsidized seeds and helps create a reliable farmer database for better implementation of agricultural and horticultural schemes. The system is expected to reduce pilferage and allow farmers to verify the quality and quantity of seeds received (Asian News International, 2022).

Limitations in Blockchain Technology



Conclusion

Blockchain is not merely a technological innovation. It's the foundation for a smarter and more transparent agricultural future which can bridge the gap between breeders and farmers by creating a secure and tamper-proof seed supply system. As the world faces increasing challenges related to food security and agricultural sustainability, the adoption of blockchain technology in seed supply chain offers promising path forward. Traceability, accountability, and transparency can revolutionize the agricultural sector, empowering farmers while strengthening consumer confidence. The seed of tomorrow may not only grow crops but also cultivate trust through blockchain-enabled agriculture.

"If agriculture goes wrong, nothing else will have a chance to go right" -M. S. Swaminathan

References

Asian News International. (2022, August 18). Jharkhand is India's 1st to use blockchain technology to distribute seed to farmers. NDTV. https://www.ndtv.com/india-news/jharkhand-is-indias-1st-to-use-blockchain-technology-to-distribute-seed-to-farmers-3266915

Lightwala, N., Sherdiwala, M. and Kanade, A. (2022). *Seed certification using blockchain technology*. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 8(6): 280-286.

Ahuja, R., Chugh, S. and Singh, R. (2024). Seed Chain: A secure and transparent blockchain-driven framework to revolutionize the seed supply chain. *Future Internet*, 16(4): 132.

Food and Agriculture Organization of the United Nations (FAO) & International Telecommunication Union (ITU). (2019). E-agriculture in action: Blockchain for agriculture opportunities and challenges. FAO. https://openknowledge.fao.org/server/api/core/bitstreams/66ce8120-ed1b-4469-a4ca-08529d3b0774/content

GeeksforGeeks. (2025). *Hash functions and types of hash functions*. GeeksforGeeks. https://www.geeksforgeeks.org/hash-functions-and-list-types-of-hash-functions/

Li, H. (2025). Research on agricultural product seed traceability system based on blockchain technology. In Proceedings of the 3rd International Conference on Management Research and Economic Development (Vol. 177, pp. 108-114).

Raikwar, M., Gligoroski, D. and Kralevska, K. (2019). *SoK of used cryptography in blockchain*. IEEE Access, 7: 148550-148575.

SettleMint. (2022). *Jharkhand introduces blockchain technology in seed distribution.* SettleMint News. https://news.settlemint.com/news/jharkhand-blockchain-seed-distribution

The Fungal Pharmacy: Unlocking the Hidden Health Benefits of Mushrooms

Shivam

Abstract

Mushrooms have been an interesting part of human life for generations. Fungi, which are neither plants nor animals, are members of their own unique kingdom. They are a vast, primarily underground network of mycelial threads that sometimes raise their fruiting bodies above the ground. Western science is only now starting to understand the molecular principles underlying the centuries-old Eastern medical traditions' veneration of mushrooms as powerful tonics for lifespan. Mushrooms are much more than just a low-calorie culinary curiosity, according to contemporary analytical methods. They are dense pharmacological factories that produce complex carbohydrates, special antioxidants, and substances that stimulate nerve growth and interact with human biology in a seamless manner.

Introduction

The nutritional foundation: More than just water

Before diving into the complex medicinal compounds, it is crucial to appreciate the baseline nutritional profile of edible fungi. Mushrooms are composed of roughly 90% water, but the remaining 10% is exceptionally nutrient-dense. They are one of the few non-animal sources of ergosterol, a precursor to Vitamin D_2. When exposed to ultraviolet light (either naturally from the sun or commercially via UV lamps post-harvest), mushrooms convert this ergosterol into bioavailable vitamin D, making them a crucial dietary component for bone health and immune function. Furthermore, mushrooms provide a robust array of B-vitamins particularly riboflavin, niacin and pantothenic acid which are essential for cellular energy production.

Minerals are also abundant. Mushrooms act as bio-accumulators, absorbing trace elements from their substrate. They are particularly rich in selenium, a critical cofactor for antioxidant enzymes, as well as potassium and copper.

Key insight: While standard button mushrooms excel in basic vitamins, functional varieties like Reishi and Lion's Mane dominate in specialized polysaccharides and antioxidants, making the choice of mushroom highly dependent on your health goals.

Immunomodulation: The Beta-Glucan Connection

Perhaps the most rigorously studied aspect of mycotherapy (the use of mushrooms for health) is their impact on the human immune system. This effect is primarily driven by beta-glucans, a class of complex, heavy-weight polysaccharides found in the

Shivam
Research Scholar, Department of Plant Pathology, Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh

fungal cell walls. Unlike simple sugars that provide immediate energy, beta-glucans act as biological response modifiers. When consumed, these molecules pass through the stomach and reach the intestines, where they interact with specialized immune tissue called Peyer's patches. The human body recognizes fungal beta-glucans as foreign likely a deeply conserved evolutionary alarm system meant to detect pathogenic fungi. However, rather than triggering a destructive inflammatory cascade, these specific mushroom polysaccharides gently "wake up" the immune system. They bind to specific receptors (such as Dectin-1 and TLR2) on the surface of our innate immune cells.

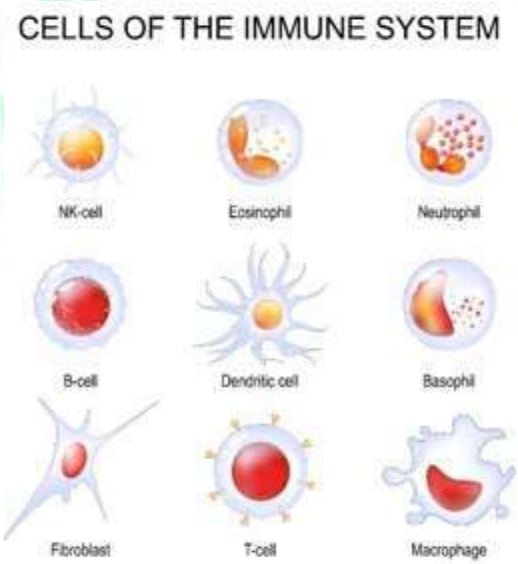


Fig. 1 Immune cells activated by fungal beta-glucans (Source: ttsz / Getty Images)

This binding process primes several critical immune players:

Macrophages: The "pac-man" cells that engulf and destroy cellular debris and pathogens. Beta-glucans increase their phagocytic activity.

Natural Killer (NK) Cells: Lymphocytes that specialize in identifying and destroying virally infected or cancerous cells.

T-Cells and B-Cells: The targeted snipers of the adaptive immune system, whose communication is enhanced by the cytokines released during beta-glucan interaction.

By priming these cells, mushrooms like Shiitake (*Lentinula edodes*) and Turkey Tail (*Trametes versicolor*) don't overstimulate the immune system which could lead to autoimmunity but rather modulate it, bringing it to a state of heightened readiness.

Neuroprotection: Fungi for the Brain

While immune support is a generalized benefit of many basidiomycete fungi, one specific mushroom has captured the attention of neurologists globally: Lion's Mane (*Hericium erinaceus*).

Recognizable by its cascading, icicle-like white spines, Lion's Mane produces two unique classes of neurotrophic (nerve-growing) compounds:

- ✓ **Hericenones:** Found primarily in the visible fruiting body of the mushroom.
- ✓ **Erinacines:** Found mostly in the subterranean mycelial network.

Both of these compounds are remarkable because they are small enough to cross the blood-brain barrier. Once inside the brain, they stimulate the synthesis of Nerve Growth Factor (NGF) and Brain-Derived Neurotrophic Factor (BDNF). These proteins are the biological equivalent of fertilizer for neurons. They promote neurogenesis (the growth of new neurons), aid in the repair of damaged myelin

sheaths (the protective coating around nerves), and enhance synaptic plasticity. Clinical trials and in vivo studies suggest that regular consumption of Lion's Mane extract can improve cognitive function, mitigate age-related cognitive decline and potentially offer protective effects against neurodegenerative conditions like Alzheimer's and Parkinson's diseases.

Key insight: While standard button mushrooms excel in basic vitamins, functional varieties like Reishi and Lion's Mane dominate in specialized polysaccharides and antioxidants, making the choice of mushroom highly dependent on your health goals.

Antioxidant Arsenals: Ergothioneine and Glutathione

Cellular aging is largely driven by oxidative stress, the accumulation of highly reactive free radicals that damage DNA, proteins, and cell membranes. To combat this, the human body relies on antioxidants. Mushrooms happen to be the highest dietary source of two exceptionally potent intracellular antioxidants: Ergothioneine (ERGO) and Glutathione (GSH). Ergothioneine is particularly fascinating. It is an amino acid derivative synthesized exclusively by fungi and certain mycobacteria; humans cannot produce it. However, human cells possess a highly specific transport protein (OCTN1) dedicated solely to pulling ergothioneine out of the bloodstream and moving it directly into cells that are under high oxidative stress. The existence of this dedicated receptor suggests that ERGO plays an evolutionarily vital role in human survival. Higher dietary intake of ergothioneine has been strongly correlated with lower incidences of chronic inflammatory diseases and reduced cardiovascular risk. Varieties like Porcini and Oyster mushrooms contain massive concentrations of both ERGO and GSH, acting as powerful anti-aging tools at the cellular level.

Gut Health: Prebiotic Properties

The human microbiome the trillions of bacteria residing in our digestive tract dictates everything from our mood to our metabolism. Mushrooms support this ecosystem by acting as potent prebiotics. The chitin and beta-glucans that make up the structural integrity of a fungal fruiting body are largely indigestible by human stomach enzymes. As they pass intact into the colon, they become a prime food source for beneficial bacteria like Bifidobacterium and Lactobacillus. As these bacteria ferment the fungal fibres, they produce short-chain fatty acids (SCFAs) like butyrate, which reduce gut inflammation, repair the intestinal lining, and regulate systemic metabolism.

Conclusion

The intersection of mycology and human physiology is one of the most exciting frontiers in modern nutritional science. As we move past viewing mushrooms merely as culinary ingredients and begin to understand the biochemical complexity of their fruiting bodies and mycelium, their role in preventative medicine becomes undeniable. From the immune-modulating beta-glucans to the neuro-regenerative erinacines, the fungal pharmacy offers a vast, natural toolkit for optimizing human health.

References

Beelman, R. B., Kalaras, M. D. and Richie, J. P. (2019). Micronutrients and bioactive compounds in mushrooms: A recipe for healthy aging?. *Nutrition Today*, 54(1): 16-22.

Friedman, M. (2015). Chemistry, nutrition, and health-promoting properties of *Hericium erinaceus* (Lion's Mane) mushroom fruiting bodies and mycelia and their bioactive compounds. *Journal of Agricultural and Food Chemistry*, 63(32): 7108-7123.

Roupas, P., Keogh, J., Noakes, M., Margetts, C. and Taylor, P. (2012). The role of edible mushrooms in health: Evaluation of the evidence. *Journal of Functional Foods*, 4(4): 687-709.

Valverde, M. E., Hernández-Pérez, T. and Paredes-López, O. (2015). Edible mushrooms: Improving human health and promoting quality life. *International Journal of Microbiology*, 2015: 376387.

Wasser, S. P. (2017). Medicinal mushrooms in human clinical studies. Part I. Anticancer, oncoimmunological, and immunomodulatory activities: A review. *International Journal of Medicinal Mushrooms*, 19(4): 279-317.

Innovations in Vegetable Production Technology for Food Security

Yeshwanth B. and Kaameshvaran A.

Introduction

Food security remains one of the greatest challenges facing the world today. The rapid growth of the global population, urbanization, climate change, and shrinking agricultural resources have increased the demand for nutritious food. Vegetables play a vital role in ensuring food and nutritional security because they are rich sources of vitamins, minerals, fiber, and antioxidants. They help combat malnutrition and improve overall human health. However, traditional methods of vegetable cultivation often face challenges such as low productivity, pest and disease outbreaks, water scarcity, and environmental degradation. To overcome these challenges and ensure a stable supply of vegetables, various innovations in vegetable production technology have been developed. These technologies aim to increase productivity, improve quality, conserve resources, and promote sustainable agriculture, thereby contributing significantly to food security.

Importance of Vegetable Production for Food Security

Vegetables are an essential component of a balanced diet and are often referred to as protective foods because they provide nutrients necessary for growth, development and disease prevention. Increasing vegetable production is important not only for meeting nutritional requirements but also for generating income and employment opportunities, especially in rural areas. As populations continue to grow, the demand for fresh vegetables is increasing rapidly. Therefore, improving vegetable production through technological innovations is crucial for ensuring adequate food availability, accessibility, and affordability. Modern technologies enable farmers to produce more vegetables on limited land while reducing environmental impacts and production costs.

Protected Cultivation Technology

Protected cultivation is one of the most significant innovations in vegetable production. It involves growing crops under structures such as greenhouses, polyhouses, shade nets, and low tunnels, where environmental conditions can be partially or fully controlled. This technology protects crops from unfavorable weather conditions such as excessive rainfall, high temperatures, frost, and strong winds. Protected cultivation allows year-round production of vegetables and ensures higher yields compared to open-field farming. Crops such as tomato, cucumber, capsicum, and leafy vegetables perform exceptionally well under protected structures. By providing an optimal growing environment, protected cultivation enhances crop quality, reduces

Yeshwanth B. and Kaameshvaran A.
Department of Vegetable Science, SRM College of Agricultural Sciences, SRM College of Agricultural Sciences, Chengalpattu, Tamil Nadu

pest and disease incidence, and increases farmers' income while contributing to food security.

Precision Farming in Vegetable Production

Precision farming is a modern agricultural approach that uses advanced technologies such as Global Positioning Systems (GPS), sensors, drones, satellite imagery, and data analytics to optimize crop management practices. In vegetable production, precision farming helps farmers monitor soil conditions, nutrient status, water requirements, and crop health with great accuracy. By applying inputs such as water, fertilizers, and pesticides only where and when they are needed, precision farming reduces waste and improves resource-use efficiency. This technology helps maximize yields while minimizing environmental impacts. The adoption of precision farming is particularly important in areas where resources are limited and efficient production is necessary to meet growing food demands.

Drip Irrigation and Fertigation

Water scarcity is a major challenge affecting vegetable production worldwide. Drip irrigation has emerged as an effective solution by delivering water directly to the root zone of plants through a network of pipes and emitters. This method significantly reduces water losses due to evaporation and runoff. Fertigation, the practice of applying fertilizers through irrigation systems, further enhances nutrient -use efficiency by providing nutrients directly to plant roots. Together, drip irrigation and fertigation improve crop growth, increase yields, and reduce production costs. These technologies are especially beneficial in arid and semi-arid regions where water conservation is critical. By improving water and nutrient management, drip irrigation and fertigation contribute substantially to sustainable vegetable production and food security.

Hydroponics Technology

Hydroponics is an innovative method of growing plants without soil by using nutrient-rich water solutions. In hydroponic systems, plant roots are supplied with all essential nutrients dissolved in water, allowing crops to grow efficiently in controlled environments. This technology requires significantly less water than conventional agriculture and can be practiced in urban areas, rooftops, and regions with poor soil quality. Hydroponic cultivation produces high-quality vegetables with faster growth rates and higher yields. Crops such as lettuce, spinach, basil, tomato, and cucumber are commonly grown using hydroponic systems. As agricultural land becomes scarce, hydroponics offers a promising solution for increasing vegetable production and ensuring food availability.

Vertical Farming

Vertical farming is an advanced agricultural technique that involves growing crops in vertically stacked layers within controlled environments. This system utilizes artificial lighting, climate control, and hydroponic or aeroponic technologies to maximize space utilization. Vertical farming is particularly suitable for urban areas where land availability is limited. It enables year-round vegetable production with minimal water use and reduced

dependence on weather conditions. Since crops are grown close to consumers, transportation costs and post-harvest losses are also minimized. Vertical farming has the potential to revolutionize urban food systems and contribute significantly to food security by providing fresh vegetables through-out the year.

Improved Varieties and Hybrid Technology

The development of high-yielding and hybrid vegetable varieties has greatly enhanced agricultural productivity. Plant breeders have developed improved varieties with characteristics such as higher yield potential, resistance to pests and diseases, tolerance to drought and heat stress, and improved nutritional quality. Hybrid varieties often exhibit superior vigor and productivity compared to traditional varieties. These improved cultivars help farmers achieve higher yields even under challenging environmental conditions. The widespread adoption of improved vegetable varieties has contributed significantly to increasing food production and ensuring a stable supply of nutritious vegetables for growing populations.

Biotechnology in Vegetable Production

Biotechnology has become an important tool for enhancing vegetable production and addressing agricultural challenges. Techniques such as tissue culture, molecular breeding, genetic engineering, and genome editing enable scientists to develop improved crop varieties more efficiently. Biotechnology helps create vegetables that are resistant to pests, diseases, and environmental stresses, thereby reducing crop losses and increasing productivity. It also enables the development of nutrient-enriched vegetables that can help address micronutrient deficiencies. By accelerating crop improvement and enhancing resilience, biotechnology plays a crucial role in achieving sustainable food security.

Integrated Nutrient Management

Maintaining soil fertility is essential for sustainable vegetable production. Integrated Nutrient Management (INM) involves the balanced use of organic manures, biofertilizers, crop residues, and chemical fertilizers to meet crop nutrient requirements. This approach improves soil health, enhances nutrient availability, and increases crop productivity. Organic inputs such as compost and farmyard manure improve soil structure and microbial activity, while chemical fertilizers provide immediate nutrient supply. By combining different nutrient sources, INM ensures sustainable crop production while minimizing environmental degradation. The adoption of integrated nutrient management practices contributes to long-term food security by maintaining productive agricultural soils.

Integrated Pest Management

Pests and diseases cause significant losses in vegetable production. Integrated Pest Management (IPM) is an environmentally friendly approach that combines biological, cultural, mechanical, and chemical control methods to manage pests effectively. IPM emphasizes the use of resistant varieties, biological control agents, crop rotation, pheromone traps, and regular monitoring to reduce pest populations. Chemical pesticides are used only when neces-

sary and in a targeted manner. This approach reduces pesticide dependence, minimizes environmental contamination, and ensures the production of safe and healthy vegetables. By protecting crops from losses while preserving ecological balance, IPM contributes to sustainable food production.

Internet of Things (IoT) in Vegetable Farming

The Internet of Things (IoT) has transformed modern agriculture by enabling real-time monitoring and management of crop production systems. IoT devices such as soil moisture sensors, temperature sensors, humidity sensors, and automated irrigation systems collect and transmit data continuously. Farmers can access this information through smartphones or computers and make informed decisions regarding irrigation, fertilization and crop protection. Automated systems can also respond to changing environmental conditions without human intervention. IoT technology improves resource efficiency, reduces labor requirements and enhances productivity, making it a valuable innovation for ensuring food security.

Artificial Intelligence and Drone Technology

Artificial Intelligence (AI) and drone technology are increasingly being integrated into vegetable production systems. AI algorithms analyze large amounts of agricultural data to predict crop performance, detect diseases, optimize irrigation schedules, and recommend management practices. Drones equipped with cameras and sensors provide aerial images of fields, enabling rapid assessment of crop health and identification of problem areas. These technologies improve decision-making, reduce production costs, and increase productivity. Their application in vegetable farming helps farmers manage crops more efficiently and contributes to sustainable food production.

Climate-Smart Vegetable Production

Climate change poses serious threats to agricultural productivity through rising temperatures, irregular rainfall, droughts, floods, and increased pest pressures. Climate-smart vegetable production technologies aim to improve resilience while maintaining productivity. Practices such as mulching, rainwater harvesting, conservation agriculture, protected cultivation, and the use of climate-resilient varieties help farmers adapt to changing environmental conditions. These approa-ches improve water-use efficiency, protect soil resources, and reduce vulnerability to climate-related risks. Climate-smart agriculture is essential for ensuring stable vegetable production and long-term food security.

Urban and Peri-Urban Vegetable Farming

Urban and peri-urban agriculture has emerged as an important strategy for increasing food production close to consumers. Rooftop gardens, terrace farming, community gardens, and vertical farming systems enable vegetable cultivation in cities and surrounding areas. These production systems reduce transportation costs, provide fresh produce, and enhance local food security. Urban agriculture also promotes environmental sustainability by utilizing unused spaces and reducing the

carbon footprint associated with food distribution. As urban populations continue to grow, urban vegetable farming will play an increasingly important role in ensuring access to nutritious food.

Conclusion

Innovations in vegetable production technology are transforming agriculture and strengthening food security across the world. Technologies such as protected cultivation, precision farming, drip irrigation, hydroponics, vertical farming, biotechnology, IoT-based monitoring systems, artificial intelligence, and climate-smart agriculture have significantly improved productivity, resource-use efficiency, and sustainability. These innovations enable farmers to produce more vegetables with fewer resources while overcoming challenges such as climate change, water scarcity, and declining agricultural land. By increasing the availability of nutritious vegetables and supporting sustainable agricultural development, modern vegetable production technologies contribute directly to food and nutritional security. Continued investment in research, extension services, farmer training, and technology adoption will be essential for meeting future food demands and ensuring a healthy and food-secure population.

References

Keatinge, J. D. H., Yang, R. Y., Hughes, J. d'A., Easdown, W. J. and Holmer, R. (2011). The importance of vegetables in ensuring both food and nutritional security in attainment of the Millennium Development Goals. *Food Security*, 3(4): 491-501.

Bora, S. D. and Bora, G. C. (2026). Problems and prospects of vegetable production improvement in India: A review. *Agricultural Sciences: Techniques and Innovations*, 9: 45-66.

Kumar, A. (2025). Advances and challenges in vegetable science for sustainable food security. *International Journal of Agricultural Sciences.* https://doi.org/10.18782/2582-7146.273

Pandey, S., Sagar, V., Krishnan, N., Devi, J., Yadav, P. S. and Kujur, S. N. (2024). Trends and developments in vegetable research in India: A review. *Current Horticulture*, 12(3): 3-23.

Rajput, S., Choudhary, P., Eraqui, S., Belchandan, S., Sahu, N., Sahu, C. K., Thakur, H. and Veerapur, S. (2026). Smart vegetable farming: AI and precision technologies-A comprehensive review. *International Journal of Agronomy and Agricultural Research*, 9 (Special Issue 4).

Microgreens: Tiny Greens with Powerful Nutrition

Harithraadevi L.

Abstract

Healthy eating begins with choosing foods that nourish the body, yet modern lifestyles often make it difficult to access fresh and nutrient-rich produce. In this context, microgreens have emerged as a simple but powerful addition to everyday diets. Harvested at an early stage of growth, these tender greens are packed with vitamins, minerals, antioxidants and other beneficial plant compounds that support health and well-being. They are easy to grow, require very little space and can be produced throughout the year, making them suitable for homes, schools and urban farming. Beyond their use as fresh greens, microgreens can also be incorporated into a range of value-added products, opening new opportunities for healthier foods and small-scale entrepreneurship. With their remarkable nutritional quality, sustainability and culinary versatility, microgreens are proving that even the smallest greens can make a meaningful contribution to better nutrition and a healthier future. This article explores their nutritional importance, cultivation, diverse uses and growing potential as a smart food for the modern world.

Introduction

Good health begins with the food we eat. However, changing lifestyles, rapid urbanisation and busy schedules have altered our dietary habits, making it increasingly difficult to consume fresh and nutritious foods every day. Have you ever noticed tiny green seedlings decorating salads, sandwiches or gourmet dishes? These delicate greens, known as microgreens, are much more than an attractive garnish. Microgreens are more than just tiny vegetables. They are functional foods that nourish the body. They provide extra health benefits and reduce the risk of certain diseases. Despite their small size, they are packed with nutrients, vibrant flavours and health-promoting compounds, earning them the title of "superfoods in miniature." Their short growth cycle, minimal space requirement and year-round cultivation make them an ideal choice for home gardens, urban farming and sustainable food production. As consumer awareness of nutrition and preventive healthcare continues to grow, micro-greens are rapidly emerging as a smart food for the future, offering a simple way to enrich daily diets with fresh, nutrient-dense greens.

What are microgreens?

Microgreens are the young edible seedlings of vegetables, herbs and a few grains. They are harvested at a very early stage of growth, when the first true leaves begin to emerge. They are typically ready within 7-21 days after germination, when the

Harithraadevi L.
M. Sc. Scholar, Department of Postharvest Technology, Horticultural College and Research Institute, TNAU, Periyakulam, Theni, Tamil Nadu

cotyledons have fully opened. At harvest, they are only 2.5-7.5 cm (1-3 inches) tall, making them small in size but remarkably vibrant in appearance and flavour (Heena *et al.*, 2026). These tender greens are produced from a wide range of crops, including broccoli, cabbage, kale, mustard, radish, beetroot, coriander and sunflower. Because they grow quickly and require very little space, they can be cultivated easily in homes, balconies, rooftops or even on a sunny windowsill. Although they are often confused with sprouts, microgreens are quite different. Sprouts are grown in water and consumed whole, including the roots, whereas microgreens are grown in a suitable growing medium with adequate light and only the stem and leaves are harvested. This cultivation method gives microgreens their characteristic texture, vibrant colour and concentrated flavour. Often described as "tiny greens with a big impact," microgreens combine freshness, convenience and exceptional nutritional value, making them an ideal addition to modern healthy diets.



Fig. 1: Journey of Broccoli Microgreens: From Seed to Superfood

Nutritional Powerhouses and Health Benefits

Don't let their tiny size fool you. Microgreens are among the most nutrient-dense foods nature has to offer. They are often called as "vegetable confetti" because of their vibrant colours and delicate appearance. These young greens are packed with essential nutrients that support overall health (Yadav *et al.*, 2019). They contain significantly higher levels of vitamins, minerals and antioxidants than their mature counterparts. They are excellent sources of vitamins C, E, and K, along with important minerals such as iron, zinc, calcium, potassium and magnesium. These nutrients contribute to healthy bones and muscles, support the immune system and aid oxygen transport in the body. They also support vision and promote normal metabolic functions (Kyriacou *et al.*, 2021). What makes microgreens even more special is their abundance of natural bioactive compounds, including phenolics, flavonoids, carotenoids, vitamin C (ascorbic acid), vitamin E (tocopherols) and vitamin K (phylloquinone). These compounds act as powerful antioxidants that protect the body's cells from damage caused by harmful free radicals, thereby supporting long-term health. Among the different types of microgreens, *Brassica* microgreens such as broccoli, cabbage, kale, mustard and radish deserve special attention. They are naturally rich in glucosinolates, which are converted into isothiocyanates when the greens are cut or chewed. These naturally occurring compounds have been widely studied for their antioxidant, anti-inflammatory and potential cancer-protective properties, making Brassica microgreens an excellent choice for health-conscious consumers (Marchioni *et al.*, 2021).

Table 1: Microgreens with nutritional benefits

Microgreens	Nutritional Highlights	Reference
Broccoli	Higher levels of magnesium (Mg), manganese (Mn), copper (Cu) and zinc (Zn)	Weber (2017)
Red cabbage	Contains about twice the vitamin C (ascorbic acid) compared to mature red cabbage	Wu *et al.* (2023)
Parsley	Provides 1.8 times more lutein and 2.8 times more β-carotene than mature parsley	El-Nakhel *et al.* (2021)
Celery	Richer in essential macronutrients, including nitrogen (N), phosphorus (P), sodium (Na), calcium (Ca) and sulphur (S)	Singh *et al.* (2023)
Coriander	Contains higher amounts of β-carotene, vitamins C, E, and K, along with essential minerals such as calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), selenium (Se) and molybdenum (Mo), while having lower nitrate content	Dhakshayani *et al.* (2022)

Interestingly, studies have shown that microgreens often contain higher concentrations of vitamins, minerals, and health-promoting phytochemicals than their fully mature vegetables. This means that even a small handful of these tender greens can provide a concentrated nutritional boost, making them a simple yet powerful addition to everyday meals.

A Rainbow of Choices: One of the most exciting features of microgreens is the wide variety of crops they can be grown from. Popular microgreens include broccoli, cabbage, kale, radish, mustard, spinach, lettuce, beetroot, amaranth, coriander (cilantro), basil, celery, arugula, mizuna, buckwheat and sunflower. Each variety offers its own unique combination of colour, texture, flavour and nutrients, ranging from mildly sweet and earthy to pleasantly spicy and peppery. This diversity not only enhances the visual appeal of meals but also allows consumers to enjoy a range of health benefits by including different microgreens in their daily diet.

Growing microgreens at home: Apart from being highly nutritious, microgreens are remarkably easy to grow. They require very little space, mature within two to three weeks and can be cultivated throughout the year. Whether on a balcony, terrace, windowsill or any well-lit indoor space, they fit easily into modern homes. Indoor cultivation is often preferred as it allows better control over light, temperature and humidity, resulting in healthy, uniform growth. This makes microgreens an excellent choice for urban households, apartments, schools and anyone interested in producing fresh vegetables year-round.

Choosing the Right Growing Medium: Microgreens can be grown in a variety of growing media, including cocopeat, potting soil, tissue paper and hydroponic mats. Among these, a mixture of cocopeat, vermiculite and perlite (5:2:1) is commonly preferred as it provides good moisture retention, proper aeration and favourable conditions for healthy root development. Since the nutrients stored within the seed are sufficient to support early growth, microgreens generally do not require additional fertilisers during their short cultivation period, making their production simple and cost-effective. Healthy germination mainly depends on maintaining adequate moisture, suitable temperature and proper light. However, excessive watering or poor air circulation can encourage fungal infection. Therefore, careful watering and good hygiene are essential for producing fresh and healthy microgreens.

Sowing the Seeds: Select good-quality, untreated seeds suitable for microgreen production. Spread the

seeds evenly over the moist growing medium without overcrowding, then gently press them to ensure good contact with the surface. Mist the seeds lightly with water and keep them moist until germination. Most microgreens do not require additional fertilisers during their short growing period, as the seed itself provides sufficient nutrients for early growth.

Caring for the Crop: Once the seeds germinate, place the trays where they receive adequate light and good air circulation. Regular but gentle watering helps maintain moisture without waterlogging. Maintaining a clean growing environment and avoiding excessive humidity can minimise the risk of fungal growth and produce fresh, healthy micro-greens.

Harvesting at the Right Time: Most microgreens are ready for harvest within 7-21 days, depending on the crop and growing conditions. Harvest them when the seed leaves have fully opened and the first true leaves begin to emerge. Using clean scissors, cut the seedlings just above the growing medium to obtain fresh, tender greens with the best flavour and nutritional quality.

Storage and Marketing: Freshly harvested micro-greens are highly perishable and should be handled carefully. After harvest, they should be kept cool and stored in clean, food-grade containers to retain freshness and quality. Under refrigeration, they remain fresh for several days. Owing to their attractive appearance, delicate flavour and except-ional nutritional value, microgreens are in increasing demand among households, supermarkets, health food stores and restaurants. Their short production cycle, year-round cultivation and premium market value also make them an excellent option for small-scale entrepreneurs and urban growers.

Delicious Ways to Eat Microgreens: Microgreens are not only nutritious but also add freshness, vibrant colour and flavour to everyday meals. Their mild, peppery or slightly sweet taste makes them a perfect addition to salads, sandwiches, wraps, soups, curries, pizzas, pasta, omelettes and smoothies. They can also be used as an attractive garnish to enhance the appearance and nutritional value of a dish. Since prolonged heating can reduce some vitamins and bioactive compounds, microgreens are best enjoyed fresh or added just before serving. For maximum freshness and safety, choose crisp, healthy micro-greens from reliable sources or grow them hygienically at home. After a gentle wash, store them under refrigeration and consume them within a few days to preserve their flavour, texture and nutritional quality.

Value Addition in Microgreens: Beyond fresh consumption, microgreens can also be value-added into a variety of products, including soups, smoot-hies, green juices, pesto, chutneys, dried powders, functional beverages, bread, biscuits, pasta, noodles and instant soup mixes. Drying microgreens into powder is particularly gaining popularity, as it extends shelf life while allowing their nutrients to be incorporated into a wide range of food products.

Prospects and Conclusion

Microgreens are the next-generation smart foods, rapidly gaining global recognition for their exceptional nutritional value, vibrant flavours and ease of cultivation. Despite their tiny size, these young edible seedlings are packed with vitamins, minerals and bioactive compounds that support overall health, making them an ideal choice for health-conscious consumers. With a short production cycle, minimal space requirements and year-round cultivation, microgreens are well suited for home gardens, urban farming and other sustainable food production systems. Their versatility extends beyond fresh consumption, as they can be incorporated into value-added products such as soups, juices, smoothies, powders and other functional foods, creating opportunities for innovation and entrepreneurship. As scientific evidence continues to highlight their nutritional and health-promoting potential, microgreens are poised to play an increasingly important role in future diets, preventive nutrition and global food and nutritional security.

"Tiny in size but mighty in nutrition, microgreens prove that good health can grow in the smallest of leaves."

References

Bhaswant, M., Shanmugam, D. K., Miyazawa, T., Abe, C. and Miyazawa, T. (2023). Microgreens- A comprehensive review of bioactive molecules and health benefits. *Molecules*, 28(2): 867.

Dhakshayani, G. M. and Alias, P. S. J. (2022). A comparative study of phytochemical, antioxidant, anticarcinogenic, and antidiabetic potential of coriander (*Coriandrum sativum* L.): Microgreen and mature plant. *Foods and Raw materials*, 10(2):, 283-294.

El-Nakhel, C., Pannico, A., Graziani, G., Giordano, M., Kyriacou, M. C., Ritieni, A., ... and Rouphael, Y. (2021). Mineral and antioxidant attributes of *Petroselinum crispum* at different stages of ontogeny: Microgreens vs. baby greens. *Agronomy*, 11(5): 857.

Heena, Jindal, N. and Riar, C. S. (2026). Microgreens: a comprehensive review on growth conditions, nutritional quality, and their applications. *Food Reviews International*, 42(4): 2405-2437.

Kyriacou, M. C., El-Nakhel, C., Pannico, A., Graziani, G., Zarrelli, A., Soteriou, G. A., ... and Rouphael, Y. (2021). Ontogenetic variation in the mineral, phytochemical and yield attributes of brassicaceous microgreens. *Foods*, 10(5): 1032.

Marchioni, I., Martinelli, M., Ascrizzi, R., Gabbrielli, C., Flamini, G., Pistelli, L. and Pistelli, L. (2021). Small functional foods: Comparative phytochemical and nutritional analyses of five microgreens of the Brassicaceae family. *Foods*, 10(2): 427.

Singh, M., Nara, U., Rani, N., Pathak, D., Kaur, K. and Sangha, M. K. (2023). Comparison of mineral composition in microgreens and mature leaves of celery (*Apium graveolens* L.). *Biological Trace Element Research*,

201(8): 4156-4166.

Weber, C. F. (2017). Broccoli microgreens: A mineral-rich crop that can diversify food systems. *Frontiers in Nutrition*, 4: 7.

Wu, Y., Pham, Q., Wang, Y., Huang, H., Jiang, X., Li, R. W., ... and Wang, T. T. (2023). Red cabbage microgreen modulation of gut microbiota is associated with attenuation of diet-induced obesity risk factors in a mouse model. *Food & Function*, 14(14): 6654-64.

Yadav, L. P., Koley, T. K., Tripathi, A. and Singh, S. (2019). Antioxidant potentiality and mineral content of summer season leafy greens: Comparison at mature and microgreen stages using chemometric. *Agricultural Research*, 8(2): 165-175.

Role of Women in Sustainable Agriculture and Rural Development

Nomula Prathyusha

Abstract

Women play a vital role in agriculture and rural development and contribute significantly to crop production, livestock management, food processing, and natural resource conservation. Their knowledge and participation are fundamental to sustainable agriculture, food security, and environmental protection. Despite their immense contribution, women farmers often face challenges such as limited access to land, credit, technology, training, and decision-making opportunities. This article highlights the diverse roles of women in agriculture, reviews available literature on their contributions, discusses major constraints faced by women farmers, and emphasizes the need for gender-responsive policies and institutional support. Empowering women through education, skill development, access to productive resources, and leadership opportunities is essential for achieving sustainable agriculture and inclusive rural development.

Introduction

Agriculture is the backbone of the Indian economy and provides livelihoods to a large section of the rural population. Women constitute a substantial proportion of the agricultural workforce and are involved in almost every farming activity, from seed selection and sowing to harvesting and post-harvest processing. Their contributions extend to livestock management, kitchen gardening, food preservation, and household nutrition. Sustainable agriculture depends on the efficient management of natural resources, biodiversity conservation, and social inclusion, all of which are significantly influenced by women's participation.

Review of Literature

Boserup (1970) highlighted that women make substantial contributions to agricultural production but often remain invisible in development planning and resource allocation.

Agarwal (2018) emphasized that women's participation in agriculture is crucial for food security and rural livelihoods, yet they continue to face inequalities in land ownership and access to productive resources.

The Food and Agriculture Organization (2011) reported that if women had the same access to productive resources as men, farm yields could increase substantially and millions of people could be lifted out of hunger.

Doss (2014) observed that women contribute extensively to agricultural labor, livestock management and household food security and argued that their contributions should be formally recognized in agricultural policies.

Nomula Prathyusha
Young Professional-1, AICRP -PJTAU, Hyderabad, Telangana

FAO (2023) emphasized that empowering women in agrifood systems contributes directly to poverty reduction, improved nutrition, climate resilience, and sustainable development.

Discussion

Women perform multiple responsibilities in agriculture and allied sectors. They actively participate in land preparation, sowing, transplanting, weeding, irrigation management, harvesting, storage and marketing activities. Women are also major contributors to dairy farming, poultry rearing, and kitchen gardening, which provide nutritional security and supplementary income. Women promote sustainable agriculture through the conservation of traditional knowledge, indigenous seed varieties, and environmentally friendly farming practices such as organic farming, composting, integrated nutrient management, and crop diversification. However, women farmers continue to encounter barriers including limited land ownership, inadequate access to finance, insufficient training opportunities, and low participation in agricultural decision-making processes. Promoting gender equality, strengthening women-centric extension services, improving digital literacy, and increasing access to agricultural technologies can significantly enhance women's contributions to sustainable agriculture and rural development.

Conclusion

Women are the backbone of agriculture and rural development and are indispensable for achieving sustainable and resilient agricultural systems. Their contributions encompass agricultural production, environmental conservation, household food security, and community development. Recognizing women as farmers and providing them with equal access to resources, education, technologies and institutional support will not only improve their socio-economic status but also contribute significantly to food security and sustainable rural development.

References

Boserup, E. (1970). Women's Role in Economic Development. George Allen and Unwin.

Agarwal, B. (2018). Gender Challenges. Oxford University Press.

Doss, C. (2014). If Women hold up Half the Sky, How Much of the World's Food do they produce? *Global Food Security*, 3(3-4): 119-123.

Food and Agriculture Organization (FAO). (2011). The State of Food and Agriculture 2010-11: Women in Agriculture - Closing the Gender Gap for Development.

Food and Agriculture Organization (FAO). (2023). The Status of Women in Agrifood Systems.

United Nations. (2020). The Sustainable Development Goals Report.

United Nations Development Programme (UNDP). (2023). Gender Equality and Sustainable Development.

International Fund for Agricultural Development (IFAD). (2022). Rural Women's Economic Empowerment.

World Bank. (2012). World Development Report 2012: Gender Equality and Development.

Government of India. (2024). Agricultural Statistics at a Glance. Ministry of Agriculture and Farmers Welfare.

National Sample Survey Office (NSSO). (2019). Situation Assessment of Agricultural Households in India.

Traditional Paddy Varieties under Natural Farming: Nutritional, Medicinal and Cultural Significance

R. Sangeetha and B. Ramya

Introduction

As part of the Rural Agricultural Work Experience (RAWE) programme, I had the opportunity to stay in Manapparai**,** Tamil Nadu, where I gained firsthand experience by interacting with farmers, visiting villages, and observing diverse farming systems. The programme provided valuable practical exposure to sustainable agricultural practices and strengthened my understanding of traditional farming methods. During one of the field visits, I met Mr. Rex, a school teacher and dedicated natural farmer who has successfully established an integrated farming system on his farm. His farming philosophy is rooted in service rather than commercial profit. The farm products are sold only to people who genuinely need them and at affordable prices, making healthy food accessible to the local community. The farm is managed primarily by Mr. Rex with the support of a few labourers. Indigenous cattle and native goat breeds are reared as integral components of the integrated farming system, contributing to nutrient recycling and overall farm sustainability. Remarkably, no inorganic fertilizers, synthetic pesticides, or chemical inputs are used anywhere on the farm. Instead, the entire production system relies on natural farming principles that maintain soil health and ecological balance. One of the farms most sought after products are multicereal flour, prepared organically and valued for its traditional medicinal benefits rather than commercial gain. During my visit, I also had the opportunity to observe several traditional paddy varieties cultivated under natural farming conditions. These indigenous rice varieties represent a rich agricultural heritage and are widely appreciated for their nutritional quality, medicinal significance, and adaptability to local environments. The experience inspired me to document these valuable traditional rice varieties and highlight their importance in promoting sustainable agriculture and healthy living.

Natural Farming

Natural farming is a time tested agricultural system that has been practiced for centuries by our ancestors. It is based on the principle of working in harmony with nature, allowing natural processes to sustain crop production while maintaining ecological balance. Unlike conventional farming, natural farming minimizes external interventions and completely avoids the use of synthetic fertilizers, chemical pesticides, herbicides, and other artificial inputs. The natural farming system observed on Mr. Rex's farm follows the philosophy of “Do Nothing Farming,”

R. Sangeetha and B. Ramya
Mother Terasa College of Agriculture, Pudukkottai, Tamil Nadu

where crops are allowed to grow under conditions that closely resemble natural ecosystems. Farming activities are guided by the five great elements (Pancha Bhootas) Earth, Water, Air, Fire (Sunlight), and Space which are considered essential for maintaining the health and productivity of the farming ecosystem. Crop cultivation is carried out according to seasonal conditions, respecting the natural climate and local biodiversity. Traditional practices, such as the construction of long and narrow field bunds for paddy cultivation, are followed to improve water management, conserve soil moisture, and enhance crop growth. Indigenous livestock are integrated into the farming system to support nutrient recycling and overall farm sustainability. By relying entirely on natural resources and ecological principles, this farming approach promotes healthy soils, biodiversity conservation, safe food production, and long-term agricultural sustainability. This article aims to document the traditional paddy varieties cultivated under a natural farming system and highlight their nutritional value and traditionally recognized health benefits. Many indigenous rice varieties have long been valued in Tamil Nadu for their unique culinary qualities and are widely believed in traditional knowledge systems to support overall health and wellbeing when consumed as part of a balanced diet. Although a few varieties may have originated outside the region, they have become an integral part of Tamil Nadu's agricultural heritage and food culture. The traditional belief that "Food is the first medicine" reflects the close relationship between diet and health that guided the lifestyles of our ancestors. However, with modernization and the Green Revolution, cultivation has increasingly shifted toward high yielding, short duration varieties to ensure food security. While these modern varieties play a vital role in meeting the food demands of a growing population, the conservation of indigenous paddy varieties is equally important because they represent valuable genetic resources, cultural heritage, and nutritional diversity. The traditional paddy varieties documented in this article were cultivated entirely under a natural farming system without the application of synthetic fertilizers, chemical pesticides, or other artificial agrochemicals. By documenting these varieties and their traditional uses, this article seeks to promote awareness of heritage rice, encourage the conservation of indigenous germplasm, and emphasize the importance of sustainable natural farming practices for future generations.

Traditional Paddy Varieties Cultivated under Natural Farming

Milagu Samba: Milagu Samba is an indigenous traditional rice variety of Tamil Nadu characterized by its small, hardy grains and a mild pepper like flavour, from which it derives its name (*Milagu* means pepper in Tamil). It is a long duration variety requiring approximately five months maturing and is well suited to natural farming systems. For generations, Milagu Samba has been an important component of the traditional diet and is valued in indigenous knowledge systems for its nutritional and

health promoting properties. Traditional practitioners believe that regular consumption of Milagu Samba supports digestive health, enhances immunity and contributes to overall well-being. The rice is commonly prepared as Thayir Sadam (curd rice), Elumichai Sadam (lemon rice), Puli Sadam (tamarind rice), and Nei Sadam (ghee rice) because its firm grains retain their texture after cooking. Nutritionally, Milagu Samba contains magnesium, B complex vitamins (particularly thiamine), bioactive phytochemicals, and essential trace minerals that contribute to its dietary value (Chandrasekaran *et al.*, 2010; Babu *et al.*, 2014; DRR, 2014).



Fig. 1: Plant and Dehulled grains of the traditional rice variety Milagu Samba (Milaku Samba) cultivated under a natural farming system.

Karudan Samba: It is a traditional long duration rice (5 month) variety cultivated under natural farming systems in Tamil Nadu. The grains are distinguished by their reddish outer bran and white inner kernel, reflecting the presence of natural pigments and valuable nutrients. This indigenous variety has been cultivated for generations and is highly regarded in traditional food culture. According to traditional knowledge, regular consumption of Karudan Samba is believed to support eye health, enhance overall vitality, and contribute to general well being. Its nutrient-rich bran contains naturally occurring bioactive compounds that make it a nutritious addition to a balanced diet. Karudan Samba is commonly prepared as Puttu, Idiyappam, Lemon Rice (Elumichai Sadam), and Curd Rice (Thayir Sadam) because of its pleasant texture and taste. Nutritionally, it is a good source of iron, plant-based protein, carotenoid precursors of vitamin A**,** and essential minerals such as potassium and sodium in trace amounts, contributing to its nutritional significance (Babu *et al.*, 2014; DRR, 2014; Rathna Priya *et al.*, 2019).



Mappillai Samba: Mappillai Samba is one of the most renowned traditional rice varieties of Tamil Nadu in 6 month duration and recognized for its coarse, dark-red grains and exceptional nutritional quality. The name *Mappillai* (meaning “bridegroom” in Tamil) originates from a traditional belief that newly married men consumed this rice to enhance physical strength and stamina. Cultivated as a long-duration crop under natural farming systems, Mappillai Samba has been an integral part of the traditional Tamil diet for centuries. It is valued for its high dietary fibre, essential minerals, and low glycaemic index, making it a preferred choice for health-conscious consumers. Due to its slow digestibility and nutrient-rich composition, it is often

included as part of a balanced diet and is traditionally believed to support sustained energy levels, physical endurance, and overall well-being. Mappillai Samba is commonly prepared as steamed rice, idli, dosa, and kanji (rice porridge), all of which preserve its distinctive flavour and nutritional benefits. Nutritionally, this heritage rice is rich in iron, zinc, dietary fibre, and possesses a low glycaemic index, contributing to improved nutritional quality and healthy dietary patterns (Babu *et al*., 2014; Rathna Priya *et al*., 2019; ICAR-IIRR, 2020).





Kattuyanam: Kattuyanam is a remarkable 6 month duration indigenous rice variety of Tamil Nadu, renowned for its vigorous growth and tall stature, with plants reaching up to 2 metres in height. The variety produces attractive red grains and is highly adapted to natural and traditional farming systems. Because of its robust growth, Kattuyanam is considered resilient under low-input cultivation and has been conserved by farmers for generations. Traditionally, this rice has been valued for its nutritional richness and is widely included in the diets of rural communities. It is particularly preferred for preparing kanji (rice porridge) and other wholesome traditional foods because of its rich flavour and easy digestibility.

Local communities believe that regular consumption of Kattuyanam supports bone health, promotes recovery during illness, contributes to cardiovascular well-being, and provides sustained energy. Kattuyanam is commonly prepared as idli, dosa, kanji, koozh, adai and puttu. Nutritionally, it is a valuable source of calcium, iron, vitamin B_2 (riboflavin), natural antioxidants and other essential micronutrients that contribute to a healthy and balanced diet (Babu *et al*., 2014; Rathna Priya *et al*., 2019; ICAR-IIRR, 2020).





Karuppu Kavuni (Black Rice): Karuppu Kavuni, popularly known as Black Rice, is a heritage rice variety believed to have been introduced into Tamil Nadu through ancient trade routes from Burma (Myanmar) and parts of China. It has 5-6 month duration over centuries, it has become naturalized and is now regarded as an important component of Tamil Nadu's traditional rice heritage. The grains possess a distinctive dark purple to black colour due to their high concentration of anthocyanins, naturally occurring antioxidant pigments. Traditionally, Karuppu Kavuni has been considered a premium functional food because of its exceptional nutritional profile and health-promoting properties. It is widely believed to support overall health, improve antioxidant status, and contribute to cardiovascular wellness, while its high dietary fibre content promo-

tes digestive health and healthy weight management as part of a balanced diet. The grains are commonly prepared as kanji, kozhukattai, payasam and puttu, preserving their unique flavour and nutritional value. Nutritionally, Karuppu Kavuni is rich in anthocyanins, dietary fibre, crude protein, vitamins, and essential minerals, making it one of the most nutrient-dense traditional rice varieties cultivated in South India (Rathna Priya *et al*., 2019; Shao *et al*., 2018; ICAR-IIRR, 2020).



References

Babu, V. R., Shreya, K., Dangi, K. S., Usharani, G. and Nagesh, P. (2014). Genetic diversity studies for quality traits in indigenous rice (*Oryza sativa* L.) landraces. *Journal of Rice Research*, **7**(1): 52-58.

Chandrasekaran, B., Annadurai, K. and Somasundaram, E. (2010). *A Textbook of Agronomy*. New Age International Publishers.

Rathna Priya, T. S., Nelson, A. R. L. E., Ravichandran, K. and Antony, U. (2019). Nutritional and functional properties of coloured rice varieties of South India: A review. *Journal of Ethnic Foods*, 6: 11.

Directorate of Rice Research (DRR). (2014). *Rice Knowledge Management Portal: Traditional Rice Varieties*. ICAR-Directorate of Rice Research, Hyderabad.

ICAR-Indian Institute of Rice Research (ICAR-IIRR). (2020). *Traditional Rice Varieties of India*. Hyderabad, India.

Shao, Y., Xu, F., Sun, X., Bao, J. and Beta, T. (2018). Phenolic acids, anthocyanins and antioxidant capacity in black rice varieties. *Food Chemistry*, 239: 733-741.

From Classroom to Cultivation: Inspiring Journey of a Woman Entrepreneur at Pasumai Illam

Rithisha, M. Nithyasri, R. Sangeetha, V. Santhiya, I. Narmatha, T. Rojasri, S. Ponnila, B. Sathiyaraja and B. Ramya

In an era where agriculture is rapidly evolving beyond traditional farming, inspiring stories of rural entrepreneurship are paving the way for a sustainable future. One such remarkable example is Pasumai Illam, a vibrant hub of natural agricultural products located in Senthurathinapuram, Manapparai, in the Tiruchirappalli district of Tamil Nadu. As part of the Rural Agricultural Work Experience (RAWE) Programme, our visit to Pasumai Illam turned into a truly enriching experience offering not just knowledge, but inspiration rooted in sustainability, innovation, and determination.

A Bold Shift: The Story Behind the Success

At the heart of Pasumai Illam is Mrs. R. Chitra Devi, a former Assistant Professor in Computer Science who made a courageous transition from academics to agriculture. Armed with a Master's degree and a passion for sustainable living, she stepped into the world of natural farming with a vision to promote eco-friendly agricultural practices. Her journey began with specialized training at ICAR Krishi Vigyan Kendra, Siruganur, where she gained insights into natural farming techniques inspired by the legendary agricultural scientist G. Nammalvar. What started as a small initiative in 2017 has today grown into a thriving enterprise employing nearly 40 workers. Over the past nine years, Pasumai Illam has become a trusted name in organic inputs and natural products, reflecting her dedication and entrepreneurial spirit.



Recognition that Speaks Volumes

Mrs. Chitra Devi's relentless efforts have earned her more than 27 prestigious awards, including:

- ✓ Best Social Service Award (2021)
- ✓ Female Achiever Award (2022)
- ✓ Tamil Pasumai Viruthu (2022)
- ✓ Indian Women Talent Award (2022)
- ✓ Tanishq Puthumaipenn Award (2023)
- ✓ Green Champion Award (2025, Tamil Nadu Government).

These accolades are a testament to her impactful contributions toward sustainable agriculture and women empowerment.

Rithisha, M. Nithyasri, R. Sangeetha, V. Santhiya, I. Narmatha, T. Rojasri, S. Ponnila, B. Sathiyaraja and B. Ramya
Mother Terasa College of Agriculture, Pudukkottai, Tamil Nadu



A Hub of Organic Innovation

Pasumai Illam is not just a shop it is a learning center for natural agriculture. It offers a wide range of organic inputs that support both farmers and urban gardeners:

Natural Farming Inputs

Vermicompost: Enhances soil fertility naturally

Panchakavya and Jeevamrutham: Traditional bio-enhancers boosting plant growth

Fish Amino Acid: A powerful organic nutrient

Herbal Pest Repellents: Safe and eco-friendly crop protection

Coco Peat and Grow Bags: Ideal for terrace gardening

These inputs promote soil health, reduce dependency on chemicals, and support sustainable farming practices.

Sweet Success: Value-Added Honey Products

One of the highlights of Pasumai Illam is its diverse range of natural honey products, including:

- ✓ Murungai Poo Honey
- ✓ Malai Honey
- ✓ Jamun Honey
- ✓ Multi-flower Honey

In addition, traditional dairy products like country cow ghee further enhance the value-added product line, offering both nutrition and authenticity.

Eco-Friendly Innovations for a Greener Tomorrow

Pasumai Illam stands out for its creative eco-friendly products that combine sustainability with

Seed-Based Innovations

Seed Balls: A simple yet effective solution for reforestation

Seed Pens and Pencils: Write, plant, and grow! These biodegradable products carry seeds that can be planted after use turning everyday items.

Terrace Garden Kits

Complete gardening kits with seeds, grow bags, and organic inputs make urban farming accessible and enjoyable for everyone.

Empowering Through Entrepreneurship

Beyond products, Pasumai Illam represents a movement one that empowers women, promotes sustainable agriculture and creates rural employment. Mrs. Chitra Devi actively spreads awareness about organic farming, inspiring farmers and youth to adopt eco-friendly practices. Her journey proves that agriculture today is not just about cultivation it is about innovation, value addition, and community impact.

Morphological Characterization of Major Agricultural Crops: Structures, Assessment Methods and Emerging Phenotyping Tools

Chandru B., M. Saravana Kumar and K. Pooja

Abstract

Morphological characterization is a fundamental approach in crop science for evaluating plant diversity, identifying cultivars, and supporting crop improvement programmes. It involves the systematic assessment of observable plant traits, including root architecture, stem characteristics, leaf morphology, floral structures, and seed attributes, which are influenced by both genetic and environmental factors. Conventional methods such as visual observations, morphometric measurements, and field phenotyping have long been employed to characterize major agricultural crops, including cereals, pulses, oilseeds, and fiber crops. However, the increasing demand for rapid, accurate, and large-scale phenotypic evaluation has accelerated the adoption of advanced phenotyping technologies. Modern instruments such as digital calipers, leaf area meters, SPAD chlorophyll meters, root scanners, RGB and multispectral imaging systems, unmanned aerial vehicles (UAVs), LiDAR, and high-throughput phenotyping platforms enable precise, non-destructive, and automated measurement of morphological traits. These technologies improve the efficiency of germplasm characterization, variety identification, genetic diversity assessment, and plant breeding while reducing human error and increasing data reproducibility. This review synthesizes the morphological structures of major agricultural crops, outlines conventional and emerging methods of morphological characterization, and discusses the instruments commonly used in crop phenotyping. Furthermore, it highlights the applications of morphological characterization in germplasm conservation, cultivar development, precision agriculture, and climate-resilient crop improvement. Integrating traditional morphological descriptors with digital phenotyping technologies offers a robust framework for accelerating crop research and developing high-yielding, stress-tolerant cultivars to meet the challenges of global food security and sustainable agriculture.

Introduction

Morphological characterization is the systematic study of the external structure and physical traits of crop plants. It forms the foundation of plant taxonomy, varietal identification, crop improvement, seed certification, and germplasm conservation. Morphological traits are generally stable, heritable, and easily observable under field conditions, making them indispensable for evaluating genetic diversity and selecting superior genotypes. Although molecular tools have become increasingly important, morphological characterization remains the primary

Chandru B., M. Saravana Kumar and K. Pooja
Department of Agronomy, SRMCAS, SRMIST, Chengalpattu, Tamil Nadu

approach for describing crop varieties due to its simplicity, low cost, and direct relevance to agronomic performance (UPOV, 2023; Bioversity International, 2007).

Morphological structures of major agriculture crops

Crop	Important Morphological Structures
Rice (*Oryza sativa*)	Root system, culm, tillers, leaves, ligule, auricle, panicle, spikelet, grain
Wheat (*Triticum aestivum*)	Fibrous roots, stem, nodes, internodes, leaves, spike, spikelets, awns, grains
Maize (*Zea mays*)	Brace roots, stalk, leaves, tassel, ear, silk, kernels
Sorghum (*Sorghum bicolor*)	Fibrous roots, culm, leaves, panicle, florets, grains
Pearl millet (*Pennisetum glaucum*)	Root system, stem, leaves, spike, spikelets, grains
Cotton (*Gossypium hirsutum*)	Tap root, monopodial and sympodial branches, leaves, flowers, boll, lint, seed
Groundnut (*Arachis hypogaea*)	Tap root, stem, leaves, flowers, peg, pod, kernels
Soybean (*Glycine max*)	Tap root with nodules, stem, trifoliate leaves, flowers, pods, seeds
Chickpea (*Cicer arietinum*)	Tap root, stem, compound leaves, flowers, pods, seeds
Pigeonpea (*Cajanus cajan*)	Deep tap root, stem, leaves, racemes, pods, seeds

Important Morphological Characters Studied

Root Characteristics

Root type (tap root/fibrous root), root length, root volume, root diameter, number of lateral roots, root biomass, root nodulation (legumes).

Importance: Water absorption, nutrient uptake, drought tolerance and crop anchorage.

Stem Characteristics

Stem height, culm diameter, internode length, stem thickness, tiller number (rice, wheat), branch number (cotton, legumes)

Importance: Stem morphology influences lodging resistance, biomass production, and grain yield.

Leaf Characteristics

Leaf length, leaf width, leaf area, leaf angle, leaf color, leaf thickness, chlorophyll content and pubescence.

Importance: Leaf morphology determines photo-synthetic efficiency and canopy architecture.

Flower Characteristics

Flowering time, number of flowers, inflore-scence type, floral morphology, anthesis duration and pollen viability.

Fruit and Seed Characteristics

Grain length, grain width, grain thickness, thousand-seed weight, pod length, pod number, seed color, seed shape.

Plant Architecture

Plant height, growth habit, canopy spread, branching pattern, lodging resistance.

Methods used for Morphological Character-ization

Visual Observation Method: The simplest method where qualitative characters are observed directly in the field. Examples: Leaf colour, grain colour, plant growth habit, pubescence and flower colour. This method is commonly employed following descript-ors developed by UPOV, IBPGR (now Bioversity International), and national crop research institutes.

Morphometric Measurement: Quantitative plant traits are measured using standard measuring tools. Measured traits include: Plant height, leaf length, panicle length, ear length, root length, stem diameter and pod length.

Field Phenotyping: Plants are evaluated throughout

different growth stages under field conditions. Traits observed include: Germination percentage, days to flowering, days to maturity, tiller number, biomass production and yield components.

Digital Image Analysis: High-resolution digital images are analyzed using specialized software to estimate: Leaf area, canopy cover, plant height, biomass and root architecture. Image analysis minimizes observer bias and improves measurement precision.

Root Phenotyping: Roots are carefully excavated, washed, and measured using scanners or imaging systems. Common observations: Root depth, root angle, root diameter, root branching, root biomass.

UPOV Distinctness, Uniformity and Stability (DUS) Testing: Morphological descriptors are used to evaluate: Distinctness, Uniformity, Stability. DUS testing is essential for plant variety protection and registration.

Instruments used foe morphological characterization

Instrument	Purpose
Measuring tape	Plant height, root length
Meter scale	Stem and leaf measurements
Vernier caliper	Stem diameter, seed dimensions
Digital caliper	High-precision organ measurements
Leaf Area Meter	Leaf area estimation
SPAD Chlorophyll Meter	Relative chlorophyll content
Digital weighing balance	Biomass and seed weight
Root scanner	Root architecture analysis
Digital camera	Image acquisition for phenotyping
Flatbed scanner	Leaf and root imaging
GPS	Georeferencing experimental plots
Drone (UAV)	Canopy architecture and field phenotyping
Digital microscope	Surface morphology and seed characteristics
Stereomicroscope	Observation of floral and seed structures
ImageJ software	Measurement of plant organs from images
WinRHIZO software	Root morphology analysis

Advanced High-Throughput Phenotyping Instruments

- ✓ RGB imaging systems
- ✓ Multispectral cameras
- ✓ Hyperspectral imaging systems
- ✓ LiDAR scanners
- ✓ 3D laser scanners
- ✓ UAV-based imaging platforms
- ✓ Automated phenotyping platforms
- ✓ Thermal imaging cameras
- ✓ X-ray computed tomography (CT) for root studies. These technologies enable rapid, non-destructive, and accurate assessment of large plant populations, supporting precision breeding and crop improvement.

Applications of Morphological Characterization

- ✓ Germplasm characterization
- ✓ Plant breeding and selection
- ✓ Crop improvement programmes
- ✓ Variety identification
- ✓ Seed certification
- ✓ Plant variety protection (DUS testing)
- ✓ Taxonomic classification
- ✓ Assessment of genetic diversity
- ✓ Crop management and precision agriculture

Conclusion

Morphological characterization remains a fundamental approach for evaluating crop diversity and agronomic performance. The integration of conventional field observations with modern digital phenotyping tools has significantly improved the accuracy, efficiency and reproducibility of morphol-

ogical assessments. These methods provide essential information for plant breeding, germplasm conservation, crop improvement, and variety registration, ensuring the development of high-yielding and climate-resilient cultivars.

References

Bioversity International. (2007). Guidelines for the development of crop descriptor lists. *Bioversity Technical bulletin series*, 12: 2-2.

Upadhyaya, H. D., Thudi, M., Dronavalli, N., Gujaria, N., Singh, S., Sharma, S. and Varshney, R. K. (2011). Genomic tools and germplasm diversity for chickpea improvement. *Plant Genetic Resources*, 9(1): 45-58.

Cobb, J. N., DeClerck, G., Greenberg, A., Clark, R. and McCouch, S. (2013). Next-generation phenotyping: requirements and strategies for enhancing our understanding of genotype-phenotype relationships and its relevance to crop improvement. *Theoretical and Applied Genetics*, 126(4): 867-887.

Furbank, R. T. and Tester, M. (2011). Phenomics-technologies to relieve the phenotyping bottleneck. *Trends in Plant Science*, 16(12): 635-644.

Yang, W., Feng, H., Zhang, X., Zhang, J., Doonan, J. H., Batchelor, W. D., ... and Yan, J. (2020). Crop phenomics and high-throughput phenotyping: past decades, current challenges and future perspectives. *Molecular Plant*, 13(2): 187-214.

Minimum Processing and Maximum Preservation without Damaging Nutrient Value of Food in the Food Industry: A Futuristic Approach

Yoganandi Y. C., Sardar N. R., Srivastava S., Seth N. and Patel M. I.

Abstract

The modern food industry is undergoing a major transformation toward the development of minimally processed foods with enhanced nutritional quality, extended shelf life, and improved consumer safety. Increasing health awareness among consumers has created significant demand for fresh-like foods that retain their natural color, flavor, texture, and nutrient composition. Conventional thermal processing methods such as sterilization, pasteurization, canning, and high-temperature drying often lead to degradation of heat-sensitive nutrients, including vitamins, antioxidants, bioactive compounds, and essential fatty acids. Minimum processing technologies are designed to reduce physical, chemical, and thermal damage to food materials while preserving their sensory and nutritional characteristics. Emerging technologies such as high-pressure processing, pulsed electric fields, cold plasma, ultraviolet treatment, membrane filtration, irradiation, smart packaging, nanotechnology, freeze drying, and artificial intelligence-based processing systems are creating new opportunities for sustainable and nutrient-preserving food manufacturing. The review preservation technologies, engineering principles, nutrient retention mechanisms, industrial applications, packaging innovations, automation systems, and future research opportunities for sustainable food processing.

Introduction

Food processing is essential for improving food safety, shelf life, transportation, storage stability, and consumer convenience. Conventional food preservation methods such as thermal sterilization, dehydration, frying, canning and chemical preservation have significantly reduced food spoilage and foodborne diseases. However, excessive processing often damages the nutritional and sensory quality of foods. Heat-sensitive nutrients such as vitamin C, folic acid, polyphenols, omega-3 fatty acids, probiotics, enzymes and natural pigments are particularly vulnerable to conventional thermal treatments. In addition, high-temperature processing may alter food texture, flavor, color, and biological activity. Modern consumers increasingly demand foods that are:

- ✓ Fresh-like in appearance
- ✓ Nutritionally rich
- ✓ Minimally processed
- ✓ Free from synthetic preservatives
- ✓ Safe and hygienic
- ✓ Environmentally sustainable

As a result, the food industry is shifting from

Yoganandi Y. C., Sardar N. R., Srivastava S., Seth N. and Patel M. I.
College of Agricultural Engineering & Technology, Anand Agricultural University, Godhra, Gujarat

intensive processing toward smart preservation systems capable of maintaining food quality with minimal nutrient degradation. Minimum processing refers to technologies and operations that preserve food while minimizing changes in nutritional, physicochemical, microbiological, and sensory properties. The primary objective is to maintain the natural quality of food while ensuring safety and shelf stability. Food engineering, biotechnology, nanotechnology, automation and artificial intelligence are playing major roles in the development of next-generation preservation systems.

Concept and Objectives of Minimum Processing

Minimum processing involves mild preservation treatments designed to maintain the natural characteristics of food products. The approach focuses on reducing the severity of processing conditions while still controlling microbial growth and enzymatic spoilage.

- ✓ Preservation of nutritional quality.
- ✓ Maintenance of natural flavor and texture.
- ✓ Reduction of chemical preservatives.
- ✓ Improvement of food safety.
- ✓ Enhancement of shelf life.
- ✓ Reduction of processing energy consumption.
- ✓ Sustainable and eco-friendly production.

Table 1: Characteristics of Minimally Processed Foods

Characteristic	Description
Fresh-like quality	Natural appearance and taste
High nutrient retention	Minimal vitamin and antioxidant loss
Mild processing	Reduced thermal damage
Enhanced safety	Controlled microbial contamination
Convenience	Ready-to-eat or ready-to-cook forms
Sustainable processing	Reduced waste and energy use

Nutrient Degradation during Conventional Processing

Nutrient degradation is one of the major concerns in food processing industries. Various factors influence nutrient loss during processing operations.

Causes of Nutrient Loss

Thermal Degradation: High temperatures accelerate destruction of vitamin C, vitamin B complex, antioxidants enzymes and natural pigments

Oxidation: Exposure to oxygen causes: Lipid oxidation, color deterioration, loss of aroma compounds nutrient degradation.

Moisture and Water Activity: Excessive drying or moisture migration affects: Texture, enzyme stability, vitamin retention.

Mechanical Damage: Cutting, grinding, and excessive mixing may increase: oxidative reactions, nutrient exposure, enzymatic browning.

Advanced Technologies for Minimum Processing

High-Pressure Processing (HPP): High-pressure processing is a non-thermal preservation technology that uses pressures between 100-600 MPa to inactivate microorganisms without significant heat generation.

Working Principle: Food products are subjected to extremely high hydrostatic pressure inside sealed chambers.

Advantages

- ✓ High nutrient retention
- ✓ Preservation of flavor and color
- ✓ Minimal thermal damage

- ✓ Extended shelf life
- ✓ Effective microbial destruction

Applications: Fruit juices Dairy products seafood meat products, ready-to-eat foods

Pulsed Electric Field (PEF) Processing: Pulsed electric field technology uses short bursts of high voltage to disrupt microbial cell membranes.

Benefits

- ✓ Low-temperature preservation
- ✓ Retention of vitamins and bioactive compounds
- ✓ Reduced processing time
- ✓ Improved juice extraction efficiency

Industrial Applications

- ✓ Liquid foods
- ✓ Fruit juices
- ✓ Milk processing
- ✓ Liquid egg products

Cold Plasma Technology: Cold plasma is an emerging non-thermal technology used for microbial decontamination.

Mechanism: Ionized gases produce reactive species that destroy microorganisms.

Advantages

- ✓ Surface sterilization without heating
- ✓ Preservation of nutrients
- ✓ Low energy consumption
- ✓ Reduced chemical usage

Applications

- ✓ Fresh fruits and vegetables
- ✓ Packaging sterilization
- ✓ Meat surface treatment

Ultraviolet (UV) Treatment: UV radiation is used to control micro-organisms in food and packaging systems.

Benefits

- ✓ Chemical-free preservation
- ✓ Low operational cost
- ✓ Reduced microbial contamination
- ✓ Improved food safety

Freeze Drying Technology: Freeze drying removes water through sublimation under low temperature and vacuum conditions.

Advantages

- ✓ Excellent nutrient preservation
- ✓ Better flavor retention
- ✓ High rehydration capacity
- ✓ Long shelf life

Limitations

- ✓ High energy requirement
- ✓ Expensive equipment

Membrane Filtration Technology: Membrane separation processes such as microfiltration, ultra-filtration, nanofiltration, and reverse osmosis are widely used for gentle food preservation.

Benefits

- ✓ Low-temperature processing
- ✓ Retention of nutrients
- ✓ Efficient separation
- ✓ Reduced thermal degradation

Applications

- ✓ Milk processing
- ✓ Beverage clarification
- ✓ Water purification
- ✓ Protein concentration

Engineering Challenges in Minimum Processing

Table 2: Technological advancements, several challenges remain

Challenge	Impact
High equipment cost	Limited industrial adoption
Scale-up difficulties	Commercialization barriers
Complex process control	Increased operational complexity
Packaging compatibility	Reduced shelf stability
Consumer acceptance	Market uncertainty
Regulatory approval	Delayed implementation

Conclusion

The future of the food industry lies in achieving maximum preservation with minimum processing damage. Conventional thermal processing technologies, although effective for microbial safety, often reduce nutritional quality and alter sensory characteristics of foods. Emerging non-thermal and intelligent preservation technologies provide promising alternatives for maintaining food quality while ensuring safety and extended shelf life. Technologies such as high-pressure processing, pulsed electric fields, cold plasma, membrane filtration, freeze drying, nanotechnology, artificial intelligence, and IoT-based monitoring systems are transforming the food processing industry toward sustainable and nutrient-preserving production systems. The integration of food engineering, automation, biotechnology, materials science, and data-driven technologies will create next-generation smart food industries capable of producing healthier, safer, and environmentally sustainable foods. Future food processing systems must prioritize nutrient retention, energy efficiency, food safety, sustainability, and consumer health simultaneously. Minimum processing combined with advanced preservation technologies represents one of the most promising futuristic approaches for sustainable global food systems.

References

Barbosa-Cánovas, G. V. and Juliano, P. (2008). Food sterilization by combining high pressure and thermal energy. *Food Engineering Reviews,* 1(1): 1-16.

Bourlieu, C., Guillard, V., Powell, H. and Gontard, N. (2018). Modelling food structure and functionality for nutrient preservation. *Current Opinion in Food Science,* 21: 44-51.

Fellows, P. J. (2017). *Food processing technology: Principles and practice* (4th ed.). Woodhead Publishing.

Floros, J. D., Newsome, R., Fisher, W., Barbosa-Cánovas, G. V., … and Scott, V. N. (2010). Feeding the world today and tomorrow: The importance of food science and technology. *Comprehensive Reviews in Food Science and Food Safety*, 9(5): 572-599.

Jideani, V. A. and Anyasi, T. A. (2018). Non-thermal technologies for food processing. *Food Engineering Reviews,* 10(2): 78-95.

Khan, I., Tango, C. N., Miskeen, S., Lee, B. H. and Oh, D. H. (2017). Hurdle technology: A novel approach for enhanced food quality and safety. *Food Control*, 73: 1426-1444.

Knorr, D., Zenker, M., Heinz, V. and Lee, D. U. (2004). Applications and potential of ultrasonics in food processing. *Trends in Food Science & Technology,* 15(5): 261-266.

Lelieveld, H., Holah, J. and Napper, D. (2014). *Hygiene in food processing: Principles and practice* (2nd ed.). Woodhead Publishing.

Misra, N. N., Schlüter, O. and Cullen, P. J. (2016). *Cold plasma in food and agriculture: Fundamentals and applications*. Academic Press.

Patras, A., Brunton, N. P., Da Pieve, S. and Butler, F. (2009). Impact of high pressure processing on total antioxidant activity, phenolic, ascorbic acid, anthocyanin content and colour of strawberry and blackberry purées. *Innovative Food Science & Emerging Technologies*, 10(3): 308-313.

Rastogi, N. K., Raghavarao, K. S. M. S., Balasubramaniam, V. M., Niranjan, K. and Knorr, D. (2007). Opportunities and challenges in high pressure processing of foods. *Critical Reviews in Food Science and Nutrition*, 47 (1): 69-112.

Rico, D., Martín-Diana, A. B., Barat, J. M. and Barry-Ryan, C. (2007). Extending and measuring the quality of fresh-cut fruits and vegetables: A review. *Trends in Food Science & Technology*, 18(7): 373-386.

Sardar, N. R., Patel, A. M., Tiwari, M., Rathod, J. P. and Tagalpallewar, G. P. (2023). Ultraviolet light food processing: A mini concept. *Emergent Life Sciences Research*. https://doi.org/10.31783/elsr.

Singh, R. P. and Heldman, D. R. (2013). *Introduction to food engineering* (5th ed.). Academic Press.

Tiwari, B. K., O'Donnell, C. P., Cullen, P. J. and Bourke, P. (2009). Effect of non-thermal processing technologies on the anthocyanin content of fruit juices. *Trends in Food Science & Technology*, 20(3-4): 137-145.

Toepfl, S., Heinz, V. and Knorr, D. (2007). High intensity pulsed electric fields applied for food preservation. *Chemical Engineering and Processing*, 46(6): 537-546.

Tucker, G. S. (2016). *Food biodeterioration and preservation*. Wiley-Blackwell.

Zhang, H. Q., Barbosa-Cánovas, G. V., Balasubramaniam, V. M., Dunne, C. P., Farkas, D. F. and Yuan, J. T. C. (2011). *Nonthermal processing technologies for food*. Wiley-Blackwell.

Zhu, J. Y. (2021). Smart food packaging technologies for food quality preservation and monitoring. *Food Packaging and Shelf Life*, 28: 100647.

Intelligent Agricultural Extension Systems: Applications of Artificial Intelligence

P. Swarnalatha and Potnuru Santosh Kumar

Agricultural extension systems are rapidly evolving from conventional information dissemination to intelligent, data-driven decision support to address challenges such as climate change, resource constraints and increasing production risks. Artificial Intelligence (AI) is driving this transformation by integrating technologies such as machine learning, computer vision, natural language processing, and IoT to deliver timely and location-specific advisory services. Unlike traditional extension approaches, AI enables predictive, diagnostic, and personalized recommendations that support informed farm-level decision-making. It also facilitates climate-smart agriculture, precision resource management, digital crop monitoring, and multilingual farmer advisory systems. Overall, AI is redefining agricultural extension into a smart, adaptive, and farmer-centric knowledge ecosystem that enhances agricultural productivity, resilience, and sustainability.

Agricultural Extension at a Turning Point

Agricultural extension is at a critical turning point as conventional advisory approaches struggle to meet the rapidly changing needs of modern farming. Increasing climate uncertainty, labour shortages, complex production systems, and the overwhelming volume of agricultural information have made traditional extension methods less effective. Farmers now require timely, location-specific, and personalized recommendations rather than generic advisory services. In this context, Artificial Intelligence (AI) is emerging not merely as another ICT tool but as an extension intelligence layer that integrates diverse data sources, generates actionable insights, and supports informed decision-making. By complementing the expertise of extension professionals, AI has the potential to make agricultural advisory services more responsive, efficient, and farmer-centric.

Evolution of Agricultural Extension

Agricultural extension has evolved significantly over the past few decades, reflecting advances in technology, communication and farmers' information needs. Initially, extension services focused on the one-way transfer of scientific knowledge from researchers to farmers through demonstrations and field visits. With the advent of information and communication technologies (ICTs), extension became more interactive, enabling timely dissemina-

P. Swarnalatha
Teaching Associate, Advanced Post Graduate Centre (APGC), Department of Statistics, ANGRAU, Lam, Guntur, Andhra Pradesh

Potnuru Santosh Kumar
Teaching Associate, Advanced Post Graduate Centre (APGC), Department of Agri Business Management, ANGRAU, Lam, Guntur, Andhra Pradesh

tion of agricultural information through mobile phones, the internet, and digital platforms. Today, the integration of Artificial Intelligence (AI) is transforming extension into an intelligent, data-driven advisory system that provides personalized, real-time recommendations. This evolution represents a shift from conventional knowledge dissemination to collaborative, technology-enabled decision support, enhancing the efficiency, accessibility, and impact of agricultural extension services. The Evolution of Agricultural Extension was depicted in Fig. 1.

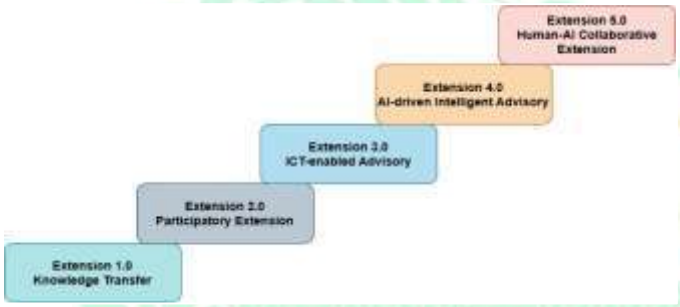


Fig. 1: Evaluation of Agricultural Extension

AI as an Agricultural Knowledge Ecosystem

Agricultural extension is no longer limited to transferring information from researchers to farmers. In the digital era, Artificial Intelligence (AI) has transformed agricultural extension into an intelligent knowledge ecosystem, where information is continuously generated, integrated, interpreted, and delivered to support informed decision-making. AI acts as the connecting force that links scientific research, real-time field data, and farmer needs, ensuring that the right knowledge reaches the right farmer at the right time. The AI-enabled agricultural knowledge ecosystem can be understood through four interconnected intelligence layers (Fig. 2).

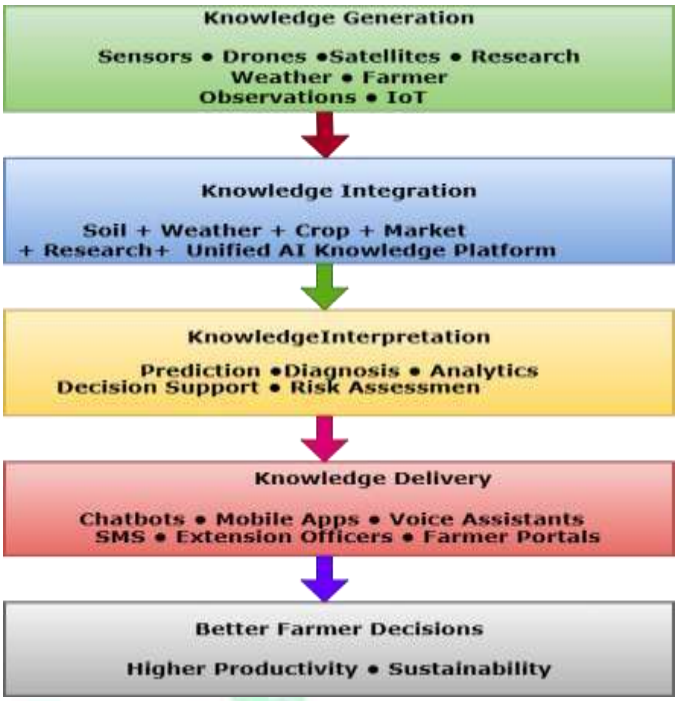


Fig. 2: AI-enabled agricultural knowledge ecosystem

Five Intelligence Functions of AI Extension

Artificial Intelligence enhances agricultural extension through five complementary intelligence functions that support informed decision-making at different stages of farming. Predictive intelligence forecasts crop yield, weather, pest outbreaks, and market trends, while diagnostic intelligence identifies crop diseases, nutrient deficiencies, and other field problems. Prescriptive intelligence provides personalized recommendations on crop management practices such as fertilizer application, irrigation scheduling and sowing time. Conversational intelligence enables farmers to interact with AI-powered chatbots and voice assistants in regional languages, whereas collective intelligence integrates knowledge from farmer communities, crowdsourced observations and digital platforms to promote collaborative learning and innovation. The five intelligent functions were illustrated in Figure.3.

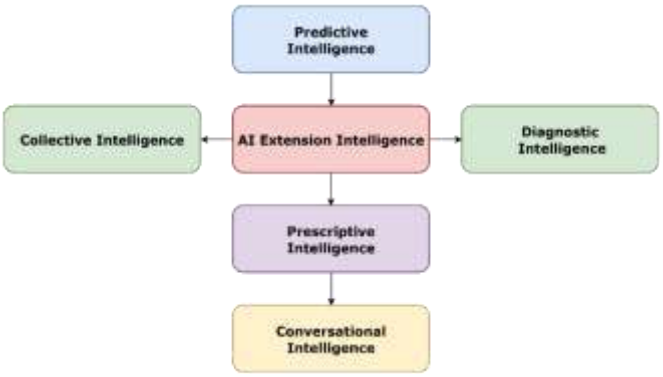


Fig. 3: Intelligence Functions of AI Extension

AI-driven Extension Models

AI-driven extension models represent the evolution of agricultural advisory services from conventional knowledge dissemination to intelligent and collaborative decision support. These models range from AI-assisted information delivery and decision support for extension professionals to human-AI collaborative systems that provide personalized, real-time recommendations for farmers. By integrating human expertise with AI capabilities, these models enhance the efficiency, accuracy, and accessibility of agricultural extension services.

Generative AI in Extension

Generative Artificial Intelligence is transforming agricultural extension by enabling intelligent, interactive, and multilingual advisory services. Large Language Models (LLMs) can answer farmers' queries, translate technical information into regional languages, interpret crop images, and provide voice-based recommendations for timely decision-making. In addition, generative AI can automatically prepare extension reports, develop training materials and summarize agricultural policies and government schemes, making agricultural knowledge more accessible, personalized and efficient for both farmers and extension professionals.

AI for Climate-Smart Agricultural Extension

Artificial Intelligence is strengthening climate-smart agricultural extension by providing real-time, data-driven advisories that help farmers adapt to climate variability and reduce environmental impacts. AI supports drought adaptation, heat stress management, water conservation, carbon farming, methane reduction, and greenhouse gas (GHG) emission estimation through predictive analytics and precision farming technologies. By delivering timely climate-risk advisories and location-specific recommendations, AI enhances farmers' resilience while promoting sustainable and climate-resilient agricultural practices.

AI-enabled Farmer Decision Cycle



Fig. 4: Farmer decision Cycle

The AI-enabled Farmer Decision Cycle transforms agricultural decision-making into a continuous, data-driven learning process. It begins with

field observations and data collection, followed by AI-based analysis, prediction, and personalized recommendations that support timely farm management decisions. Farmers implement these recommendations, while feedback from field outcomes is continuously analysed to improve future advisories. This adaptive cycle enables smarter, more precise, and sustainable farming by integrating real-time information with continuous learning.

Ethical Dimensions of AI Extension

The successful adoption of Artificial Intelligence in agricultural extension depends on addressing key ethical issues related to fairness, transparency, and accountability. Concerns such as algorithmic bias, data ownership, farmer privacy, digital exclusion, and AI governance must be carefully managed to ensure equitable access and trustworthy advisory services. Promoting explainable and responsible AI will enhance farmers' confidence, protect their rights, and support the sustainable use of AI-driven extension systems.

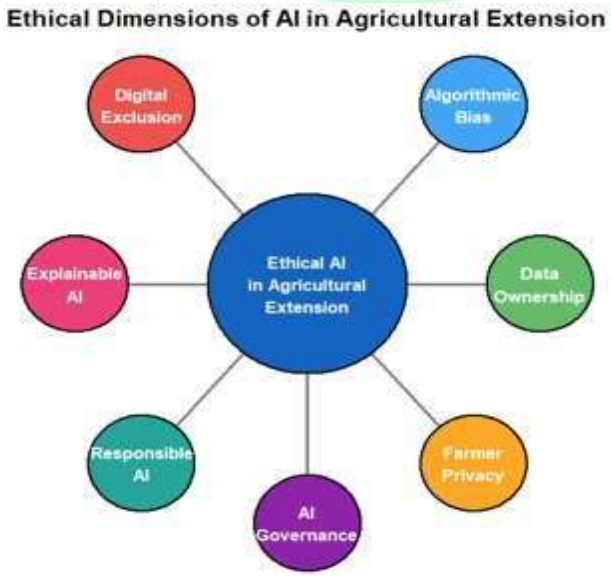


Fig. 5: Ethical Dimensions of AI Extension

Measuring the Success of AI Extension

The effectiveness of AI-enabled agricultural extension should be evaluated not only by technology adoption but also by its impact on farmers and farming systems. Key performance indicators include advisory accuracy, adoption rate of recommendations, improvements in crop productivity and farm income, resource-use efficiency, farmer satisfaction, and the timeliness of advisory services. Regular monitoring of these indicators helps assess the contribution of AI to sustainable, inclusive, and farmer-centric agricultural extension.

Conclusion

Artificial Intelligence is reshaping agricultural extension by transforming conventional advisory services into intelligent, data-driven, and farmer-centric systems. Through predictive analytics, personalized recommendations, generative AI, and climate-smart decision support, AI empowers farmers to make timely and informed management decisions. However, its successful adoption requires responsible AI practices, ethical governance, data privacy, and inclusive digital access to ensure that no farmer is left behind. Rather than replacing extension professionals, AI complements their expertise by enhancing the quality, reach, and effectiveness of advisory services. As digital technologies continue to evolve, AI-enabled agricultural extension will play a pivotal role in improving agricultural productivity, resilience, and sustainability for future farming systems.

References

Food and Agriculture Organization (FAO). (2022). *The State of Food and Agriculture 2022: Leveraging Automation in Agriculture for Transforming Agrifood Systems*. Rome: FAO.

Food and Agriculture Organization (FAO). (2024). *The State of Food and Agriculture 2024*. Rome: FAO.

Klerkx, L., Jakku, E. and Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and Agriculture 4.0: New contributions and a future research agenda. *NJAS: Wageningen Journal of Life Sciences*, 90-91: 100315.

Liakos, K. G., Busato, P., Moshou, D., Pearson, S. and Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors*, 18(8): 2674.

Rose, D. C. (2021). The role of artificial intelligence in improving agricultural extension and advisory services. *Outlook on Agriculture*, 50(2): 105-112.

International Food Policy Research Institute (IFPRI). (2024). *Digital Agriculture and Artificial Intelligence for Sustainable Food Systems*. Washington, DC: IFPRI.

Wolfert, S., Ge, L., Verdouw, C. and Bogaardt, M. J. (2017). Big data in smart farming: A review. *Agricultural Systems*, 153: 69-80.

OECD. (2023). *Artificial Intelligence in Agriculture and Food Systems*. Paris: Organisation for Economic Co-operation and Development (OECD).

United Nations Educational, Scientific and Cultural Organization (UNESCO). (2023). *Guidance for Generative AI in Education and Research*. Paris: UNESCO.

Talaviya, T., Shah, D., Patel, N., Yagnik, H. and Shah, M. (2020). Implementation of artificial intelligence in agriculture for optimisation of irrigation and application of pesticides and herbicides. *Artificial Intelligence in Agriculture*, 4: 58-73.

Precision Irrigation: A New Era in Grapevine Cultivation

Monika Jain and Aditya Nama

Abstract

Water scarcity has become a major constraint to sustainable agriculture, particularly in regions facing declining freshwater resources and changing climatic conditions. Although grapevine (*Vitis vinifera* L.) is relatively drought tolerant, optimum water management is essential for achieving high yields and superior fruit quality. Both excessive and inadequate irrigation can negatively affect vine growth, berry development, nutrient uptake, and fruit composition. Precision irrigation has emerged as an efficient approach that delivers the right amount of water at the right time and place based on crop water requirements, soil moisture, and weather conditions. Modern irrigation techniques such as drip irrigation, Regulated Deficit Irrigation (RDI) and Partial Root Zone Drying (PRD) improve water-use efficiency, reduce water losses, and enhance grape yield and quality. By integrating advanced technologies and scientific irrigation scheduling, precision irrigation offers a sustainable solution for conserving water while ensuring profitable and climate-resilient grapevine cultivation.

Introduction

Grapevine (*Vitis vinifera*) is one of the most important fruit crops in India. The country is among the world's leading producers of table grapes, with major cultivation concentrated in Maharashtra, Karnataka, Tamil Nadu, Telangana, Andhra Pradesh, and Punjab. Maharashtra is the leading grape-producing state, contributing more than 75-80% of India's total grape production followed by Karnataka. The Nashik region of Maharashtra is widely known as the "Grape Capital of India" due to its extensive vineyard area and significant exports of fresh table grapes. India is one of the world's leading producers of table grapes, with exports primarily destined for Europe, the Middle East, Bangladesh, and Southeast Asian countries. Traditional flood irrigation often results in water wastage, nutrient losses, soil salinity, and uneven vine growth. With increasing water scarcity and climate variability, grape growers are shifting toward precision irrigation, which uses sensors, weather data, automation, and drip systems to optimize water use. Precision irrigation represents a new era in viticulture by improving water-use efficiency, fruit quality, and farm profitability.

Importance of Grapevine Cultivation in India

State	Major districts	Major use
Maharashtra	Nashik, Sangli, Solapur, Pune, Ahmednagar	Table grapes, raisins, wine grapes
Karnataka	Bijapur, Bagalkot, Belagavi, Koppal	Table grapes and wine grapes
Tamil Nadu	Theni, Dindigul, Coimbatore	Table grapes
Telangana	Ranga Reddy, Mahabubnagar, Medak	Table grapes
Andhra Pradesh	Anantapur, Chittoor, YSR Kadapa	Table grapes
Punjab	Bathinda, Muktsar, Fazilka	Table grapes

Monika Jain and Aditya Nama
RNT College of Agriculture, Kapasan, Chittorgarh, Rajasthan

Economic Importance of Grapevine Cultivation in India

Grapevine cultivation is one of the most profitable and commercially important horticultural enterprises in India. Unlike many fruit crops, grapes are cultivated primarily as a high-value cash crop, generating substantial income for farmers, traders, processors, and exporters. The crop plays a signifI-cant role in enhancing rural livelihoods, promoting agribusiness, and contributing to the country's horticultural economy. Its economic importance extends beyond fresh fruit production to processing industries, export earnings, employment generation, and value addition.Water is one of the most critical inputs in grapevine cultivation, directly influencing vine growth, yield, berry size, fruit quality, and vineyard longevity. Although grapevines are considered relatively drought-tolerant due to their deep and extensive root system, they require an adequate and well-managed water supply throughout the growing season to achieve optimum productivity. Both water deficit and excessive irrigation adversely affect vine health and fruit quality. Insufficient water during flowering and fruit set can severely reduce yield. Therefore, understanding the water requirement of grapevines is fundamental for developing efficient irrigation schedules and implementing precision irrigation techniques.

Components of Precision Irrigation Management

Drip Irrigation System: Drip irrigation is the cornerstone of precision irrigation in grapevine cultivation. It delivers water directly to the root zone of individual vines through a network of pipes and emitters, ensuring precise and efficient water application. This method minimizes water losses caused by evaporation, runoff, and deep percolation, thereby improving water use efficiency and promoting sustainable vineyard management. In addition, drip irrigation facilitates fertigation, allowing nutrients to be supplied along with irrigation water to enhance nutrient uptake and vine performance.

Benefits

- ✓ Ensures accurate and uniform water distribution to the root zone.
- ✓ Reduces water losses through evaporation, runoff, and deep percolation.
- ✓ Improves water use efficiency and conserves irrigation resources.
- ✓ Limits weed growth by wetting only the targeted root area.
- ✓ Increases fertilizer use efficiency through fertigation.
- ✓ Enhances vine growth, grape yield, and fruit quality.

Soil Moisture Monitoring: Soil moisture monitoring is an essential component of precision irrigation, enabling informed irrigation scheduling based on the actual water status of the soil. By using soil moisture sensors and monitoring devices, growers can accurately assess the amount of water available in the root zone and determine the optimal timing and quantity of irrigation. This approach prevents both over-irrigation and water stress, resulting in improved water use efficiency and healthier grapevine

growth.

Benefits

- ✓ Enables accurate irrigation scheduling based on soil water availability.
- ✓ Prevents over-irrigation and water deficit conditions.
- ✓ Improves water use efficiency and conserves irrigation resources.
- ✓ Promotes healthy root development and vine growth.
- ✓ Supports consistent grape yield and fruit quality.

Crop Water Requirement Assessment: Assessment of crop water requirements is a fundamental aspect of precision irrigation management. It involves estimating the amount of water needed by grapevines based on factors such as weather conditions, soil properties, vine growth stage, and crop evapotranspiration (ET). Accurate evaluation of these parameters enables growers to apply the appropriate quantity of water at the right time, thereby enhancing irrigation efficiency, conserving water resources and maximizing vineyard productivity.

Benefits

- ✓ Determines the precise water requirements of grapevines at different growth stages.
- ✓ Improves irrigation scheduling using evapotranspiration and climatic data.
- ✓ Prevents water stress as well as excessive irrigation.
- ✓ Enhances water productivity and resource conservation.
- ✓ Supports optimum vine growth, grape yield, and fruit quality.

Regulated Deficit Irrigation (RDI): Regulated Deficit Irrigation (RDI) is an advanced precision irrigation technique in which irrigation water is intentionally reduced during specific phenological stages of grapevine development. The aim is to impose a controlled level of water stress that improves fruit quality while minimizing any adverse effects on vine growth and yield. This strategy enhances water use efficiency by supplying less than the full crop water requirement during periods when the vine is relatively less sensitive to moisture deficits.

Working Principle: In RDI, irrigation is strategically restricted during selected stages of the grapevine growth cycle, such as post-fruit set or berry development, while ensuring adequate water supply during critical periods like flowering and early fruit establishment. The controlled water deficit limits excessive vegetative growth, encourages efficient allocation of assimilates to the developing berries, and improves fruit composition, including sugar accumulation, colour development and phenolic content. Successful implementation of RDI requires continuous monitoring of soil moisture, climatic conditions, and vine water status to maintain an optimal level of stress.

Advantages

- ✓ Reduces irrigation water consumption and enhances water conservation.
- ✓ Improves grape quality by increasing sugar conc-

entration, berry colour and phenolic compounds.

- ✓ Controls excessive vegetative growth and vine vigour.
- ✓ Enhances berry colour development and overall fruit composition.
- ✓ Increases irrigation and water use efficiency.
- ✓ Promotes sustainable vineyard management under limited water availability.

Limitations

- ✓ Requires careful planning and continuous monitoring of vine water status.
- ✓ Excessive or prolonged water stress may reduce grape yield and berry size.
- ✓ Accurate knowledge of vine water requirements and growth stages is essential for successful implementation.
- ✓ Effectiveness may vary depending on grape cultivar, soil type, and climatic conditions.

Partial Root Zone Drying (PRD)

Partial Root Zone Drying (PRD) is an innovative precision irrigation strategy designed to maximize water use efficiency while sustaining grapevine growth, yield, and fruit quality. Unlike conventional irrigation, PRD alternately irrigates different sections of the root system, allowing controlled soil drying on one side while maintaining adequate moisture on the other.

Working Principle: In the PRD technique, irrigation is applied to only one side of the grapevine root zone, while the opposite side is allowed to dry. After a predetermined interval, the irrigation is switched so that the previously dry side receives water and the irrigated side is allowed to dry. This alternating irrigation pattern creates a controlled water deficit without exposing the entire root system to drought stress.

Mechanism: As the soil dries on one side of the root zone, the drying roots produce chemical signals, particularly the plant hormone abscisic acid (ABA) which are transported to the leaves. These signals induce partial stomatal closure, reducing transpiration and improving water use efficiency. At the same time, the irrigated portion of the root system continues to absorb sufficient water and nutrients to support normal physiological processes, thereby minimizing reductions in grape yield while enhancing fruit quality.

Advantages

- ✓ Reduces irrigation water use by up to 50% compared with conventional irrigation.
- ✓ Improves water use efficiency without significant yield reduction.
- ✓ Maintains vine productivity under limited water availability.
- ✓ Enhances berry composition, including sugar accumulation, colour, and phenolic content.
- ✓ Controls excessive vegetative growth and improves canopy management.
- ✓ Contributes to sustainable vineyard water management.

Limitations

- ✓ Requires installation of dual drip irrigation lines on either side of the vine row.
- ✓ Involves higher initial installation and maintena-

nce costs.

- ✓ Demands careful scheduling and technical expertise for effective implementation.
- ✓ Performance may vary depending on soil type, climate, grape cultivar and vineyard management practices.

Challenges in Precision Irrigation

Although precision irrigation offers significant benefits in terms of water conservation, improved water use efficiency, and enhanced grape quality, several challenges limit its widespread adoption in vineyards. Successful implementation depends on technical expertise, reliable monitoring systems, and economic feasibility. Some of the major challenges include:

Accurate assessment of vine water status: Reliable measurement of vine water requirements using soil moisture sensors, plant-based indicators, or remote sensing technologies is essential for effective irrigation scheduling.

High initial investment: The installation of advanced irrigation systems, sensors, controllers, and monitoring equipment requires substantial capital, which may be a constraint for small and medium-scale growers.

Need for skilled management: Precision irrigation requires trained personnel to operate irrigation systems, interpret sensor data, and make timely irrigation decisions.

Variability in soil and climatic conditions: Differences in soil texture, water-holding capacity, topography, and climatic factors can influence irrigation performance, making site-specific management essential.

Continuous data collection and interpretation: Precision irrigation relies on regular monitoring and analysis of data from sensors, weather stations, and decision-support tools, which can be time-consuming and technically demanding.

Maintenance of equipment: Sensors, emitters, pipelines, and automated controllers require regular maintenance and calibration to ensure accurate operation.

Limited adoption among smallholders: High costs, inadequate technical knowledge, and limited access to modern irrigation technologies often restrict the adoption of precision irrigation by small-scale grape growers.

Allele Mining through TILLING and Eco-TILLING Approaches in Vegetable Crops

Ankita Kumari and Desh Raj Choudhary

Abstract

Vegetable crops encompass a diverse array of wild relatives, ancestral species, and landraces that offer valuable genetic resources for breeding high-yielding, climate-resilient varieties with enhanced resistance to biotic and abiotic stresses. Allele mining is an advanced technique for identifying naturally occurring genetic variations in specific genes that influence key traits, offering significant potential for the genetic enhancement of vegetable crops. This approach enables the discovery of beneficial alleles that can be harnessed to improve crop performance and resilience. Targeting Induced Local Lesions in Genomes (TILLING) and its derivative, Eco-TILLING, have proven effective for this approach. TILLING (Targeting Induced Local Lesions IN Genomes) is a technique for detecting single base-pair allelic variation in a target gene whereas Eco-TILLING identifies naturally occurring variation within the primary and secondary gene pool.

Introduction

Plant breeding mainly aims to develop improved plant characteristics for better agronomic performance. Till date, advances in plant breeding in terms of developing superior and high yielding varieties of vegetable crops was made possible by the accumulation of favourable alleles from extensive plant genetic resources existing worldwide. A large proportion of these beneficial alleles have not been fully utilized, as these were overlooked during the processes of evolution and domestication. Allele mining is best suited reverse genetic approach to identifying these novel or beneficial allele from wild relatives and introgressed them into cultivated varieties. It focused on undiscover allelic diversity linked to relevant traits within collections of genetic resources. Additionally, it is not effective in identifying functionally defective alleles, as these alleles do not produce any observable expression. So, allele mining is best to examining numerous alleles of a gene and find superior allele that have the potential to create improved cultivars (Tare *et al.*, 2023).

Importance of allele mining

- ✓ It helps in tracing the evolution of alleles.
- ✓ Identification of new haplotypes.
- ✓ Development of allele-specific markers for use in marker assisted selection.
- ✓ Helps in identify and conserve rare or lost traits that can be crucial for future breeding efforts.
- ✓ More accurate selection of desired traits.

Steps involved in allele mining

Ankita Kumari and Desh Raj Choudhary
Department of Vegetable Science and Floriculture, CSK HPKV, Palampur, Himachal Pradesh

- ✓ Selection of a target trait
- ✓ Identification and selection of desirable genotypes
- ✓ Selection of the genes associated with the traits
- ✓ PCR amplification of the identified accessions
- ✓ Sequencing of the polymorphic segment
- ✓ Comparison of sequence data with phenotypic data and identification of superior alleles.



Fig. 1: Allele mining set



Fig. 2: Development of core and mini core collection

Allele mining approaches

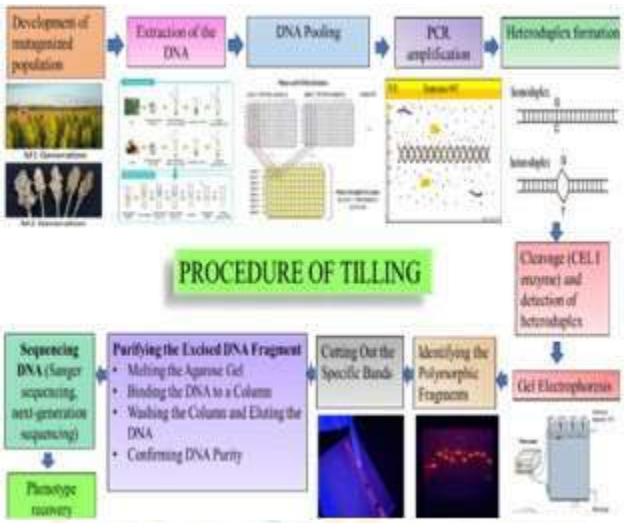
- ✓ TILLING (Targeting Induced Local Lesions IN Genomes)
- ✓ ECO-TILLING (Ecotype Targeting Induced Local Lesions in Genomes)
- ✓ Sequence based allele mining.

TILLING (Targeting Induced Local Lesions in Genomes)

It is a technique that combines chemical mutagenesis with PCR based screening to identify point mutations in regions of interest (McCallum *et al.*, 2000). This technique was first designed to detect mutation in *Arabiodopsis thaliana* treated with the chemical mutagen, EMS.

Procedure of TILLING

- ✓ Development of a mutagenized population
- ✓ DNA Extraction and pooling
- ✓ PCR Amplification
- ✓ Mismatched specific cleavage
- ✓ Gel electrophoresis
- ✓ Identifying the Polymorphic Fragment
- ✓ Purifying the Excised DNA Fragment:
- ✓ Confirming DNA Purity
- ✓ Phenotype recovery



Eco-TILLING (Ecotypic TILLING: It is a method of TILLING, except that mutations are not produced chemically. It has been used to classify natural polymorphisms in the target alleles in the primary and secondary gene pools. This method was first employed in Arabidopsis thaliana to find natural polymorphisms (Comai *et al.*, 2004).

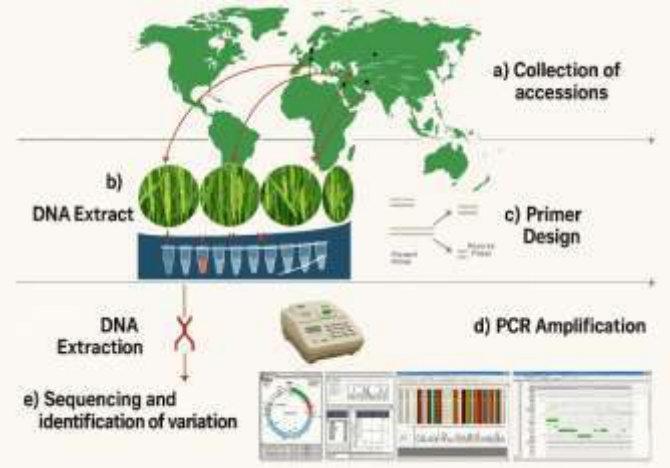


Sequencing-based allele mining: This technique involves amplifying alleles from various genotypes

using PCR, followed by the identification of nucleotide variations through DNA sequencing.

Applications of allele mining

- ✓ Identification of new variants.
- ✓ Identification of new haplotypes.
- ✓ Characterization of allelic diversity in gene banks.
- ✓ Development of allele-specific markers
- ✓ Similarity analysis and evolutionary relationship.
- ✓ Promoter mining.
- ✓ Allelic synteny and evolutionary relationships.



Conclusion

Allele mining offers a powerful method for identifying natural allelic variation in candidate genes that influence a range of biotic and abiotic traits. It serves as a connection between the effective use of genetic and genomic resources. It is possible to explore the role desired genes that are otherwise, not likely to be recovered in genetic screens, based on insertional mutagenesis/transformation. Allele mining approaches such as TILLING and Eco-TILLING have proven to be powerful tools in modern plant genetics and crop improvement. These approaches can be a viable option in the field of vegetable breeding for identifying alleles connected to important qualitative and quantitative traits.

References

McCallum, C. M., Comai, L., Greene, E. A. and Henikoff, S. (2000). Targeted screening for induced mutations. *Nature Biotechnology*, 18: 455-457.

Comai, L., Young, K. and Till, B. J. (2004). Efficient discovery of DNA polymorphisms in natural populations by Eco-tilling. *The Plant Journal*, 37: 778-786.

Tare, S., Tiwari, S., Rathore, S. M., Yasin, M., Tripathi, N., Tiwari, P. N. and Tripathi, M. K. (2016). An overview of allele mining for crop improvement: TILLING and Eco-TILLING. *Plant Cell Biotechnology and Molecular Biology*, 24: 91-103.

Quality Forage for Healthy Livestock and Sustainable Farming

A. D. S. S. A. Nikhil, Priyanka Kantwa and Dhanapati Keerthana

Abstract

Forage is the cornerstone of livestock nutrition, accounting for up to 60-80% of their total daily food intake. But an abundance of green forage does not guarantee productivity of livestock unless it is nutritionally sound and highly digestible. Good quality forage leads to better feed intake, utilization of nutrients, milk and meat yields, reproduction, health, and profitability of the farm. Forage analysis in modern times has therefore moved on from biomass assessment to the quality attributes of forage like dry matter, crude protein, fibre composition, digestibility, carbohydrates, mineral content, and energy. Technologies like Near-Infrared Reflectance Spectroscopy (NIRS), automatic fibre analysers, and hand-held sensing instruments have revolutionized forage analysis. This article focuses on the major forage quality traits, their practical significance and commonly used methods of evaluation, while highlighting their role in improving livestock productivity, enhancing the nutritional quality of animal-derived foods and promoting environmentally sustainable livestock production. Developing nutritionally superior forage cultivars through scientific breeding and modern quality assessment technologies will be essential for ensuring food security, farmer profitability and climate-resilient agriculture.

Introduction

Livestock rearing is essential in agricultural economies due to its contributions to supply of milk, meat, manure, draught power and security of livelihood to millions of farmer families. India is endowed with the largest livestock population globally, and the country has achieved tremendous success in milk production. However, for continued success in milk production, it is important to have sufficient quality forages to maintain productivity of livestock. The country produces different kinds of forage crops, which include cereals like maize, sorghum, pearl millet and oats; legumes like berseem, lucerne and cowpea; as well as perennial grasses like Napier-Bajra hybrids, guinea grass and para grass to meet nutritional needs of livestock in different agro climatic zones. Efforts have been done to increase forage production in the country. However, shortage of quality forages has remained a challenge in increasing productivity of livestock. Forages form about 60-80 percent of daily feed intake of ruminants.

A. D. S. S. A. Nikhil
Research Scholar, Division of Genetics and Plant Breeding, FoA, SKUAST-Kashmir, Srinagar, UT of J&K
Priyanka Kantwa
Research Scholar, Department of Agronomy, CCSHAU, Hisar, Haryana
Dhanapati Keerthana
Research Scholar, Department of Genetics and Plant Breeding, RLBCAU, Jhansi, Uttar Pradesh

Ruminants are capable of producing products like milk and meat through microbial fermentation of fibrous plants in the rumen. The efficacy of microbial fermentation is greatly dependent on quality rather than quantity of forages. High amounts of low-quality forage cannot satisfy the nutritional needs of the animals while lesser amounts of high-quality, easily digestible forages can significantly help in enhancing the performance of the animals. The quality of forages is the ability of forages to offer nutritious compounds which are readily digestible by the animals. This is affected by various factors such as chemical composition of the forages, digestibility, amount of fibres in forages, palatability, mineral content of forages, time of harvest, type of plant crop, genotype and method of forage preservation like hay and silage. In the past, assessment of forage was largely based on the measurement of green biomass yield. Currently, emphasis has been placed on the nutritional quality of forage crops as opposed to yield through the use of scientific parameters that define the quality of the forage crop. Scientific laboratory methods such as estimation of total nitrogen through the Kjeldahl method, detergent fiber analysis, in vitro digestibility tests, and proximate analysis, in addition to rapid methods like NIRS, are some ways of getting reliable data on forage quality very quickly. Such data enable farmers, livestock nutritionists, and crop breeders to balance feeding regimes, select high-quality forages and improve harvesting and preservation methods. With the increasing demand for milk and meat production against the back drop of climate change and depletion of grazing lands, improvement of forage quality has become just as important as improvement of forage yield.

Major forage quality traits and their evaluation

The nutritive value of forages is dependent not only on the yield of forage but also the nutritional composition and the digestibility of the forage. Various quality parameters affect the intake, digestion, and utilization of nutrients, milk/meat yield, and general well-being of animals. Proper assessment of such qualities enables farmers to cut forage at an appropriate stage, create balanced diets and produce high-quality silage using improved forages. Some of the major forage quality characteristics and their importance and methods of estimation are outlined in Table 1.

Dry Matter (DM): The quality of forage is assessed by a combination of chemical content, digestibility, and availability of nutrients. The most fundamental quality aspect in forage is the dry matter (DM) since it indicates the content that contains nutrients after moisture is removed. Because animals utilize the nutrients and not the moisture content, dry matter serves as a reliable measure to compare fodder qualities and to estimate feed intake and ration formulation. The optimum level of dry matter is as crucial when preparing hay and silage as well.

Crude Protein (CP): CP is among the most important nutritional components of forages. CP is an estimate of the amount of protein available to the rumen microorganisms responsible for forage degradation. Proper protein level helps to improve fiber

Table 1: Major Forage Quality Traits, rheir Importance and Common Methods of Evaluation

Quality trait	What it measures	Importance	Common analytical methods	References
Dry Matter (DM)	Dry portion of forage after moisture removal	Basis for ration formulation, feed comparison and silage making	Hot-air oven, Microwave drying, NIRS	AOAC International (2019); Weiss and Hall (2020)
Crude Protein (CP)	Total nitrogen × 6.25	Supports rumen microbes, growth, milk production and reproduction	Kjeldahl, Dumas combustion, NIRS	AOAC International (2019); Weiss & Hall (2020)
Neutral Detergent Fibre (NDF)	Cellulose + Hemicellulose + Lignin (total cell wall)	Predicts voluntary feed intake	Van Soest detergent fibre method, Fibre analyser, NIRS	Van Soest *et al.* (1991)
Acid Detergent Fibre (ADF)	Cellulose + Lignin	Indicates digestibility and energy value	Van Soest detergent fibre method	Van Soest *et al.* (1991)
Acid Detergent Lignin (ADL)	Lignin	Measures indigestible fibre	Sulphuric acid digestion	Van Soest *et al.* (1991)
Ash	Total mineral content	Indicates mineral composition and forage cleanliness	Muffle furnace, AAS, ICP-OES	AOAC International (2019)
Water-soluble carbohydrates (WSC)	Readily fermentable sugars	Essential for efficient silage fermentation	Anthrone method, HPLC	Yemm and Willis (1954)
IVDMD / IVOMD	Digestible proportion of forage	Estimates feeding value	Tilley & Terry method, Daisy II incubator	Tilley and Terry (1963)
Total Digestible Nutrients (TDN)	Digestible energy available from forage	Indicates energy value	Calculated from digestibility or ADF	Robinson (2005)
Relative Feed Value (RFV)	Index based on NDF and ADF	Compares forage quality	Calculated index	Rohweder *et al.* (1978)
Relative Forage Quality (RFQ)	Index based on intake and fibre digestibility	Better predictor of animal performance than RFV	Calculated index	Moore and Undersander (2002)
Silage quality	pH, lactic acid, volatile fatty acids and ammonia-N	Indicates fermentation efficiency and nutrient conservation	pH meter, HPLC, Gas chromatography	Kung *et al.* (2018)

digestion, feed efficiency, and milk and meat production, growth, reproduction and resistance to diseases. In contrast, insufficient protein intake can impair animal performance despite an adequate supply of forages.

Ether Extract (EE): It is known as crude fat, indicates the proportion of forage solvable in organic solvents. This comprises the fats, waxes, pigments and fat-soluble vitamins that increase the energy content of the forage. Even though the concentration of lipids in forage is low (2-6% DM), EE represents a good source of energy and increases palatability. Too much fat, on the other hand, may decrease microbial activity in the rumen.

Crude Fibre (CF): It is the residue of structural carbohydrates (mainly cellulose, some lignin, and a little hemicellulose) left after removing moisture, fat, and then digesting the defatted sample with acid and alkali. It is less precise than the modern detergent fibre system (NDF, ADF) but still used in feed evaluation. High crude fibre generally means lower digestibility, intake, and energy value, whereas low crude fibre indicates higher forage quality.

Detergent Fibre Fractions: The system of detergent fiber analysis developed by Van Soest has become a world standard of forage assessment since it allows a

much better comprehension of forage digestibility than the classic analysis based on crude fiber determination. Neutral Detergent Fiber (NDF) estimates the total cell wall of forage containing cellulose, hemicellulose, and lignin and is commonly used as an indicator of voluntary feed consumption. As NDF increases, forage intake declines. Acid Detergent Fiber (ADF) is an estimate of cellulose and lignin and is negatively correlated with digestibility and energy content of forages. The low level of ADF is an indicator of high-quality forages. Acid Detergent Lignin (ADL) is an estimate of lignin, the indigestible fraction of cell wall limits microbial access to cellulose. As forage crops mature, lignin content increases, reducing digestibility and overall nutritional quality.

Ash Content: The ash content indicates the total amount of minerals in the forage after combustion. Some of these minerals are calcium, phosphorus, potassium, magnesium, iron, and zinc which are required for bone formation, enzymatic actions, milk synthesis, immunity, and reproduction. The ash content is sometimes high due to soil contamination during harvest.

Water-Soluble Carbohydrates (WSC): Water soluble carbohydrates refer to simple sugars that act as the main source of energy in the fermentation process by lactic acid bacteria. Enough WSC enhances the rapid formation of lactic acid, reduction of pH value, and nutrient preservation leading to good quality silage.

Digestibility Indices: Digestibility is another important criterion of the nutritional quality of the feed; it shows how many nutrients can be assimilated by the animals. Lab tests like in vitro dry matter digestibility (IVDMD) and in vitro organic matter digestibility (IVOMD) mimic the environment of the rumen and give an accurate assessment of the feeding quality. The results of the above tests are used for calculating several practical criteria including Total Digestible Nutrients (TDN), Relative Feed Value (RFV) and Relative Forage Quality (RFQ). The first criterion provides information about the total amount of energy provided to the animals, while the second is a combination of digestibility and intake ability of different feeds.

Silage Quality Parameters: In case of conserved fodders, the silage quality plays an equally significant role. The silage that is of good quality can be described as having low pH, high lactic acid content, minimal butyric acid production, and low ammonia nitrogen. The above parameters need to be checked regularly to reduce losses during storage and ensure nutritious fodder all year round. With the emergence of new technologies, the evaluation process for quality of the forages has become much faster, accurate, and user-friendly. Although the traditional methods using the laboratory have been considered the gold standard, the fast methods like Near-Infrared Reflectance Spectroscopy (NIRS), automatic fibre analysers, hyperspectral images, and the Near-Infrared sensors can predict the several parameters of forage quality within a few minutes without requiring much sample preparation.

How farmers can improve forage quality

- ✓ Harvest cereals at boot to early flowering stage.
- ✓ Harvest legumes at 10-20% flowering.
- ✓ Avoid soil contamination during harvest.
- ✓ Prepare well-fermented silage.
- ✓ Test fodder quality before ration formulation.
- ✓ Grow improved high-quality cultivars.

Forage Quality and Human Health

Quality of forage goes beyond just improving the productive capacity of livestock. The nutrient content of the fodder used has a direct impact on the quality of the milk, meat and other livestock products that humans eat. Livestock fed on good quality and balanced fodder will produce more nutrient-rich milk and meat that contain high levels of nutrients such as omega-3 fatty acids, CLA, vitamins A and E and natural antioxidants. Such nutrients lead to improved human health. Quality fodder also increases the immunity of livestock and reduces the chances of metabolic diseases and thus reduce antibiotic use in livestock. Improved fodder is also beneficial in terms of environmental sustainability. Digestion of highly nutritious fodder leads to efficient feed conversion ratio whereby the livestock are able to produce more milk or meat from the same quantity of feed. Good digestion leads to reduced methane gas emissions from the digestive process, high nitrogen-use efficiency and less nutrient loss through the excreta of the livestock.

Future Perspectives

Improvements in forage quality have become essential as the demand for livestock increases, the grazing area decreases and climate change intesifies. The future breeding efforts should focus on developing varieties of forage that have high biomass, better nutrient content, improved digestibility and stress tolerance. Advanced technologies such as genomics, molecular breeding, high throughput phenotyping and artificial intelligence are contributing to the development of better varieties of forages whereas fast and non-destructive techniques such as NIRS, hyperspectral imaging, remote sensing and portable sensors are revolutionizing quality assessments. With the integration of precision livestock farming, these advances are enabling farmers to develop balanced diets, optimize feed utilization and manage their animals efficiently in order to improve productivity, reduce feed waste and greenhouse gases.

Conclusion

Forage quality should no longer be evaluated solely on the basis of green biomass production but rather on its ability to supply balanced, digestible nutrients that support efficient livestock production. Key quality traits, including dry matter, crude protein, fibre fractions, digestibility, mineral composition and energy value, determine the nutritional and feeding value of forage for milk, meat and other livestock products. Accurate assessment of these parameters through conventional laboratory analyses and modern rapid techniques enables informed decisions on harvesting, conservation, ration formulation and cultivar selection. In the face of climate change, shrinking natural resources and the

growing demand for livestock products, enhan-cing forage nutritional value has become as important as increasing forage yield. Integrating scientific breeding with advanced quality assessment techno-logies will accelerate the development of nutrient-rich, climate-resilient forage cultivars. Such advances will contribute to healthier livestock, improved productivity, greater farmer profitability and a more sustainable agricultural future.

References

AOAC International. (2019). Official methods of analysis of AOAC International (21st ed.). AOAC

Kung, L., Shaver, R. D., Grant, R. J. and Schmidt, R. J. (2018). Silage review: Interpretation of chemical, microbial and organoleptic compo-nents of silages. *Journal of Dairy Science*, 101: 4020-4033.

Mertens, D. R. (2002). Gravimetric determination of amylase-treated neutral detergent fiber in feeds. *Journal of AOAC International*, 85: 1217-1240.

Moore, J. E. and Undersander, D. J. (2002). Relative forage quality: An alternative to relative feed value and quality index. *Proceedings of the Florida Ruminant Nutrition Symposium*, 16-32.

Van Soest, P. J., Robertson, J. B. and Lewis, B. A. (1991). Methods for dietary fiber, neutral detergent fiber and non-starch polysacch-arides in relation to animal nutrition. *Journal of Dairy Science*, 74: 3583-3597.

Robinson, P. H. (2005). Energy prediction equations for ruminant feeds. *Proceedings of the Cornell Nutrition Conference*, 176-185.

Rohweder, D. A., Barnes, R. F. and Jorgensen, N. (1978). Proposed hay grading standards based on laboratory analyses for evaluating quality. *Journal of Animal Science*, 47: 747-759.

Tilley, J. M. A. and Terry, R. A. (1963). A two-stage technique for the in vitro digestion of forage crops. *Journal of the British Grassland Society*, 18: 104-111.

Weiss, W. P. and Hall, M. B. (2020). *Forage quality evaluation and interpretation*. The Ohio State University Extension.

Yemm, E. W. and Willis, A. J. (1954). The estimation of carbohydrates in plant extracts by anthrone. *Biochemical Journal*, 57: 508-514.

Poultry Housing and Farm Management: Simple Practices for Healthy Birds and Better Profit

Vidhi Prajapati, M. M. Pawar and Nirali Khunt

Poultry farming is one of the fastest-growing and most profitable agricultural activities. It provides farmers with a regular source of income through the production of eggs and meat while also creating employment opportunities for rural families. Success in poultry farming depends not only on good-quality birds but also on proper management and care. Birds need a clean, safe, comfortable, and well-ventilated house to protect them from extreme weather conditions, predators, and diseases. They should always have access to clean drinking water, balanced and nutritious feed, and sufficient space to move, eat, and rest comfortably. Farmers should regularly clean the poultry house, replace wet litter with dry bedding material, and maintain good hygiene to reduce the spread of harmful germs. Vaccination and bio-security measures are also important to prevent diseases and keep the flock healthy. Young chicks require special care during the brooding period because they cannot control their body temperature properly. Timely identification and removal of weak, sick, or unproductive birds through culling helps maintain a healthy flock and reduces unnecessary feed costs. When farmers follow good housing practices, proper feeding, regular health care, litter management, and disease prevention measures, the birds grow faster, produce more eggs, have lower mortality, and provide higher profits. Therefore, adopting good poultry housing and farm management practices is the key to successful, sustainable, and profitable poultry farming.

Poultry Housing Systems

A good poultry house is the foundation of successful poultry farming. Healthy birds grow faster, produce more eggs, and give better income when they are kept in a clean, safe, and comfortable environment. A poultry house protects birds from heavy rain, strong winds, direct sunlight, cold weather, predators such as dogs, cats, snakes, and wild animals, and many disease-causing organisms. It also provides birds with a stress-free environment where they can eat, drink, rest, and grow properly. A well-designed poultry house should have good ventilation so that fresh air can enter and harmful

Vidhi Prajapati
M.V.Sc. Scholar, Department of Animal Nutrition, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Junagadh, Gujarat

M. M. Pawar
Associate Professor, Department of Animal Nutrition, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Junagadh, Gujarat

Nirali Khunt
M.V.Sc. Scholar, Department of Veterinary Microbiology, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Junagadh, Gujarat

gases like ammonia can escape. It should provide enough floor space for every bird to move comfortably without overcrowding. Clean drinking water, good lighting, proper drainage, and a dry floor are also essential for maintaining bird health and improving production. Farmers should choose the most suitable housing system according to the number of birds they plan to rear, the amount of land available, local climatic conditions, labour availability and their financial capacity. Selecting the right housing system helps reduce disease, improve bird welfare, and increase farm profitability.

The commonly used poultry housing systems are:

- ✓ Deep litter system
- ✓ Cage system
- ✓ Free-range or backyard poultry system
- ✓ Environment-controlled poultry house

Cage System vs. Deep Litter System: The cage system is mainly used for commercial layer farming where birds are raised for egg production. In this system, birds are kept individually or in small groups inside specially designed wire cages placed above the floor. The eggs roll gently to the front of the cage, making egg collection quick, clean, and easy. Feeders and drinkers are attached to the cages, allowing birds to receive feed and water efficiently. Since birds have less contact with their droppings, the chances of disease transmission are reduced. Farmers can easily monitor each bird, identify sick birds, maintain production records, and manage feeding more accurately. The cage system also reduces feed wastage and produces cleaner eggs.



However, this system requires a high initial investment for purchasing cages and equipment. Birds have limited movement, so proper nutrition and management become even more important for maintaining their health and productivity.The deep litter system is one of the most popular housing systems used by small and medium-scale poultry farmers because it is economical and easy to manage. In this system, birds are reared directly on the floor, which is covered with bedding materials such as rice husk, sawdust, wood shavings, chopped straw, groundnut shells, or dry leaves. These materials absorb moisture from droppings and help keep the poultry house dry. Birds can move freely, scratch the litter, and express their natural behaviour, which reduces stress. The cost of constructing a deep litter house is much lower than a cage house, making it suitable for farmers with limited investment. However, successful deep litter farming depends on proper litter management. Wet or dirty litter produces ammonia gas, unpleasant odours, and disease-causing organisms, which may lead to respiratory infections, coccidiosis, footpad lesions, poor growth, and lower production. Therefore, farmers should regularly inspect the litter, remove wet patches, and maintain proper ventilation to keep the litter clean

and dry throughout the production period.

Environment-Controlled (EC) Poultry Farming: Environment-controlled poultry farming is a modern and scientific method of poultry production in which all environmental conditions inside the poultry house are automatically managed. Equipment such as exhaust fans, cooling pads, heaters, foggers, automatic feeders, automatic drinkers, and lighting systems help maintain the ideal temperature, humidity, ventilation, and light required by birds throughout the year. This system protects birds from extreme summer heat and winter cold, allowing them to remain comfortable and healthy under all weather conditions.Because birds experience less stress, they consume feed more efficiently, grow faster, produce more eggs, and show lower mortality. Disease outbreaks related to environmental stress are also reduced. Although environment-controlled poultry farming provides higher productivity and better flock performance, it requires a large financial investment, continuous electricity supply, skilled labour, and regular maintenance of equipment. Farmers should carefully study market demand, investment costs, and management requirements before adopting this advanced system.



Backyard Poultry Farming: Backyard poultry farming is a simple and low-cost method of raising poultry around the home using local or improved backyard breeds. Birds are usually allowed to roam freely during the daytime, where they search for insects, worms, seeds, grass, and kitchen waste as natural sources of food. At night, they are kept safely inside a simple shelter to protect them from predators and harsh weather conditions. This system is highly beneficial for small and marginal farmers because it requires less investment while providing a regular supply of fresh eggs, nutritious meat, organic manure for crops, and additional household income. Local birds generally have better resistance to diseases and adapt well to village conditions. However, farmers should still provide supplementary feed, clean drinking water, regular vaccination, proper night shelters, and protection from predators such as dogs, cats, snakes, and wild birds. Good management practices can significantly improve the productivity and survival of backyard poultry birds.



Brooding Management: Brooding is one of the most important stages in poultry farming because newly hatched chicks cannot regulate their own body temperature during the first few weeks of life. Therefore, farmers must provide sufficient warmth, balanced feed, clean drinking water, proper lighting,

and a hygienic environment to help chicks survive and grow properly. During the first week, the brooder temperature should be maintained between 32°C and 35°C and gradually reduced by about 2-3°C every week until chicks become fully feathered. Farmers should carefully observe chick behaviour every day. If chicks gather closely under the heat source, they are feeling cold. If they move far away from the heat source and start panting, the temperature is too high. When chicks spread evenly throughout the brooding area, eat feed actively, drink water regularly, and remain cheerful and active, it indicates that brooding conditions are ideal. Proper brooding management reduces chick mortality, improves immunity, promotes faster growth, and increases future egg or meat production.

Litter Management: Litter is the bedding material spread on the floor of poultry houses to absorb moisture, provide insulation, and keep birds comfortable. Good-quality litter should always be dry, soft, loose, clean, and free from mould, dust, and harmful microorganisms. Common litter materials include rice husk, sawdust, wood shavings, chopped straw, and groundnut shells. Farmers should maintain a litter depth of approximately 5-10 cm depending on the season and bird age. Wet litter should be removed immediately because excessive moisture promotes the growth of bacteria, fungi, and parasites. Leaking drinkers should be repaired without delay, and litter should be stirred regularly to improve aeration and prevent caking. Proper ventilation is equally important because it removes excess moisture and ammonia gas. Well-managed litter helps prevent diseases such as coccidiosis, respiratory infections, breast blisters, and footpad dermatitis while providing a comfortable environment for birds.



Biosecurity in Poultry Farming: Biosecurity means following all necessary measures to prevent diseases from entering or spreading within the poultry farm. It is one of the most important and cost-effective methods of protecting poultry birds from infectious diseases. A strong biosecurity programme helps reduce mortality, improve production, and increase farm profitability. Farmers should restrict unnecessary visitors from entering poultry sheds. Workers should wear clean clothes, use separate footwear inside the poultry house, and pass through disinfectant footbaths before entering. Vehicles, cages, equipment, and tools should be cleaned and disinfected regularly. Sick birds should be separated immediately from healthy birds to prevent disease transmission. Dead birds should be disposed of safely by deep burial or incineration. Farmers should also control rodents, insects, wild birds, and other animals that may spread diseases. Proper vaccination, regular cleaning, safe feed storage, clean

drinking water, and following the all-in-all-out management system greatly reduce the risk of disease outbreaks and improve overall flock health.

Culling of Poultry Birds: Culling is the process of removing weak, diseased, injured, old or unproductive birds from the flock. Keeping unhealthy birds increases feed costs, spreads diseases, and reduces the overall performance of the flock. Therefore, timely culling is an important management practice for maintaining a healthy and productive poultry farm. In layer farms, birds showing poor egg production, pale combs, low body weight, deformities or signs of illness should be removed from the flock. In broiler farms, weak and sick birds should be culled as soon as possible to prevent disease spread and improve flock uniformity. Regular observation of bird health and production helps farmers identify birds that should be culled. Proper culling reduces mortality, improves feed efficiency, increases productivity, and ultimately leads to higher profits.

Conclusion

Good poultry housing and proper farm management are the keys to successful and profitable poultry farming. Farmers should always provide clean and comfortable housing, balanced feed, fresh drinking water, proper brooding, good litter management, and strong biosecurity practices to keep birds healthy and productive. Regular monitoring of bird health, timely vaccination, proper sanitation, and culling of weak or diseased birds help reduce losses and improve farm efficiency. By following these simple and scientific management practices, farmers can increase egg and meat production, lower disease incidence, reduce production costs, and earn better income from poultry farming throughout the year.

Advancing Agricultural Engineering through Computer Science and ICT

Sunil Kumar, Jagan Singh Gora, Ved Prakash, Parmod Kumar, M. Arif, Nalawade Rohit Dilip and Ranjit H. P.

Agricultural engineering integrates engineering principles with agricultural practices, focusing on areas such as the development and usage of farming machinery, design of rural infrastructure, soil and water conservation, irrigation systems, renewable energy utilization, and post-harvest processing. Computer science plays a pivotal role in enhancing these areas by offering modern solutions to complex agricultural challenges. This article highlights how computer science contributes to agricultural engineering through various means, including system modeling, simulation, process optimization, machine design and artificial intelligence (AI). Journals such as Computers and Electronics in Agriculture provide a global platform for showcasing advancements in computer-based and electronic solutions in agriculture, spanning disciplines like agronomy, horticulture, forestry, aquaculture and livestock management. Its companion journal, Smart Agricultural Technology, focuses on intelligent technologies that optimize agricultural productivity.

Role of IT in Addressing Agricultural Challenges

Agriculture in developing regions faces numerous obstacles, including the need to increase productivity, ensure food security, and generate employment, especially in rural areas. The rapid transformation of the agricultural landscape due to global trends makes it essential to adopt information technology (IT) for enhancing productivity and market access. However, the agricultural sector lags in IT adoption compared to other industries, primarily due to infrastructural and educational barriers. This paper explores the transformative potential of IT in agriculture and agribusiness. Economic analysis and literature suggest that IT can significantly boost efficiency, productivity, and decision-making for farmers and agricultural stakeholders. Despite this potential, challenges remain in widespread IT implementation due to a lack of resources, training, and connectivity.

Information as a Catalyst for Agricultural Development

Reliable and timely information is critical for the improvement of agricultural operations, especially in countries undergoing economic transitions or market integration, such as those entering the European Union. As agricultural sectors become deregulated, access to accurate information becomes essential for stakeholders, from producers to input suppliers and buyers. The use of ICT (Information and Communication Technology) can greatly contri-

Sunil Kumar, Jagan Singh Gora, Ved Prakash, Parmod Kumar, M. Arif, Nalawade Rohit Dilip and Ranjit H. P.
ICAR-Indian Institute of Farming Systems Research, Modipuram, Meerut, Uttar Pradesh

bute to the socio-economic development of rural populations. Unfortunately, farmers often struggle to access relevant information in a format they can understand. ICT tools can support evidence-based farming through data collection, cost analysis, and advanced marketing strategies, empowering farmers to make informed decisions and improve profitability.

Key Information Needs in Agriculture

Crop Data: Information such as crop types, land use, sowing/harvesting timelines, and yield estimates can be collected and analyzed. Farmers can access this data online to plan their activities efficiently.

Production Techniques: Techniques developed by agricultural research institutions can be disseminated via digital platforms to aid farmers in adopting best practices.

Input and Equipment Information: Data about seeds, fertilizers, and machinery offered by suppliers can be made accessible to farmers for better decision-making.

Market Intelligence: Real-time market prices, export/import trends, and seasonal forecasts can guide farmers on when and where to sell their produce for maximum profit.

Additional Support: Weather updates, access to credit, pest and disease management tips, and expert guidance are also vital. However, collecting and disseminating this information requires significant effort and investment. ICT reduces the cost and increases the reach of information dissemination. Mobile phones and internet-based applications have become essential tools for farmers, especially in remote areas, allowing them to access crucial information in real time.

Enhancing Productivity through ICT

ICT benefits agricultural production in two main ways:

Direct Contributions: Technologies such as precision farming rely on ICT to optimize agricultural inputs and increase yields. Techniques include the use of satellite imagery, GIS (Geographic Information Systems), and meteorological data collected from field-based sensors. These systems monitor parameters like temperature, rainfall, soil moisture, and wind speed, providing data-driven insights for farm management. While highly effective, these solutions often require significant capital investment, making them more suitable for large-scale or corporate farms.

Indirect Contributions: ICT empowers farmers by improving access to critical information, thus enabling better decision-making. Traditional information sources often lack timeliness and accuracy. With reliable ICT tools, farmers can stay competitive in the global market by making informed choices on crops, marketing, and investments. However, digital literacy is essential for these tools to be effective. When farmers are trained in basic computing, they can utilize the internet to gather information, seek advice, and connect with peers and experts globally.

ICT Use in the European Union and Serbia

Comprehensive data on ICT adoption in EU agriculture is limited, but reports suggest that inter-

net access among farmers varies significantly by country from as low as 20% to as high as 95%. As of January 2009, around 93% of enterprises across the EU had internet access, with about 28% using mobile internet for agricultural activities. Countries like Greece, Cyprus, and Romania reported lower usage of mobile internet for business-related purposes. While mobile phone ownership is widespread, the use of advanced mobile applications for agricultural management remains minimal, with estimates ranging from 2% to 5% in some EU countries. However, smartphone usage is expected to increase rapidly in the coming years.

Adoption of Precision Farming

Precision farming (PF) serves as an indicator of agricultural automation. Although it has not been widely adopted across the EU, some countries are advancing. For instance, the Czech Republic has made notable progress in this field. Agricultural equipment manufacturers in Germany, Denmark, the Netherlands and Finland are promoting PF technologies, which include data collection and geospatial analysis. In many regions, PF remains in the research or pilot stage but holds promise for improving farm efficiency Computers and their applications changed the face of most traditional occupations including agriculture. From computerized milk collection and seed estimators to weather predictions and automated farmland assessment, computers have revolutionized farming practices. Technological advances have brought about drastic changes in farming and animal husbandry resulting in a tremendous increase in production capacity. The most common use of computers has been in replacing human effort and intervention in traditional farming machinery and other equipment. In addition, even the support functions for farming such as delivery of machinery, fertilizers and production of raw products have been successfully automated. But all these are just the labour-saving, basic uses that have been around even before the turn of the century. If computers have changed the ways of farming, then the Internet has only doubled that pace of change. Applications of Computing Technologies in Agriculture In today's times, agriculture is not just about crop production or livestock farming and associated activities. The challenges brought forth by ecological factors affecting the environment need to be a major consideration for any kind of farming activity. Farmers need to pre-empt environmental impact due to climate change and this is where modern technology comes to the rescue. In a nut-shell, the uses of computers in agriculture include: There are softwares which help in the prediction of weather conditions and estimation of agricultural production. Computers are used for record-keeping of information related to costs involved in production, transport, agricultural processes, and in the estimation and calculation of profit and/or loss. The Internet aids communication among farmers and between farmers and agriculture experts. This leads to an exchange of knowledge and serves as guidance for farmers to improve production and earn profits.

Farmland Assessment

Geographic Information Systems (GIS): GIS are being used for developing ranking systems that evaluate land and provide a site assessment to aid what is now known as precision agriculture. These hi-tech, interactive systems provide information based on a variety of factors such as soil conditions, drainage and slope conditions, soil pH and nutrient status, etc. Prior to the use of these systems, farmers were often in the dark about soil output, and unpredictable weather conditions affecting crop quality and profitability. Precision agriculture provides farmers with control by predicting vital information including fertilizer application and problems with drainage, insects, and weeds. Most government websites provide this kind of information free of cost, covering agricultural land masses across the United States. Global Positioning System (GPS) based technologies also help to monitor irrigation, field mapping, soil sampling, tractor guidance and crop scouting. This kind of technology equips farmers with enough information to increase crop yield in a manner that is consistent with the best environmental practices for sustainable agriculture.

Autonomous Farm Equipment and Tractors: Automated farm equipment, needless to say, scores over human controlled equipment in terms of consistency and reliability. Engine and machine functions such as transmission and hydraulic power output are controlled using microchips built into the equipment. Guidance technology is already being widely used in self-propelled equipment to aid crop seeding and fertilizer application. Automated feeding systems, computerized milk collection and milking machines have been around since the late 20th century, resulting in better economic yield for the dairy industry as well as livestock production. Automated tractors are probably not far away.

Farm Software: With regard to livestock farming, ready-made computer applications are available to track animals, storing and evaluating information such as age, health records, milk production, offspring productivity, and reproductive cycle status. This is often called herd recording. Similarly, most farm accounting software and other computer applications in agriculture provide services for record keeping, simulation of prediction-based models using that data, and revenue and productivity estimation. Most farm software vendors provide you with an option to customize their applications to the specific needs of your farm or ranch.

Internet Forums, Social Networking and Online Knowledge Bases: Any business in the world that you can think of, has benefited from the advent and global reach of the Internet and related communi-cation technologies (mobile computing, ecommerce, etc.). Agriculture is no different. Imagine using the power of the Internet to connect with farmers, agriculturists and agricultural scientists and other experts spread across the globe. There are several forums and social networking sites on the Internet where farmers can connect with other farmers and farming experts and exchange know-how. In addition, there are several learning repositories that

provide information on a wide variety of agricultural topics. These avenues serve to reduce the rural digital divide, influence public policies, foster partnerships and connect all stakeholders across the agricultural value chain. For instance, a farmer can easily seek out and connect with an agricultural entrepreneur and begin the exchange of ideas or business proposals. Information such as price review for grain and livestock, pest information, real-time weather information (precipitation, temperature, humidity, solar radiation, wind speed, soil moisture and soil temperature) in any part of the world is literally available at one's fingertips.

E-agriculture: An emerging field of agricultural practices, e-agriculture focuses on coming up with innovative ways and best practices to use the existing information and communication technologies (ICTs) for sustainable agricultural development and food safety standards, particularly in rural areas. E-agriculture encompasses other related technological fields such as agricultural informatics, agricultural development and business. It aims to deploy all available technologies (computers, mobile computing, satellite systems, smart cards) for the empowerment of farmers and strengthening of partnerships across the food value chain. The uses of computers in agriculture do have some real constraints such as, the lack of hardware and software infrastructure, training and skills, and research priorities. However, once these are overcome, the use of computers goes past automation and software application. In fact, it could be instrumental in bridging the digital divide and bringing prosperity to agriculturists not only in the United States, but also in other developing and emerging economies around the world. Digital transformation is acting as a game-changer for Indian agriculture. This has led to the rise and development of mobile apps which are helping existing government schemes and other agriculture-based information to reach farmers in rural India. Now, with a click of a button, farmers can access all the necessary information he needs.

List of 25 Mobile Apps that can significantly improve the Lives of Farmers – App Names and Download Links

My Agri Guru: https://play.google.com/store/apps/details?id=com.myagriguru&hl=en

Iffco Kisan: https://play.google.com/store/apps/details?id=com.IFFCOKisan

Agriplex: https://play.google.com/store/apps/details ? id=com.agriplexindia.agriplexconsumer

Market yard: https://play.google.com/store/apps/details?id=com.globalfarm.marketyard

Indian Satellite Weather: https://play.google.com/store/apps/details?id=com.shahul3d.indiasatelliteweather

Zero Budget Natural Farming: https://play.google.com/store/apps/details?id=com.oyepages.zbnf

Kisan Space: https://play.google.com/store/apps/details?id=com.kisan

Crop Insurance: https://play.google.com/store/apps/details?id=in.farmguide.farmerapp.central&hl=en

Mandi Central: https://play.google.com/store/apps

/details?id=com.tradeforsure

Machinery guide: https://play.google.com/store/apps/details?id=hu.zbertok.machineryguide& hl=en

Kisan Suvidha: https://play.google.com/store/apps/details?id=in.cdac.bharatd.agriapp

Kisan Yojana: https://play.google.com/store/apps/details?id=com.purplechai.admin.kissan yojnaapp

Krishi Network: https://play.google.com/store/apps/ details?id=com.krishi.krishi

MSAMB: https://play.google.com/store/apps/details?id=com.msamb

e-Gram: https://play.google.com/store/apps/details?id=com.reformist.krushiking001

Fasal Salah: https://play.google.com/store/apps/details?id=com.weathersys.agro

Farm Bee: https://play.google.com/store/apps/details?id=com.rml.Activities

KVSMT: https://play.google.com/store/apps/details?id=com.kvsmt.mobile

CCMobile: https://play.google.com/store/apps/details?id=com.root.ccmobile&hl=en

Bijak: https://play.google.com/store/apps/details?id=com.bedwal.bijak.mvp&hl=e n

Agromedix: https://play.google.com/store/apps/details?id=com.iqra.agromedix

BajarBhav: https://play.google.com/store/apps/details?id=com.bajarbhav

Agriculture Business: https://play.google.com/store/apps/details?id=com.AgriculturalBusiness3ds p

Agri Live: https://play.google.com/store/apps/details?id=agri.live

Agri App: https://play.google.com/store/apps/details?id=com.criyagen

Conclusion

The integration of computer science into agricultural engineering is transforming traditional farming into a more precise, efficient and sustainable practice. Through the use of advanced technologies such as artificial intelligence, geographic information systems (GIS), remote sensing, and mobile applications, farmers now have access to timely data and expert insights that enhance decision-making and productivity. Despite certain challenges especially in rural and developing areas the potential of information and communication technologies (ICT) to revolutionize agriculture is undeniable. As access to digital tools continues to expand, and awareness of their benefits grows, the agricultural sector stands to gain significantly in terms of yield improvement, market access and sustainable resource management. Embracing these digital advancements is not only a step toward modern-ization but also a critical move toward global food security and rural development.

Sustainable Poultry Production and Waste Management

Utsavkumar Varvadiya and V. V. Gamit

Abstract

Modern hatchery waste eggs, embryos, shells, chicks, and washdown water is rich in protein and calcium but perishable and pathogen-prone. Methods like composting, anaerobic digestion, and rendering can convert it into feed, fertilizer, and energy, with hatchery by-product meal (HBPM) as a key marketable output. Success demands pathogen control, fat stability, regulatory compliance, and a shift from linear disposal to a circular poultry model.

Introduction

The rapid growth of the global poultry industry has led to a proportional rise in hatchery waste generation, including infertile eggs, dead embryos, eggshells, culled chicks, and washdown wastewater. Improper disposal through dumping or landfilling creates severe environmental hazards and biosecurity risks due to rapid decomposition and pathogen growth. However, because hatchery waste is highly rich in protein, fat, and minerals, it holds significant potential for recycling into high-value feed and fertilizers. This assignment highlights sustainable management practices, nutritional upcycling, and circular economy strategies for efficient hatchery waste utilization.

Sources and Composition of Hatchery Waste

Waste arises at several stages: infertile or cracked eggs removed at candling, early-dead embryos identified during incubation, unhatched eggs and shells separated at transfer and hatch, and weak or surplus chicks culled during processing, alongside waste-water from cleaning incubators and hatching equipment. Hatchability in commercial operations typically ranges between 50 and 85 percent, meaning a meaningful share of eggs set never yields a marketable chick. Fresh hatchery waste typically contains 40-70 percent moisture, 40-45 percent crude protein and 25-30 percent fat on a dry-matter basis. It is divided into four fractions: egg shell and membrane (calcium-rich), infertile/early-dead eggs (protein- and fat-rich), late dead-in-shell embryos and culled chicks (tissue, feathers, bone), and wastewater. Composition varies seasonally, so waste characterization should be reassessed periodically.





Utsavkumar Varvadiya
M.V.Sc. Scholar, Department of Animal Nutrition, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Junagadh, Gujarat

V. V. Gamit
Associate Professor, Department of Livestock Production Management, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Junagadh, Gujarat

Table 1: Primary technological pathways

Method	Main Output	Key Advantages	Major Limitations
Composting	Organic Fertiliser	Low cost; destroys pathogens; reuses farm litter	Requires space, bulking agents & temperature control
Anaerobic Digestion	Biogas + Digestate	Renewable energy recovery; scalable via co-digestion	Sensitive to C:N ratio & pH; high capital cost
Rendering	Hatchery By-product Meal	High-value protein feed ingredient; standard industrial route	Requires dedicated rendering plant & energy inputs
Ensiling / Fermentation	Stabilised Feed Material	Low capital required; feasible for smaller hatcheries	Requires acid dosing; shorter shelf life than meal
Thermal Combustion	Steam / Electricity	Complete pathogen destruction; maximum volume reduction	Loses feed nutritional value; emission concerns

Table 2: Nutritional Upcycling and Hatchery By-Product Meal (HBPM)

Nutrient / Parameter	Typical Range	Nutritional Role & Notes
Moisture	5-7%	Low moisture prevents mould growth during storage
Crude Protein	60-61%	High biological value; comparable to fish meal
Ether Extract (Fat)	13-17%	Provides concentrated energy; needs antioxidant stabilization
Ash Content	7-16%	Reflects the proportion of eggshell in the mix
Calcium & Phosphorus	5% Ca | 2.2% P	Bioavailable mineral source, replacing limestone/dicalcium phosphate

Management Principles and Methods

Effective hatchery waste management rests on three pillars: separation, stabilisation and value-addition. On-site separation of solids from liquids using screens or centrifuges is the first step. Primary technological pathways are summarised in Table 1.

Nutritional Upcycling and Hatchery By-Product Meal (HBPM)



Because fresh hatchery waste is comparable in protein and fat content to conventional protein concentrates, it is a strong candidate for upcycling into feed once moisture and pathogen risks are addressed. Rendering is the dominant industrial method; ensiling and acid fermentation offer lower-capital alternatives. Raw waste contains avidin, requiring adequate thermal treatment to eliminate biotin binding risks are given in Table 2.

Processing Challenges and Sustainable Implementation Plan

Pathogen control (Salmonella, *E. coli*), high fat oxidation/rancidity, and avidin denaturation are major technical hurdles. Logistically, hatchery waste is perishable and bulky. A sustainable management plan ranks options hierarchically: source reduction, feed-grade upcycling, composting/anaerobic digestion, energy recovery, and landfill as a last resort.

Phase 1: Assessment (Months 0-3): Waste audit, characterising quantities, fractions, and seasonal variability.

Phase 2: Basic Controls (Months 3-9): Install solid-liquid separation screens and initiate on-site composting/ensiling.

Phase 3: Value Recovery (Months 9-18): Establish rendering contracts or on-site processing; construct wastewater settling lagoons.

Phase 4: Market Integration (Months 12-24): Develop commercial partnerships with feed mills; institute strict QA/QC testing.

Phase 5: Continuous Review (Annual): Regular review of waste volumes, treatment costs, and market opportunities.

Environmental and Economic Aspects

Unmanaged hatchery waste contributes to eutrophication, groundwater contamination, odour, greenhouse gas emissions and pathogen spread. Properly valorised waste mitigates these harms: composting and digestion stabilise nutrients, feed-grade upcycling reduces demand for resource-intensive fish meal, and energy recovery offsets fossil fuel use. Economically, valorised products offset feed and energy costs or generate direct revenue.

Conclusion

Hatchery waste is an unavoidable by-product of poultry production but not an intractable disposal problem. Given its protein, fat and calcium content, established methods can convert it into safe, market-able products. A sustainable plan should combine appropriate technology with quality assurance, monitoring, and attention to both disposal-avoidance and revenue economics.

References

Afrrin, M., Rajasekaran, B., Nandhini, R.S., *et al*. (2025). Valorization of eggshell waste for sustainable food packaging. *Food and Bioprocess Technology*, 18: 10209-10228.

Said, N. W. (1996). Processing methods for hatchery waste utilization in animal feed. *World's Poultry Science Journal*, 52(2): 179-186.

Zhang, L., Ren, J. and Bai, W. (2023). A review of poultry waste-to-wealth: Technological progress and sustainability. *Sustainability*, 15 (7): 5620.

Al-Harthi, M. A., El-Deek, A. A. and Attia, Y. A. (2010). Nutrient composition and use of hatchery by-products in poultry diets. *World's Poultry Science Journal*, 66(3): 415-426.

Feedipedia (INRAE, CIRAD, AFZ, and FAO). Hatchery by-product meal. Animal Feed Resources Information System.

Glatz, P., Miao, Z. and Rodda, B. (2011). Handling and treatment of poultry hatchery waste: A review. *Sustainability*, 3(1): 216-237.

Poultry Nutrition and Feeding Management

Tulahalli Hemanthkumar and V. V. Gamit

Abstract

Poultry nutrition determines 60-70% of production cost and directly drives growth, egg output and health. This review summarises nutrient requirements, phase feeding, feed conversion ratio (FCR), starter-finisher formulation, eggshell-quality nutrition, disease-period feeding, housing effects and broiler feeding schedules, using NRC/NASEM standards, Aviagen/Cobb breeder data and recent peer-reviewed trials, to show nutrition as a continuously re-calibrated, data-driven discipline.

Introduction

Poultry nutrition has moved a long way from the single, unchanging "all-purpose" ration of the mid-twentieth century. Modern commercial geno-types such as the Ross 308, Cobb 500 and Hy-Line/ Lohmann laying strains grow and produce at rates that would not have been considered biologically possible fifty years ago, and this genetic progress has been made possible only because nutritional science has kept pace through phase feeding, digestible amino acid formulation, precision mineral and vitamin supplementation, and constant refinement of feeding schedules. Amid HPAI outbreaks and antibiotic withdrawal.

Nutrient Requirements

Broiler starter diets are typically formulated to around 2,950-3,000 kcal AMEn kg^{-1}, rising to 3,100-3,200 kcal kg^{-1} in finisher diets, while layer diets are held at a comparatively modest 2,750-2,900 kcal kg^{-1} because excessive energy density in layers promotes fat deposition rather than egg output. Because chickens eat primarily to satisfy their energy requirement, all other nutrients are conventionally formulated relative to the energy density of the diet, and increasingly relative to lysine, using the "ideal protein" concept. Water is the most frequently overlooked nutrient. Broilers typically drink 1.6-2.0 times their feed intake by weight under thermo-neutral conditions, rising sharply in hot weather; any restriction in water availability depresses feed intake almost immediately and is one of the fastest routes to a poor flock outcome.

Phase Feeding

Diets are stepped through 3-5 phases, protein/ calcium falling and energy rising with age, saving feed cost and nitrogen excretion. Precision (daily-blended) feeding is emerging but limited by equip-ment cost.

Tulahalli Hemanthkumar
M.V.Sc. Scholar, Department of Animal Nutrition, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Junagadh, Gujarat

V. V. Gamit
Associate Professor, Department of Livestock Production Management, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Junagadh, Gujarat

Phase Feeding in Broilers: Phase feedings are given in Table 1.

Phase Feeding in Layers: Layer diets are conventionally phased by age and production stage rather than by body weight, because the limiting consideration shifts from growth to egg mass and eggshell calcification. A typical commercial program uses three to four phases: a pre-lay/Phase 1 diet (18-45 weeks, calcium approximately 3.8-4.0%), a Phase 2 diet (46-60 weeks, calcium approximately 4.0-4.2%), and a Phase 3 diet for late-lay hens (> 60 weeks, calcium approximately 4.2-4.5%). Dietary calcium is increased, not decreased, as the hen ages, because eggshell quality otherwise declines progressively with hen age even as egg size continues to increase a nutritional response to a physiological, not merely a production, problem.

Feed Conversion Ratio

FCR = feed intake ÷ weight gain; industry uses the live-weight basis. A 42-day broiler now achieves FCR 1.5-1.6, versus over 2.0 in the 1980s, mostly (85-90%) from genetic gain, the rest from nutrition and management.

Factors affecting FCR

- ✓ Diet formulation
- ✓ Health status
- ✓ Environment
- ✓ Bird age/market weight

Starter vs Finisher Diets

Starter feed (0-10 d) is a high-protein, high-calcium supporting rapid tissue and bone growth; finisher feed is a higher-energy and lower-protein as increasing proportion of feed energy is diverted from lean tissue accretion toward fat deposition and simple maintenance, so further increases in protein/amino acid density would neither improve growth nor be cost-effective . The transition from crumble to pellet mirrors development of the beak and gizzard and has an independently documented effect on feed intake and FCR. Finally, because most anti coccidials and other feed-incorporated medicat-ions carry a specified withdrawal period, the finisher (or a dedicated withdrawal) diet is reformulated without these additives long enough before slaughter to ensure the edible product is free of residues at the time of processing (Aviagen, 2025).

Eggshell Quality

Shell calcification occurs overnight in the uterus; coarse limestone, phytase and vitamin D_3 extend calcium release and cut bone mobilisation. Layer calcium needs rise with hen age as shell strength otherwise declines.

Hen age: Eggshell quality declines progressively after peak lay even though egg size continues to increase, because shell calcium output cannot keep pace with the growing surface area of a larger egg the rationale for the age-graded calcium increase in phase-fed layer programmes.

Trace minerals: Manganese, zinc and copper are required for the organic shell matrix (the protein/ this effect.

Mycotoxins: Contamination of feed ingredients, particularly with ochratoxin A, can impair renal and hepatic vitamin D metabolism mucopolysaccharide

Table 1: Representative commercial broiler feeding schedule. *Cumulative feed intake at end of phase, as-hatched average (Source: Adapted from Cobb-Vantress (2022) performance objectives and Aviagen (2025) Broiler Pocket Guide)

Phase	Age (days)	Feed form	Crude protein (%)	AMEn (kcal kg^{-1})	Digestible lysine (%)	Calcium (%)
Starter	0-12	Crumble	21-22	2900	1.26	0.96
Grower 1	13-28	Pellet	19-20	2950	1.16	0.80
Grower 2	29-39	Pellet	18-19	3050	1.06	0.74
Finisher 1	40-49	Pellet	17-18	3100	0.96	0.72
Finisher 2 / withdrawal	> 50	Pellet	17-18	3150	0.86	0.68

Table 2: Summary of nutritional interventions for major poultry disease/stress challenges (Source: Compiled from EW Nutrition (2026) and Feed Strategy/WATT Global Media (2024)

Challenge	Primary nutritional intervention
HPAI / general immune support	Marginal-to-generous vitamin E, selenium, vitamin A and C; feed/feed-vehicle biosecurity
Necrotic enteritis / coccidiosis	Moderated, highly digestible crude protein; insoluble fibre; phytogenics, probiotics, organic acids; coccidiostats in starter/grower
Heat stress	Adjusted electrolyte balance (↑ K^+, Na^+; ↓ Cl^-); vitamin C and E; increased nutrient density per kg feed
Mycotoxin contamination	Toxin binders/sequestrants; increased antioxidant (vitamin E, selenium) provision; avoid affected ingredient lots

Table 3: Nutritional adjustments commonly applied across laying-hen housing systems (Source: Adapted from Hendrix Genetics/Laying Hens (2024)

Housing system	Typical nutritional adjustment relative to conventional cage
Conventional / enriched cage	Reference diet; lowest energy requirement due to limited activity
Barn / aviary (indoor cage-free)	Energy density increased ~2-5%; amino acid % may be reduced if feed intake rises, holding total daily intake constant
Free-range / organic	Further increase in energy allowance for thermoregulation and activity; calcium/phosphorus and vitamin levels essentially unchanged

scaffold on which calcium carbonate crystallises); marginal deficiency weakens shell structure even when calcium supply is adequate.

Electrolyte balance and heat stress: Hens under heat stress pant, which lowers blood CO_2 and bicarbonate available for eggshell carbonate formation, thinning the shell; adjusting the dietary electrolyte balance (increasing potassium and sodium bicarbonate) and supplementing vitamin C partly offsets and depress eggshell quality independent of the formulated calcium level

Feeding During Disease Outbreaks: Nutrition cannot cure disease but supports immunity (vitamin E, selenium) and limits necrotic enteritis via lower digestible protein, insoluble fibre and probiotics; electrolyte balance is adjusted for concurrent heat stress (Table 2).

Housing Systems: High broiler stocking density impairs intake and FCR via heat and litter-ammonia stress. Cage-free layer systems need slightly higher dietary energy for activity/ thermoregulation; calcium and vitamins stay largely unchanged (Table 3).

Conclusion

Poultry feeding is a continuously moving target: nutrient requirements themselves are being actively revised, the diet is deliberately changed several times across the production cycle to track those requirements, efficiency is constantly meaured and benchmarked against genetic potential and the

diet must be adapted, sometimes on short notice, to the physiological demand of eggshell formation, to disease pressure, to the housing system in use and to the practical logistics of feed manufacture and delivery.

References

Aviagen. (2022 and 2025). Ross Broiler Nutrition Specifications and Pocket Guide.

Cheeke, P. R. and Dierenfeld, E. S. (2010). Comparative Animal Nutrition and Metabolism.

Cobb-Vantress. (2022). Cobb500 Broiler Performance and Nutrition Supplement.

Crampton, E. W. and Harris, L. E. (1969). Applied Animal Nutrition.

EW Nutrition. (2026). Pillars of Poultry Health; Lessons of 2025 for Poultry and Feed Producers.

Feed Strategy/WATT Global Media. (2024). Poultry Nutrition and Feed Survey.

Hervo, F. *et al*. (2023). Phytase and Limestone Particle Size in Laying Hens. *Poultry Science*.

Leeson, S. and Summers, J. D. (2005). Commercial Poultry Nutrition, 3rd ed.

Maynard, L. A. *et al*. (1987). Animal Nutrition, 7th ed.

McDonald, P. *et al*. (2011). Animal Nutrition, 7th ed.

National Foods Stockfeeds. (2024). Broiler Feed Guide.

National Research Council (NRC). (1994). Nutrient Requirements of Poultry, 9th ed.

Nutrinews. (2024). Preview of the NRC 10th Edition. Overview of the Nutrient Requirements of Poultry, 10th ed. (2025). Poultry Science Association Symposium.

Comprehensive Guide to Hatchery and Breeder Flock Management

Harsh Kantariya and V. V. Gamit

Introduction to Poultry Reproduction and Hatchery Operations

The global poultry industry relies heavily on the efficiency health, and productivity of broiler breeder flocks and the laying breeder stock. Breeder flock management and hatchery operations are closely linked; the quality of a day-old chick is a depend on the parent flock's health, nutritional status, and genetic potential, combined with the precise environmental control provided during egg storage and incubation. Modern breeders possess immense genetic potential for rapid growth and high meat yield. However, this genetic selection for breeder traits often works antagonistically against reproductive efficiency. Thus, parent stock production demands tight management controls with strict standards to be imposed on all areas including, but not limited to, bodyweight management, photostimulation, and nutrient supply. Even small error in breeder management practices can lead to a sharp drop in fertility, egg production and, hence, chick production.

Hatchery Management

Hatchery management involves the coordinated of biosecurity, environmental control, and logistical planning to transform fertilized eggs into healthy day-old chicks. It is a highly specialized facility where the biological needs of the developing embryo dictate the engineering and operational protocols.

Site Selection and Layout

The geographical location of a hatchery is critical.it must be away from the commercial poultry farm and also from the highway and industrial area. A minimum distance of 3 to 5 kilometers from other poultry operations is standard industry practice. The site should contain the proper clean water source, uninterrupted electricity (with backup generators), and well-maintained access roads for the smooth transport of eggs and chicks. The internal layout of the hatchery must follow the strict rules of 'one-way flow' or 'dirty-to-clean' progression. This means that eggs and personnel move in a single direction: from the egg receiving room (cleanest) > egg storage > setter room > hatcher room > chick processing > chick dispatch (dirtiest). There must be no back-tracking.

Biosecurity and Sanitation

Biosecurity in a hatchery is more critical than in any other segment of poultry production due to

Harsh Kantariya
M.V.Sc. Scholar, Department of Animal Nutrition, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Junagadh, Gujarat
V. V. Gamit
Associate Professor, Department of Livestock Production Management, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Junagadh, Gujarat

the ideal environment (high heat and humidity) that prevent the bacterial and fungal growth.

Personnel Hygiene: All staff and visitors must shower in and wear designated, color-coded hatchery clothing. Also Cloths and working gloves should be clean.

Fumigation and Disinfection: For fumigation formaldehyde gas was traditionally used, alternatives like hydrogen peroxide, peracetic acid and quaternary ammonium compounds applied via thermal fogging in modern poultry farms.

Ventilation and Air Pressure: Airflow must follow the one-way principle. Egg storage rooms must have the highest positive pressure, while hatcher and wash rooms should have negative pressure. This ensures that when doors are opened, air flows from clean areas to dirty areas, never the revers.

Egg Handling and Storage

Eggs must be collected from the breeder farms frequently (at least 4-5 times a day) to minimize their time in the nest, during the nesting time it comes in contact with the pathogens and also temperature is fluctuate during this time period. Upon arrival at the hatchery, eggs are graded, and dirty, cracked, or misshapen eggs are rejected. Storage is necessary to accumulate enough eggs to fill the incubators. The critical objective during storage is to arrest embryonic development, and maintain the eggs on physiological zero temperature (approximately 24°C or 75°F). At this temperature embryo is neither grow or die.

1-3 days: 20-23°C (68-73°F) and 75% Relative Humidity (RH).

4-7 days: 15-18°C (59-64°F), 75-80% RH.

Over 7 days: 12-15°C (54-59°F), 80-85% RH.

Long storage of eggs (over 7 days) caused to reduce the hatchability and the chick quality by cellular degradation and loss of water. SPIDES (Short Periods of Incubation during Egg Storage) is applied to prevent it.

Egg Incubation

Incubation is the controlled environmental process that supports embryonic development. In which temperature and humidity is maintain at optimum level. The domestic chicken requires 21 days of incubation. This period is divided into two phases: the setter phase (Days 1-18) and the hatcher phase (Days 19-21).

Embryonic Development

Day 1-3: Formation of the primitive streak, head, eyes, and the beginning of a heartbeat.

Day 4-6: Appendages (wings and legs) begin to form. The embryo begins to turn and lie on its left side.

Day 7-10: Feather are appear, and the beak hardens.

Day 11-14: Rapid growth seen during this period and the embryo consumes large amounts of calcium from the shell.

Day 15-18: The embryo is fully formed during this period. Fluid decreases, and the embryo prepares for hatching.

Day 19-21: Internal pipping is followed by external pipping, rotation, and emergence.

Incubation Parameters

Temperature: It is necessary for the maintain the metabolic rate. Optimal setter temperature is generally 37.5°C to 37.7°C. In the hatcher, temperature is lowered slightly to 36.9°C to 37.2°C.

Humidity: Controls moisture loss during incubation. An egg must lose ~11-12% of its weight. Setter humidity is typically 50-60% RH; hatcher humidity is increased to 70-75% RH.

Turning: Eggs must be turned 45 degrees in opposite directions every hour during the first 14-18 days it prevents the adhesion of embryo with egg wall and also help in gaseous exchange.

Ventilation: Ensures a constant supply of O_2 (optimal 21%) and removal of CO_2 (should not exceed 0.4% in the setter). If the O_2 Level is decrease at 1% it decrease the also hatchability at 5%.

Fertility and Hatchability

Definitions and Calculations

Fertility: Percentage of total eggs laid that contain a viable blastoderm.

Hatchability of Total Eggs (HOTE): (Number of chicks hatched / Total eggs set) x 100. Economic metric.

Hatchability of Fertile Eggs (HOFE): (Number of chicks hatched / Total fertile eggs set) x 100.

Even under perfect conditions, 100% hatch-ability is impossible. A flock at peak production (around 32-35 weeks) should achieve >96% true fertility and >90% Hatchability of Total Eggs. Good efficient hatcheries analyse the unhatched egg to determine the stage of embryo death.

Broiler Breeder (Parent Stock) Management

Managing broiler breeders aims to raise a bird genetically programmed to grow rapidly, yet restrict its growth to maintain reproductive fitness. If fed ad libitum, they become obese and produce few fertile eggs.

Rearing Phase and Uniformity

The objective of the rearing phase (Weeks 0-20) is to hit target body weights and maximize flock uniformity (>85%). Severe feed restriction is employed through methods like Skip-a-Day (SAD), 4/3 or 5/2 programs, or highly calibrated Everyday Feeding (ED).

Photoperiod and Mating Management

Birds are reared on a short day length (8 hours). Around 21-22 weeks, they are 'photo-stimulated' by increasing daylight to 11-14 hours. A standard mating ratio is 1 male to 10 females (10%). Mating management involves sex-separate feeding systems and 'Spiking' introducing young sexually mature males into an older flock to boost fertility.

Sexing

Farmers can raise males and females separately after sexing. They will have much better conversion of feed and the flock will be much more homogeneous.

Vent Sexing (Japanese Method): Squeezing chick in the hand so that cloaca everts & identifying the presence of an incipient organ of copulation. Skill and time consuming process.

Feather sexing: Based on genes of fast (k+) and slow (K) feathering. Chicks can be rapidly and non-invasively separated by looking at primary or coverts

feathers. This method is predominant in broilers.

Color Sexing: Based on sex-linked genes affecting plumage color (silver/gold, etc.); primarily employed on commercial egg layers.

In-Ovo Sexing: State of the art in-Ovo sex determination, whether by means of allantoic fluid testing or by using hyperspectral imaging of infertile egg and developing embryos. This technique is considered as a technology for the future of poultry breeding.

Conclusion

Mastering the intersection of broiler breeder management and hatchery operations requires strict adherence to biosecurity, precision nutrition, and highly regulated incubation environments. By understanding the biological needs of both the parent stock and the developing embryo, poultry producers can optimize their operations and ensure a consistent supply of day-old chicks.

Sustainable Crop Residue Management: A Pathway from Waste to Wealth

Bhim Singh, A. P. Singh and Ayushi Sharma

Introduction

The contemporary global agricultural landscape is navigating a critical socio-ecological juncture. Rapid human population growth, climate change uncertainties, and widespread edaphic degradation are spurring the annual generation of over 4 billion metric tons of unmanaged agricultural crop residues globally. Over the past six decades, intensive agronomic practices introduced after the Green Revolution dramatically increased cereal crop yields, helping avert widespread food insecurity. However, this intensive production paradigm relied heavily on an over-dependence on synthetic agrochemical inputs, deep mechanical inversion tillage, and monoculture cropping systems, which collectively catalyzed severe long-term edaphic degradation. Globally, agricultural soils are exhibiting chronic symptoms of structural fatigue, characterized by the rapid depletion of Soil Organic Carbon (SOC) reserves, the collapse of indigenous soil microbial biodiversity, and the physical compaction of the sub-surface profile. Historically, within extensive cereal-based production systems such as the intensive rice-wheat rotations, crop residue has been perceived by smallholder farming communities as a major operational liability rather than a valuable agro-ecosystem asset. The widespread adoption of mechanical combine harvesters revolutionized harvesting speed but simultaneously introduced a severe agronomic bottleneck: it leaves behind massive quantities of loose, unchopped straw alongside tall standing stubbles measuring up to 40 cm in height. Because the optimum physiological planting window between the harvest of summer crops and the sowing of subsequent winter crops is exceptionally narrow often restricted to a brief 15-to-21-day turnaround farmers face immense logistical pressure to clear the fields rapidly. Under these acute operational constraints, open-field residue burning emerged as the most economically immediate and labor-saving strategy for field clearance, providing a clean seedbed for subsequent mechanical sowing operations at virtually zero localized cost.

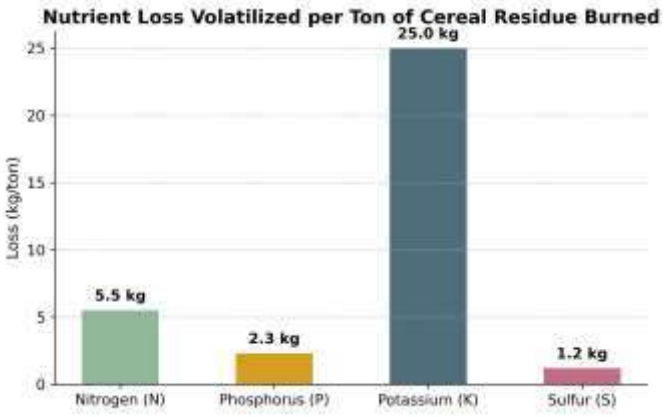


Figure 1: Absolute atmospheric volatilization of essential macronutrients per metric ton of cereal crop residue burned in open-field conditions

The cumulative environmental, atmospheric, and biochemical toll of open-field biomass burning is catastrophically high and inherently unviable

Bhim Singh, A. P. Singh and Ayushi Sharma
Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu, UT of Jammu & Kashmir

under modern climate-resilience frameworks. The intense thermal shock generated during open-field burning reaches temperatures between 300°C and 400°C at the immediate soil-atmosphere interface. As illustrated in Figure 1, this causes the rapid vaporization and irreversible loss of vital macro-nutrients and micronutrients, while simultaneously sterilizing the upper 0-to-5 cm edaphic layer and destroying beneficial epigeic microbial populations.

Biogeochemical Mechanisms of Residue Decomposition

The in-situ decomposition of retained crop residue is not a static mechanical breakdown, but a highly complex, multi-trophic biogeochemical process that governs the restoration of degraded agro-ecosystems. When crop residues are preserved on the soil surface or shallowly incorporated, they initiate a sequential cascade of physical fragmentation, chemical leaching, and microbially mediated enzymatic depolymerization.

Microbial Succession and Enzymatic Kinetics

The structural architecture of cereal crop residues consists of a recalcitrant lignocellulosic matrix primarily composed of cellulose (35-45%), hemicellulose (25-35%) and lignin (10-20%). Initially, the labile water-soluble fractions of the residue such as simple sugars, amino acids, and organic acids are rapidly metabolized by fast-growing, r-strategist zymogenous bacteria and pioneer fungi, driving an immediate spike in soil respiration rates. The degradation of the remaining complex polymeric framework requires the recruitment of K-strategist cellulolytic and ligninolytic microbial communities. These organisms excrete a sophisticated suite of extracellular enzymes that synergistically hydrolyze the crystalline cellulose fibers and cleave the highly stable aromatic linkages of lignin. This microbially driven enzymatic depolymerization directly increases the Soil Microbial Biomass Carbon (MBC) pool.

Stoichiometric Imbalances and Nitrogen Immobilization

A major agronomic constraint during the initial phases of in-situ residue management stems from the distinct elemental stoichiometry mismatch between crop biomass and soil microbial communities. While the ideal elemental C:N ratio required by soil heterotrophic microflora for balanced cellular metabolism ranges between 8:1 and 12:1, cereal residues possess an exceptionally wide C:N ratio, frequently exceeding 80:1 to 100:1. When these high-carbon residues are introduced into the soil matrix, the native microbial population experiences an acute nitrogen deficit. To bridge this stoichiometric gap, they aggressively scavenge inorganic nitrogen fractions (NH_4^+ and NO_3-) directly from the surrounding soil solution. This biological competition drives a severe phase of temporary nitrogen immobilization, effectively locking available soil nitrogen within the microbial biomass and rendering it inaccessible to the emerging crop roots. Clinically, this manifests as early-season crop chlorosis, reduced tillering, and developmental stunting if starter nitrogen applicatio-

ns are not reconfigured.

Mechanization Engineering and Operational Trade-offs

The large-scale field adoption of conservation agriculture frameworks is fundamentally governed by the mechanical architecture, energy efficiency, and operational reliability of specialized sowing implements designed to operate within high-volume residue matrices. The deployment of engineered interventions introduces serious technical trade-offs, mechanical constraints, and economic inputs.

Happy Seeder Architecture	Super Seeder Architecture
Executes pure zero-tillage by utilizing a tractor-powered rotor with curved flail tynes to shred and displace standing residues.	Integrates a heavy-duty rotary tiller that actively chops and partially incorporates high-volume biomass into the shallow 0-to-10 cm topsoil layer.
Leaves an undisturbed, uniform surface mulch layer that preserves maximum edaphic moisture and suppresses weed germination cohorts.	Provides a highly uniform seedbed but drastically alters the physical stratification of organic carbon compared to pure zero-tillage.
Prone to 'hairpinning' under damp conditions, where unchopped residue is pushed into the furrow slot, reducing seed-soil contact.	Significantly higher power take-off (PTO) demand, requiring high-horsepower tractors (50-75 HP) and increasing volumetric diesel fuel consumption.

A major agronomic obstacle observed during the field deployment of direct-drilling machinery is the spatial variation in seed placement depth and subsequent germination uniformity. When tractors operate across fields with unevenly distributed residue windrows, the cutting mechanisms of the furrow openers often fail to slice cleanly through damp, compressed straw sheets. This mechanical limitation leads to 'hairpinning,' preventing direct contact between the seed coat and the surrounding mineral soil matrix. Furthermore, the high power requirement translates directly into elevated volumetric diesel fuel consumption, which can significantly increase operational costs during the narrow post-harvest planting window.

Socio-Economic Drivers and the Circular Bioeconomy

While in-situ residue retention remains a fundamental requirement for edaphic restoration, achieving a true 'Waste-to-Wealth' ecosystem relies heavily on creating self-sustaining industrial ex-situ value chains. Modern circular bioeconomy frameworks actively decouple crop residues from agricultural waste, reimagining biomass as a high-value feedstock. The primary industrial pathways gaining scientific and commercial traction include Compressed Biogas (CBG) Production, where anaerobic digestion technologies utilize processed straw to generate bio-methane; Thermal Power Co-Firing, which blends pelletized agricultural residues with coal; and Biochar Thermochemical Synthesis, which pyrolyzes surplus crop residues into highly stable, recalcitrant carbon matrices. However, agricultural straw possesses a low bulk density, rendering long-distance transport economically unviable. Overcoming this logistical constraint requires establishing regional networks of high-density baling hubs, consolidating raw biomass within a tight 15-to-25 km radius. The primary hurdle determining the velocity of conservation agriculture adoption among smallholder farming

collectives is immediate financial viability. Bridging the gap requires restructuring classic agricultural extension models and prioritizing the establishment of decentralized, village-level machinery cooperatives. These grassroots alliances play a critical role in mitigating individual operational risks through the institutionalization of Custom Hiring Centers (CHCs). By clustering advanced machinery within community pools, CHCs democratize access to high-horsepower implements, allowing smallholders to rent them on an hourly basis without bearing individual capital debt.

Conclusion

The critical synthesis of global and regional empirical data confirms that the traditional paradigm of treating crop residue as an operational waste burden is ecologically and agronomically unsustainable. Open-field residue burning represents a profound loss of natural capital, stripping agricultural soils of vital organic carbon fractions and essential plant nutrients while triggering severe atmospheric crises. Reimagining crop residue through a multi-dimensional 'Waste-to-Wealth' lens establishes a transformative pathway toward landscape-scale soil edaphic restoration and long-term cropping system sustainability. Ultimately, scaling conservation agriculture requires moving beyond isolated technical interventions toward a highly integrated socio-economic ecosystem. Mechanical innovations must be actively supported by responsive, logistically sound institutional policies, including streamlined Direct Benefit Transfer (DBT) frameworks, optimized regional machinery mapping, and decentralized custom hiring networks. By aligning grassroots community extension models with regional circular bioeconomy frameworks, modern agriculture can effectively transition post-harvest biomass from a disposal hazard into a core pillar of climate-resilient, high-yielding, and truly sustainable food production systems.

Revolutionizing Crop Improvement through Application of AI

Sheetal Gupta

Plant breeding has traditionally played an important role in crop improvement. Traditional plant breeding involves crossing parent plants with desirable traits and then growing and evaluating thousands of offspring over multiple generations. This can take a decade or more for a single new variety. The sheer volume of data involved from genetic markers to field performance is immense and often overwhelming for human analysis. This is where Artificial Intelligence (AI) steps in. AI, specifically machine learning (ML), can process and analyze vast datasets at speeds and scales impossible for humans. By identifying patterns and making predictions, AI helps breeders make smarter, faster decisions. Artificial Intelligence refers to computer systems that can perform tasks typically requiring human intelligence, such as learning from data, recognizing patterns, and making predictions. In the context of plant breeding, AI helps analyze vast amounts of complex biological data, automate labor-intensive processes, and accelerate decision-making all of which are essential in developing high-performing crops. Here are some key applications of AI in plant breeding:

High-Throughput Phenotyping and Trait Selection: Phenotyping is the measurement of a plant's physical characteristics, like height, leaf area, or disease resistance. Manual phenotyping is slow and prone to error. AI is transforming this with computer vision. Drones, robots, and sensors capture high-resolution images of plants in the field. AI algorithms then analyze these images to automatically and quickly measure various traits, allowing breeders to screen a massive number of plants and identify superior ones much faster.

Genomic Selection and Prediction: Genomic selection (GS) is a breeding approach that uses genomic information to predict the breeding value of individuals, even before they are physically grown or phenotyped. AI-powered machine learning models enhance this process by analyzing huge genomic datasets. They can identify complex genetic interactions that influence traits, helping breeders make more informed selection decisions and shorten breeding cycles.

Breeding for Disease and Pest Resistance: Early and accurate detection of crop diseases and pests is critical for preventing crop loss. AI-powered image recognition systems can detect subtle symptoms on leaves or stems that are invisible to the human eye. This early warning system enables timely intervention, reducing the need for broad-spectrum pesticides. AI also helps breeders identify the genes associated with disease resistance, allowing them to develop more robust crops.

Climate Adaptation and Resilience: As the climate

Sheetal Gupta
Research Scholar, Department of Genetics and Plant Breeding, MPUAT, Udaipur, Rajasthan

changes, crops must be able to withstand extreme temperatures, droughts, and floods. AI can analyze massive amounts of environmental data like temperature, rainfall, and soil moisture alongside genetic data. This helps identify genes linked to climate resilience and predict how different crop varieties will perform under various environmental scenarios, allowing breeders to select and develop varieties better adapted to current and future climate conditions.

Optimized Breeding Programs and Virtual Breeding: AI can optimize the entire breeding program by recommending the best parent plants to cross and maximizing the probability of creating a desirable new variety. Furthermore, virtual plant breeding platforms use AI to simulate how plants will grow and perform under different conditions. This lets breeders predict the performance of new genetic combinations without extensive and costly physical field trials.

Genome Sequencing and Analysis: Advances in DNA sequencing technologies generate an enormous amount of genomic data for various crop species. AI algorithms are crucial for making sense of this "big data." They can be used for tasks like base calling, error correction, genome assembly, identifying gene function, and predicting the phenotypic effects of genetic variations. This deep understanding of the genetic basis of traits is invaluable for guiding targeted breeding efforts and even for gene editing applications.

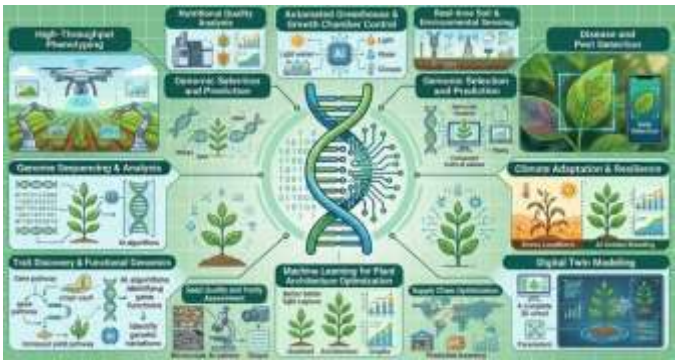


Fig. 1: Application of Artificial Intelligence in crop improvement

Challenges and the road ahead despite the immense potential, the widespread adoption of AI in plant breeding faces several challenges:

Data Quality and Availability: AI models are only as good as the data they are trained on. High-quality, diverse, and well-annotated datasets from various environmental conditions are crucial but often lacking.

Interoperability: Integrating diverse data streams (genomic, phenotypic, environmental) from different sources can be complex due to varying data formats and standards.

Cost and Accessibility: The initial investment in AI infrastructure, specialized software, and skilled personnel can be significant, potentially limiting access for smaller breeding programs or developing countries.

Ethical Considerations: Concerns about data privacy, algorithmic bias, and the potential impact on traditional farming knowledge need to be addressed.

The future of AI in plant breeding is bright, but it requires collaborative efforts between plant breeders, AI researchers and agricultural technologists to overcome these hurdles. The integration of

AI isn't just an incremental improvement; it's a fundamental shift that will revolutionize how we develop the crops needed to feed a growing world in a changing climate.

Conclusion

Artificial intelligence is not simply automating existing breeding tasks it is changing what breeders can ask of their data. From predicting a plant's genetic value before it is grown, to diagnosing disease from a photograph, to simulating how a not-yet-existing variety might perform in a future climate, AI is compressing timelines that once spanned over a decade or more. As global food demand rises and climate volatility accelerates, this fusion of genomics, phenomics, and machine learning may prove to be the decisive tool that allows plant breeding to keep pace with the challenges ahead.

References

Eftekhari, M., Ma, C. and Orlov, Y. L. (2024). Applications of artificial intelligence, machine learning, and deep learning in plant breeding. *Frontiers in Plant Science*, 15: 1420938.

Farmonaut. (2025). AI in plant breeding: 7 powerful advancements for 2025. Farmonaut. https://farmonaut.com/blogs/ai-in-plant-breeding-7-powerful-advancements-for-2025

Khan, M. H. U., Wang, S., Wang, J., Ahmar, S., Saeed, S., Khan, S. U., and Feng, X. (2022). Applications of artificial intelligence in climate-resilient smart-crop breeding. *International Journal of Molecular Sciences*, 23 (19): 11156.

Ma, J., Cheng, Z., and Cao, Y. (2025). Artificial intelligence-assisted breeding for plant disease resistance. *International Journal of Molecular Sciences*, 26(11): 5324.

Wu, H., Luo, M., Liu, Y., Yang, J., and Cao, Y. (2025). Integrated biotechnological and artificial intelligence innovations for plant improvement. *Frontiers in Plant Science*, 16: 1736707.

Zhu, W., Li, W., Zhang, H., and Li, L. (2025). Big data and artificial intelligence-aided crop breeding: Progress and prospects. *Journal of Integrative Plant Biology*, 67(3): 722-739.

Current Status of Agriculture in India: Growth, Food Security and Farmer Welfare

Narendra Yadav and Diksha Bohra

Agriculture continues to be the backbone of the Indian economy, providing livelihood to nearly half of the country's workforce while ensuring food and nutritional security for over 1.4 billion people. In recent years, the sector has witnessed significant transformation through increased public investment, technological advancement, policy reforms, and welfare-oriented schemes. These initiatives have strengthened agricultural productivity, improved farmers' income support, and enhanced resilience against production risks. The current status of Indian agriculture reflects sustained growth in output, diversification towards high-value crops, and expanding social security measures for farmers.

Growth and Economic Contribution

- ✓ The agriculture and allied sectors remain a vital pillar of India's economy, contributing around 18 per cent of the Gross Value Added (GVA). Over the last decade, the sector has demonstrated consistent economic growth. The GVA of agriculture increased from ₹20.9 lakh crore in 2014-15 to ₹48.7 lakh crore in 2023-24, registering a Compound Annual Growth Rate (CAGR) of 8.83 per cent at current prices. This growth highlights the increasing contribution of agriculture to national income despite rapid industrialization and expansion of the service sector.
- ✓ Within the agricultural economy, the crop sector has recorded remarkable progress. The Gross Value Added from crops nearly doubled, rising from ₹12.92 lakh crore in 2014-15 to ₹26.52 lakh crore in 2023-24, reflecting improvements in crop productivity, market expansion, and better adoption of modern farming practices.
- ✓ Government policy has played a crucial role in driving this growth. Public investment in agriculture has increased substantially, with budgetary allocation rising from ₹27,663 crore in 2013-14 to ₹1,40,528.78 crore in 2026-27. These investments have supported agricultural infrastructure, irrigation, research and development, mechanization, digital agriculture, input subsidies and farmer welfare programmes, thereby strengthening the overall agricultural ecosystem.

Crop Production and Food Security

- ✓ India has made remarkable progress in achieving food security through sustained growth in agricultural production. Total foodgrain production increased from 265.05 million tonnes in 2013-14 to 357.73 million tonnes in 2024-25, reflecting substantial gains in productivity and cultivated output. The increase has been driven primarily by higher production of rice, wheat, maize, pulses, and coarse cereals, including

Narendra Yadav and Diksha Bohra
Research Scholar, Department of Agricultural Economics and Management, MPUAT, Udaipur, Rajasthan

millets, which are now promoted under the national initiative as "Shree Anna" to encourage climate-resilient and nutritious crops.

- ✓ The National Food Security and Nutrition Mission (NFSNM) have significantly contributed to this achievement by promoting the adoption of high-yielding seed varieties, improved agronomic practices, balanced fertilizer use, and advanced production technologies for rice, wheat, pulses, and coarse cereals.
- ✓ India has consolidated its position as the world's largest producer of rice, with rice production increasing by 42.38 per cent since 2014-15. Wheat production reached a historic record of 117.94 million tonnes in 2024-25, while maize production registered an impressive 79 per cent increase over the same period, reflecting rapid technological advancement and increased cultivation.
- ✓ The oilseed sector has also achieved notable progress. Production reached an all-time high of 42.99 million tonnes in 2024-25, representing a 56 per cent increase compared with 27.51 million tonnes in 2014-15. This expansion has contributed towards the national objective of Atmanirbhar Bharat by reducing dependence on imported edible oils. Consequently, India's edible oil import dependence declined from 63.2 per cent in 2015-16 to 56.25 per cent in 2023-24, indicating gradual progress toward self-reliance.
- ✓ The horticulture sector has emerged as one of the fastest-growing components of Indian agriculture. Fruits, vegetables, spices, flowers, plantation crops, and medicinal plants together contribute nearly 37 per cent of the Gross Value Output (GVO) of the crop sector. Increasing consumer demand, improved production technologies, better market linkages and export opportunities have encouraged farmers to diversify toward these high-value crops, thereby enhancing farm profitability.

Farmer Welfare and Social Security: Improving farmers' income and ensuring social protection have become central objectives of India's agricultural policy. Several flagship welfare schemes have been introduced to provide direct financial support, risk management, and pension security to farming households.

Income Support through PM-KISAN: The Pradhan Mantri Kisan Samman Nidhi (PM-KISAN) provides ₹6,000 annually to every eligible farmer family through the Direct Benefit Transfer (DBT) mechanism. The scheme currently benefits more than 9.44 crore farmers across the country. Notably, over one-fourth of the beneficiaries are women, demonstrating the programme's inclusive approach towards strengthening rural household incomes and promoting gender equity.

Crop Insurance through PMFBY: Agricultural production remains vulnerable to climate variability, natural disasters, and pest outbreaks. To reduce farmers' financial risks, the Pradhan Mantri Fasal Bima Yojana (PMFBY) offers a comprehensive and affordable crop insurance system covering the entire

crop cycle, including pre-sowing risks and post-harvest losses.

The scheme operates on the principle of "One Nation, One Crop, One Premium," ensuring uniform premium rates for farmers across the country. Today, more than four crore farmers are insured annually, making PMFBY one of the world's largest agricultural insurance programmes and significantly improving resilience against production shocks.

Pension Security through PM-KMY: Recognizing the need for financial security during old age, the government introduced the Pradhan Mantri Kisan Maan-Dhan Yojana (PM-KMY). The scheme provides a monthly pension of ₹3,000 after the age of 60 years to eligible farmers. As of February 2026, approximately 24.95 lakh farmers had enrolled under the programme, strengthening social protection for small and marginal farmers.

Minimum Support Price and Procurement System

- ✓ The Minimum Support Price (MSP) remains one of the most important policy instruments for protecting farmers against price fluctuations and ensuring remunerative returns. Every year, the Government of India announces MSPs for 22 mandated crops before the sowing season, enabling farmers to make informed production decisions.
- ✓ Since 2018-19, MSPs have been fixed at a minimum of 50 per cent above the all-India weighted average cost of production, fulfilling the government's commitment to providing remunerative prices to cultivators.
- ✓ Public procurement supported by MSP has expanded considerably over the last decade. The total value of procurement during 2014-2026 has been approximately 3.5 times higher than that during 2004-2014, indicating stronger government intervention in agricultural markets and improved income support for farmers, particularly in major foodgrain-producing states.

Conclusion

Indian agriculture has undergone significant transformation over the past decade through sustained policy support, rising public investment, technological advancement, and comprehensive farmer welfare programmes. Strong growth in agricultural Gross Value Added, record foodgrain and horticultural production, expansion of oilseed output, and gradual reduction in edible oil import dependence demonstrate the sector's increasing productivity and resilience. Simultaneously, flagship initiatives such as PM-KISAN, PMFBY, PM-KMY, and an enhanced Minimum Support Price (MSP) framework have strengthened farmers' income security, risk management, and social protection. While challenges related to climate change, fragmented landholdings, and market volatility continue to persist, the current trajectory indicates that Indian agriculture is steadily progressing towards greater sustainability, food security, farmer prosperity, and long-term economic development.

Ultrasonication in Food Processing: Principles, Applications, Advantages and Future Prospects

Akanksha

Abstract

Ultrasonication is an emerging non-thermal food processing technology that has gained considerable attention due to its ability to improve processing efficiency while preserving the nutritional and sensory quality of food products. It involves the application of high-frequency sound waves (above 20 kHz) that generate acoustic cavitation, leading to the formation and collapse of microscopic bubbles in a liquid medium. The resulting mechanical, thermal, and chemical effects enhance mass transfer, disrupt cellular structures, and facilitate various food processing operations. Ultrasonication has been widely applied in the extraction of bioactive compounds, homogenization, emulsification, drying, crystallisation, fermentation, microbial and enzyme inactivation, and food preservation. Compared with conventional thermal methods, ultrasound-assisted processing offers several advantages, including reduced processing time, lower energy consumption, improved extraction yield, enhanced product quality, and better retention of heat-sensitive nutrients and bioactive compounds. In the dairy industry, ultrasonication improves milk homogenization, yoghurt texture, cheese ripening, and ice cream quality. In fruit and vegetable processing, it enhances juice extraction, drying efficiency, and antioxidant retention. Furthermore, the technology contributes to food safety by reducing microbial load and extending shelf life. Despite its numerous advantages, challenges such as high equipment cost, process optimisation, and industrial-scale implementation remain. Ongoing research is focused on integrating ultrasonication with other emerging technologies, including high-pressure processing, pulsed electric fields, cold plasma, and artificial intelligence, to improve efficiency and sustainability. With increasing consumer demand for minimally processed, nutritious, and environmentally sustainable foods, ultrasonication is expected to become an indispensable technology in modern food processing and preservation.

Introduction

The food industry is continuously evolving to meet consumer demand for safe, nutritious, minimally processed and high-quality foods. Conventional thermal processing techniques, although effective in ensuring microbial safety, often result in undesirable changes in nutritional value, flavor, texture, and color of food products. Consequently, the development of novel non-thermal food processing technologies has become a major focus of research. Among these technologies, ultrasonication has emerged as an efficient, environmentally friendly

Akanksha
Centre of Food Technology, Institute of Professional Studies, University of Allahabad, Prayagraj, Uttar Pradesh

and economically viable processing method with wide-ranging applications in food preservation and value addition. Ultrasonication refers to the application of sound waves with frequencies higher than the upper limit of human hearing (>20 kHz). In food processing, high-intensity ultrasound (20–100 kHz) is commonly employed because it generates acoustic cavitation, which is responsible for most of the physical and chemical effects observed during ultrasonic treatment. The rapid formation, growth, and collapse of microscopic bubbles create intense localized pressure, temperature, and shear forces, enhancing mass transfer, disrupting cellular structures and improving processing efficiency. In recent years, ultrasonication has gained considerable attention for applications such as extraction of bioactive compounds, emulsification, homogenization, drying, microbial inactivation, enzyme inactivation, crystallization, fermentation, and food preservation. It offers significant advantages including shorter processing time, reduced energy consumption, improved product quality, higher extraction efficiency, and better retention of nutrients and bioactive compounds. These benefits make ultrasonication an attractive technology for sustainable food processing and industrial applications.

Principle of Ultrasonication

The working principle of ultrasonication is based on the phenomenon of acoustic cavitation. When ultrasonic waves pass through a liquid medium, alternating cycles of compression and rarefaction are produced. During the rarefaction cycle, tiny vapor-filled bubbles are formed. As the ultrasonic waves continue, these bubbles grow until they reach an unstable size and collapse violently. The implosion of cavitation bubbles generates localized temperatures of nearly 5000 K, pressures exceeding 1000 atmospheres, shock waves, and high-velocity micro-jets. These extreme localized conditions produce several beneficial effects in food systems, including disruption of plant and microbial cell walls, enhanced diffusion of solvents, reduction in particle size, improved mixing, and increased mass transfer. As a result, ultrasonication significantly accelerates extraction processes, improves emulsification and homogenization, enhances drying efficiency, and contributes to microbial and enzyme inactivation. The effectiveness of ultrasonic processing depends on factors such as frequency, power intensity, treatment time, temperature, characteristics of the food material, and processing medium.

Applications of Ultrasonication in Food Processing

Ultrasonication has found extensive applications across various sectors of the food industry because of its ability to improve product quality while reducing processing costs and energy requirements. One of the most important applications is the extraction of bioactive compounds from plant materials. Ultrasound-assisted extraction facilitates the release of intracellular compounds by disrupting plant cell walls through cavitation. This technique has been successfully employed for extracting phenolic compounds, flavonoids, carotenoids, antho-

cyanins, essential oils, pigments, proteins and anti-oxidants from fruits, vegetables, herbs, spices, and medicinal plants. Compared with conventional extraction methods, ultrasonication offers higher extraction yields, shorter extraction times, lower solvent consumption, and better preservation of heat-sensitive compounds. In the dairy industry, ultrasonication has become an effective alternative to conventional homogenization and processing techniques. Ultrasonic treatment reduces the size of milk fat globules, resulting in improved homogenization and enhanced emulsion stability. It also improves the texture, viscosity, and water-holding capacity of yogurt while reducing syneresis. In cheese manufacturing, ultrasound enhances moisture retention, accelerates ripening, and improves flavor development. Similarly, in ice cream production, ultrasonication produces smaller fat globules and air cells, leading to increased overrun, smoother texture, improved creaminess, and enhanced melting resistance. Ultrasonication is also widely used in fruit and vegetable processing. It increases juice extraction efficiency, improves clarification, preserves natural color and flavor, and enhances the retention of vitamins and antioxidants. Ultrasound-assisted processing reduces enzymatic browning and maintains the freshness of fruit juices and beverages. Furthermore, it facilitates osmotic dehydration and drying of fruits and vegetables, thereby reducing drying time while maintaining nutritional quality and sensory characteristics. The technology has shown promising applications in the meat and seafood industry. Ultrasonication improves meat tenderness by disrupting muscle fibers and connective tissues. It enhances marination efficiency by increasing the penetration of curing solutions into meat tissues, leading to improved flavor, texture, and water-holding capacity. In seafood processing, ultrasound assists in cleaning, tenderization, and microbial reduction without significantly affecting nutritional quality. Another important application is in edible oil extraction. Ultrasound-assisted extraction improves oil recovery from oilseeds such as soybean, sunflower, mustard, sesame, olive, and groundnut by increasing cell permeability and enhancing solvent penetration. Consequently, higher oil yields are achieved in a shorter time with lower solvent consumption and reduced processing costs. Ultrasonication has also become valuable in drying technology. Ultrasound-assisted drying enhances moisture removal through improved internal water diffusion, reducing drying time and energy consumption. It preserves heat-sensitive nutrients, natural color, flavor, and texture better than conventional drying methods. Similar improvements have been observed during freeze-drying and osmotic dehydration processes. The technology is increasingly applied for the preparation of stable emulsions and nanoemulsions. Ultrasonic cavitation produces extremely fine droplets with narrow size distribution, resulting in highly stable emulsions without the need for excessive emulsifiers. These nanoemulsions improve the solubility and bioavailability of lipophilic bioactive compounds, vitamins,

essential oils, and nutraceuticals used in functional foods.

Role in Food Preservation

Food preservation is one of the most significant applications of ultrasonication. The collapse of cavitation bubbles damages microbial cell membranes through mechanical stress and localized heating, resulting in the destruction of bacteria, yeasts, and molds. Although ultrasonication alone may not completely sterilize foods, its effectiveness increases substantially when combined with mild heat (thermosonication), pressure (manosonication), or both (manothermosonication). Ultrasonication also contributes to the inactivation of spoilage enzymes such as polyphenol oxidase, peroxidase, lipoxygenase and pectin methylesterase. Inactivation of these enzymes helps reduce enzymatic browning, preserve color, maintain texture, and extend the shelf life of fresh and processed foods. Consequently, ultrasonication has become an important technology for producing minimally processed foods with superior nutritional and sensory quality.

Advantages of Ultrasonication

Ultrasonication offers numerous advantages over conventional food processing methods. It is considered an environmentally friendly and sustainable technology because it requires less energy and fewer chemical solvents. The process significantly reduces processing time while improving extraction efficiency, homogenization, emulsification, drying, and preservation. Since it is a non-thermal technology, losses of vitamins, antioxidants, flavors and other heat-sensitive compounds are minimized. Additional advantages include improved product quality, better texture, increased shelf life, enhanced bioavailability of nutrients, reduced microbial load, and lower production costs. Ultrasonication is also compatible with other emerging technologies, allowing the development of hybrid processing systems that further improve food quality and safety.

Limitations

Despite its numerous advantages, ultrasonication also has certain limitations. The initial investment for ultrasonic equipment is relatively high, limiting its adoption by small-scale industries. The effectiveness of ultrasonic treatment varies depending on the physical properties of the food material, including viscosity, composition, and particle size. Excessive ultrasonic treatment may generate free radicals that accelerate lipid oxidation or negatively affect texture and color in certain food products. Moreover, scaling up laboratory ultrasonic systems for continuous industrial production remains a significant engineering challenge. Therefore, optimization of processing parameters such as frequency, power intensity, treatment time, and temperature is essential for each food product.

Future Prospects

The future of ultrasonication in food processing appears highly promising. Current research is focused on integrating ultrasonication with advanced technologies such as high-pressure processing, pulsed electric fields, cold plasma, microwave processing, and membrane filtration to develop high-

ly efficient hybrid processing systems. Ultrasound-assisted encapsulation of bioactive compo-unds, nanoemulsion production, extraction of functional ingredients, and intelligent process monitoring using artificial intelligence are emerging areas of research.

Conclusion

Ultrasonication is an innovative non-thermal food processing technology that has revolutionized several operations within the food industry. By utilizing the principle of acoustic cavitation, it enhances extraction, homogenization, emulsification, drying, microbial inactivation and preservation while maintaining the nutritional and sensory quality of foods. The technology provides numerous advantages, including higher processing efficiency, lower energy consumption, improved product quality and enhanced retention of bioactive compounds. Although challenges related to equipment cost and industrial-scale implementation remain, ongoing technological advancements continue to expand its applications. As the demand for sustainable, safe, and high-quality foods increases worldwide, ultrasonication is expected to become one of the most important emerging technologies in modern food processing.

References

Chavan, P., Sharma, P., Sharma, S. R., Mittal, T. C. and Jaiswal, A. K. (2022). Application of high-intensity ultrasound to improve food processing efficiency: A review. *Foods*, 11 (1): 122.

Mgoma, S. T., Basitere, M., Mshayisa, V. V. and De Jager, D. (2025). A systematic review on sustainable extraction, preservation, and enhancement in food processing: the advancement from conventional to green technology through ultrasound. *Processes*, 13(4): 965.

Embryonic Nutrition and Early Chick Management

Induri Pavan Kumar and V. V. Gamit

Abstract

Embryonic and early chick mortality remain among the most significant, yet controllable, constraints on hatchability and flock output in commercial poultry production. Mortality follows a characteristic U-shaped distribution across the 21-day incubation period, with a first peak during early differentiation (Day 1-7), driven largely by genetic defects, poor egg storage and breeder deficiencies of riboflavin, folic acid, B-vitamins and essential fatty acids, and a second peak during late maturation (Day 15-21), attributable to malposition, hypoxia, weak eggshell mineralisation and inadequate late-incubation management. Beyond hatch, a further critical window of vulnerability arises from unavoidable post-hatch fasting (12-72 hours) imposed by hatchery processing and transport logistics, which depletes the finite yolk-sac reserve and compromises intestinal and immune maturation before the chick ever reaches the farm. In-ovo feeding has emerged as a physiologically targeted nutritional intervention that exploits the embryo's natural amniotic-fluid swallowing behaviour from Day 17 onward to deliver carbohydrates, amino acids, HMB, L-carnitine, vitamins and probiotics directly into the developing gut, thereby improving villus development, digestive enzyme activity, hatch weight and post-hatch livability. In the Indian poultry context where broiler and layer production is expanding rapidly but is constrained by high ambient temperatures, inconsistent hatchery infrastructure, variable breeder nutrition standards and long-distance chick transport embryonic and chick mortality losses translate directly into reduced farm profitability and food-security shortfalls. Wider adoption of in-ovo feeding and vaccination technologies, alongside improved breeder nutrition and hatchery climate control, therefore represents a high-priority strategy for narrowing India's hatchability and chick-quality gap relative to global standards.

Embryonic Development (Day 1-21): Overview

Three phases: Differentiation (D1-4, organo-genesis) → Growth (D5-14, yolk-sac membrane and chorioallantoic membrane fully vascularised by D9-10; amniotic-fluid swallowing begins D13-14) → Maturation (D15-21, internal pipping ~D19.5-20, hatch D21). The internalised residual yolk sac is the chick's principal nutrient and IgY (immunoglobulin) reserve for the first 24-72 h post-hatch.

Embryonic Mortality: Early vs Late (Key Focus)

Induri Pavan Kumar
M.V.Sc. Scholar, Department of Animal Nutrition, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Junagadh, Gujarat

V. V. Gamit
Associate Professor, Department of Livestock Production Management, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Junagadh, Gujarat

Mortality follows a U-shaped curve across incubation peaks in early (D1-7) and late (D15-21) windows, with a trough during mid-incubation (D8-14).

Early mortality (D1-7): genetic/chromosomal defects, poor egg storage/handling, incorrect early temperature or turning; deficiencies of riboflavin, folic acid, B_{12}, biotin, manganese and essential fatty acids impair organogenesis and neural-tube closure. Breakout finding: blood ring / arrested blastoderm.

Late mortality (D15-21): malposition, hypoxia/ hypercapnia, weak shell/skeletal mineralisation (vitamin D_3, calcium, manganese, zinc deficiency), bacterial shell penetration and EFA deficiency impairing pulmonary surfactant/membrane synthesis. Finding: fully formed but malpositioned, unhatched or pipped-not-hatched embryo.

Table 1: Early vs late embryonic mortality – causes and corrective focus (adapted from Whitehead & Siller, 1985; North & Bell, 1990)

Feature	Early Mortality (D1-7)	Late Mortality (D15-21)
Phase affected	Differentiation (organogenesis)	Maturation (pre-hatch transition)
Nutritional cause	Riboflavin, folic acid, B_{12}, biotin, Mn	Vitamin D_3, Ca/ Mn/Zn, essential fatty acids
Non-nutritional cause	Genetic defects, poor storage, faulty early turning	Malposition, hypoxia, weak shell, bacterial entry
Corrective focus	Breeder vitamin/mineral nutrition, egg handling	Late hatcher T°/ RH/ventilation, shell quality

Riboflavin deficiency → clubbed down/ micromelia; folic acid/B_{12} → skeletal and syndactyly defects; manganese/biotin → chondrodystrophy ('perosis'), peaking around D19–21; linoleic acid deficiency depresses hatchability at both early and late windows.

Essential Fatty Acids and Hatchability

- ✓ Beyond their role in fertilisation, essential fatty acids influence hatchability through their contribution to early embryonic membrane synthesis, yolk sac membrane vascularisation, and energy provision during the latter half of incubation when lipid beta-oxidation becomes the dominant metabolic pathway of the embryo.
- ✓ Linoleic acid (n-6) and α-linolenic acid (n-3) are dietary-essential; yolk fatty-acid profile mirrors breeder diet. A moderate n-6:n-3 ratio of 5:1-10:1 with adequate vitamin E/selenium favours fertility, hatchability and chick vigour.
- ✓ PUFA supplementation without matched vitamin E/selenium increases peroxidative embryo mortality risk fatty-acid and antioxidant nutrition must be managed jointly.

In-ovo Feeding

- ✓ Injection of nutritive solutions into the amnion, air cell or yolk sac, typically Day 17-19, exploiting active amniotic-fluid swallowing (from D13-14) to deliver nutrients directly into the gut lumen before hatch.
- ✓ Rationale: primes brush-border enzymes (sucrase -isomaltase, maltase-glucoamylase) and PepT1 transporter, induces hepatic glycogen/ gluconeogenic enzymes and advances GALT/ IgA maturation softening the abrupt shift from yolk-lipid to exogenous carbohydrate-protein nutrition.
- ✓ Amnion is the preferred site (least embryo trauma; coincides with peak fluid volume); Day-

18 co-injection with vaccine reduces labour, cost and contamination risk.

- ✓ Substrates studied: sucrose/dextrose/maltose (villus height +25-30%, crypt depth +15-20%, goblet cells +30-40%, sucrase-isomaltase activity +40-60% vs control), HMB (anti-catabolic, ↑breast-muscle yield), L-carnitine (↑β-oxidation & hatchability), vitamin C/zinc/ probiotics (antioxidant, immune and microbiota support).

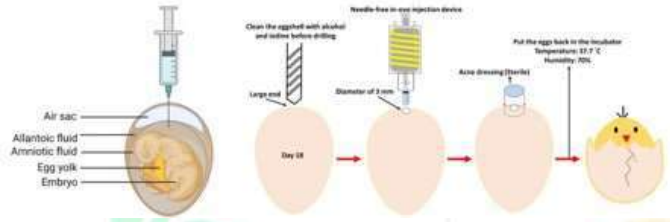


Figure 1. Egg compartments targeted for in-ovo injection (left) and the standard Day-18 needle/ needle-free in-ovo injection sequence (right). Source: Pas Reform Hatchery Technologies (2018).

Strict aseptic technique (shell disinfection, sterile needles) is non-negotiable contamination of amniotic/air-cell fluid is the principal risk of the technique.

In-ovo Vaccination

- ✓ Administered Day 17.5-19 (standard D18), once the bursa (active from D12-14) and thymus (colonised from D6) can mount primary immune responses; amniotic delivery reaches gut-associated lymphoid tissue (Peyer's patches, caecal tonsils, bursa) for combined mucosal and systemic priming.
- ✓ Marek's disease (HVT / HVT-SB1) original, most established application; IBD immune-complex vaccines overcome maternal-antibody neutralisation; Newcastle disease - recombinant HVT-vector avoids embryo pathogenicity and maternal-antibody interference; Infectious Bronchitis - strain-dependent, variable hatch-ability impact; Coccidiosis - live Eimeria oocysts remain dormant till post-hatch, supporting antibiotic-free production; Mycoplasma gallis-epticum - ts-11 strain safe, unlike lethal F-strain. Requires precision automated injectors, uninterr-upted vaccine cold-chain and strict hatchery hygiene to avoid puncture-site contamination.

Post-hatch Fasting and Gut Development

Hatchery logistics (hatch window, sexing, vaccination, transport) commonly impose 12-72+ h fasting; the only nutrient source is the residual yolk sac (~4-6 g lipid/protein/IgY).

- ✓ Fasting causes dose-dependent villus atrophy and shallower crypts with depressed sucrase-isomaltase, PepT1 and alkaline-phosphatase activity (e.g., 72 h fasting: villus height ↓30-40%, Day-7 body weight ↓15-20%); beyond 48 h, villus-tip apoptosis and increased gut perme-ability raise bacterial-translocation/ endotox-aemia risk.
- ✓ Early feed/water access accelerates beneficial microbiota (*Lactobacillus, Bifidobacterium*) establishment over pathogenic Enterobacte-riaceae/Clostridium; in-ovo or day-of-hatch probiotics (*Bacillus subtilis, L. salivarius*) further improve gut morphometry and pathogen exclusion.

The principal determinants of chick quality

include: (i) breeder hen age and nutritional status, which determines yolk and albumen nutrient reserve composition; (ii) egg storage conditions, particularly duration and temperature, with prolonged storage depressing hatchability and chick quality progressively beyond Day 7 of storage; (iii) incubator temperature, humidity and CO_2 profiles throughout the 21-day incubation cycle; (iv) egg turning frequency and angle during the setting stage; (v) transfer timing from setter to hatcher; (vi) hatcher temperature, humidity and ventilation during the final three days; and (vii) the duration of the post-hatch holding period in the hatcher and chick processing area.

Chick Quality Assessment - PASGAR Score

A composite, hatchery-applicable measure of morphological, behavioural and physiological readiness, predictive of early livability, growth and immune competence.

Table 2: PASGAR chick-quality scoring parameters (Pas Reform Hatchery Technologies, 2018)

Parameter	What is assessed	Score (0–2)
Posture	Standing ability, righting reflex	0=cannot stand – 2=normal
Activity	Alertness, vocalisation, eye brightness	0=moribund – 2=alert
Size	Body weight vs flock standard	0=deviant – 2=optimal
Gut/yolk sac	Navel closure, yolk retraction	0=open navel – 2=closed,dry
Abnormalities	Deformities (beak, legs, eyes)	0=severe – 2=none
Residual down	Down coverage/cleanliness	0=abnormal – 2=full,clean

Individual subscores are diagnostic - a low 'G' (navel) score implicates late incubator/hatcher temperature faults; a low 'A' (abnormality) score implicates breeder nutrient deficiency or genetics.

Complementary tools: Tona scoring, Bristol navel score, plasma glucose/corticosterone, heterophil: lymphocyte ratio and yolk-free body weight. Indian hatcheries face added summer heat-stress, storage-facility variability and long-distance transport challenges that make routine PASGAR monitoring especially valuable. A total PASGAR score of 10-12 indicates excellent chick quality, 7-9 indicates acceptable to borderline quality, and scores below 7 signal significant hatchery or flock management problems requiring immediate investigation.

References

Bhanja, S. K., Suresh, M., Bhatt, V. and Devanath, S. S. (2022). Epigenetic programming of hepatic gluconeogenic genes by in ovo carbohydrate supplementation. *Frontiers in Veterinary Science*, 9: 874321.

Cobb-Vantress Inc. (2022). Cobb breeder management guide (5th ed.). Cobb-Vantress.

Córdova-Noboa, H. A., Oviedo-Rondón, E. O., Sola-Oriol, D. and Pérez, J. F. (2023). In ovo feeding of carbohydrates and carnitine combination improves intestinal barrier function. *Poultry Science*, 102(2): 102424.

Fatemi, S. A., Elliott, K. E. C., Bello, A., Huber, H. and Scholtz, B. (2021). In ovo sucrose and L-carnitine feeding improves villus height and tight-junction protein expression. *Poultry Science*, 100(5): 101069.

Pas Reform Hatchery Technologies. (2018). Hatchery management guide: Optimising the hatchery process. Pas Reform Academy.

Maiorka, A., Santin, E., Borges, S. A., Opalinski, M. and Macari, M. (2020). Gastrointestinal tract development in broiler chicks. *World's Poultry Science Journal*, 76(3): 424-440.

North, M. O. and Bell, D. D. (1990). Commercial chicken production manual (4th ed.). Van Nostrand Reinhold.

Uni, Z. and Ferket, P. R. (2004). Methods for early nutrition and their potential. *World's Poultry Science Journal*, 60(1): 101-111.

Uni, Z., Ferket, R. P., Tako, E. and Kedar, O. (2005). In ovo feeding improves energy status of late-term chicken embryos. *Poultry Science*, 84 (5): 764-770.

Whitehead, C. C. and Siller, W. G. (Eds.). (1985). Sturkie's avian physiology (6th ed.). Springer.

Integrated Pest Management: A Practical Path to Sustainable Crop Protection

Shiksha Jha

Abstract

For decades, pest control in agriculture has depended almost entirely on chemical pesticides, a habit that has bred resistant pest populations, wiped out natural enemies, and left rising input costs and pesticide residues behind it. Integrated Pest Management (IPM) offers a more durable alternative, combining cultural, mechanical, biological, and chemical tactics through field monitoring and economic thresholds rather than routine spraying. This article outlines the principles behind IPM, its major components, and the reasons its wider adoption still meets resistance on the ground.

Ask an extension officer what a farmer usually does the moment pest damage shows up in a field, and the answer is nearly always the same: reach for a pesticide. It is an understandable reflex chemical control is fast, the results are visible within days, and it asks nothing in the way of scouting or record-keeping. The trouble is that the cost of this habit rarely shows up on the day it is incurred. Repeated, calendar-based spraying has bred resistance into hundreds of insect and mite species. It has removed the very predators and parasitoids that would otherwise keep pest numbers in check, occasionally turning a minor pest into a major one within a single season a pattern entomologists call pest resurgence. It leaves residues on produce, raises health concerns for farm workers, and adds a recurring cost to every cropping cycle without addressing why the pest keeps coming back. Integrated Pest Management grew out of an attempt to correct this, not to abandon chemical control altogether. The idea was first formalised in 1959 by Stern, Smith, van den Bosch, and Hagen, who argued that chemical and biological control ought to be integrated rather than treated as rivals. The concept has since broadened well beyond biological control to cover every tool available to a grower, and the Food and Agriculture Organization now recommends it as the default approach to crop protection worldwide.

What Integrated Pest Management Really Means

IPM is often mistaken for simply spraying less or growing crops organically. It is neither. It is a decision-making framework: a grower monitors pest populations in the field, compares the count against an economic threshold, and only then chooses whichever combination of tactics fits the situation. The economic threshold level (ETL) is the pest density at which control action should begin, calcul-

Shiksha Jha
MBA (Agri-Business Management) Student, College of Agribusiness Management, BAU, Sabour, Bihar

ated to prevent the population from reaching the economic injury level the point at which the resulting crop loss would exceed the cost of controlling it. A cotton field carrying two bollworm larvae per plant may need no intervention at all; the same field at eight or ten larvae per plant almost certainly does. IPM asks growers to know that difference for their own crop and pest, rather than spraying on a fixed calendar.

The IPM Toolkit

No single tactic carries an IPM programme on its own; several are layered together, each covering a gap the others leave open.

Cultural control comes first, mainly because it is the cheapest to fold into normal farming practice. Crop rotation breaks the life cycle of pests tied to one host; timely sowing lets a crop outgrow its most vulnerable stage before pest numbers build up; field sanitation denies pests a place to overwinter. Even fertilisation matters heavily nitrogen-fed plants push out soft, sappy growth that aphids and jassids find easier to exploit.

Mechanical and physical control covers the hands-on measures: hand-picking egg masses early in an infestation, light traps for adult moths, sticky traps for whiteflies and thrips, or soil solarisation ahead of sowing. None of these handle a large outbreak alone, but they keep small, early populations from becoming large ones.

Biological control leans on ecology already present in the field. *Trichogramma* wasps parasitise pest eggs before they can hatch and are now reared and released commercially against a wide range of pests. Ladybird beetles, lacewings, and predatory mites feed on pests directly. Microbial agents add a further layer *Bacillus thuringiensis* (Bt) and nucleopolyhedrovirus (NPV) target specific larvae, while fungi such as *Beauveria bassiana* infect a broader range of soft-bodied insects. None of it works if the field is sprayed with a broad-spectrum insecticide the week before release, which is why timing matters as much as the agents themselves.

Host plant resistance moves the defence into the crop itself, through varieties bred to be less palatable to a pest or to recover more readily from its damage.

Pheromone-based tools turn a pest's own chemistry against it. Synthetic sex pheromones loaded into traps let growers track how a pest population is building through the season and, at higher trap densities, disrupt mating outright.

Table 1: Core Components of Integrated Pest Management

Component	Representative Practices	Primary Role
Cultural control	Crop rotation, timely sowing, field sanitation, balanced fertilisation	Reduces pest establishment and build-up
Mechanical / physical control	Hand-picking, light and sticky traps, soil solarisation	Suppresses small, early-stage populations
Biological control	Trichogramma release, predatory insects, Bt, NPV, entomopathogenic fungi	Uses natural enemies to regulate pest numbers
Host plant resistance	Resistant or tolerant crop varieties	Lowers pest damage at the plant level
Pheromone-based tools	Monitoring and mass-trapping lures	Tracks population build-up; disrupts mating
Chemical control	Selective, need-based insecticide use	Backstop when thresholds are exceeded

Chemical control still has a place IPM does not remove it, only demotes it from first resort to last. Where thresholds are crossed and other tactics fall short, the guidance is to choose selective products over broad-spectrum ones, rotate between modes of action to slow resistance, and time sprays to do the least damage to pollinators and natural enemies.

Monitoring: Where the Decisions Get Made

None of this works without regular field monitoring. Growers, or trained scouts, need to walk fields on a fixed schedule and count pests against a standard method, while pheromone and light traps give early warning of a pest's flight period before visible damage appears in the crop. Cotton offers a familiar illustration. Through much of the late twentieth century, the bollworm complex drove some of the heaviest insecticide use of any crop, occasionally requiring a dozen or more sprays in a single season, with resistance building up to match. An IPM package built around pheromone traps for monitoring, timed Trichogramma releases against bollworm eggs, NPV where thresholds were crossed, and need-based rather than calendar-based spraying brought insecticide use down considerably wherever it was properly followed, while keeping bollworm damage within manageable limits. The lesson was not that chemicals became unnecessary, but that most of the sprays being applied had never needed to happen.

Worth the Effort, Not Without Its Hurdles

The case for IPM rests on more than ecology. Fewer, better-timed sprays lower costs over a season; reduced residues matter to both domestic and export markets; conserved natural enemies keep pest control running in the background at no extra charge; and rotating chemical classes slows resistance, protecting the useful life of the products still on the shelf. None of this makes IPM an easy sell, though. It demands more knowledge than picking a pesticide off the shelf correct pest identification, an understanding of thresholds, and tolerance for a little visible damage that would once have triggered an immediate spray. Results in the first season or two are often less dramatic than a chemical spray's, biocontrol agents and pheromone lures are not always available locally, and market demand for blemish-free produce keeps pulling growers back toward the spray tank even when thresholds have not been crossed. Closing these gaps depends less on new technology than on sustained extension support a reliable local supply of biocontrol agents and traps, and training that treats IPM as the default recommendation rather than an optional add-on.

The Way Forward

IPM was never meant to be a product a grower could buy off a shelf. It is closer to a discipline watching a field closely enough to know when action is actually needed, and drawing on a full toolbox rather than reaching for the same tool every time. That asks more of growers and extension systems than calendar spraying ever did. But with resistance continuing to spread and input costs continuing to climb, it remains one of the more durable answers agriculture has to the pest problem,

not because it eliminates pests, but because it manages them without managing away the rest of the field's ecology in the process.

References

Stern, V. M., Smith, R. F., van den Bosch, R. and Hagen, K. S. (1959). The integrated control concept. *Hilgardia*, 29(2): 81-101.

Kogan, M. (1998). Integrated pest management: historical perspectives and contemporary developments. *Annual Review of Entomology*, 43: 243-270.

Food and Agriculture Organization of the United Nations (FAO). Integrated Pest Management - Concepts and Approaches.

National Research Council. (1996). Ecologically Based Pest Management: New Solutions for a New Century. National Academies Press.

Pedigo, L. P. and Rice, M. E. Entomology and Pest Management. Pearson Education.

Market for Agricultural Inputs in India: Trends, Challenges and Future Opportunities

Ravi Raj

Abstract

Agricultural inputs are central to raising crop productivity, safeguarding food security, and improving farmers' livelihoods. A sound input market gives farmers timely access to quality seeds, fertilizers, crop-protection products, farm machinery, irrigation equipment, and other essential resources. India's input market has changed considerably on account of policy reform, technological progress, growing private-sector involvement, and wider use of digital tools. This review looks at the structure, demand pattern, competitive landscape, promotional practices, and principal challenges of the agricultural input market, while also pointing to emerging opportunities such as digital agriculture, sustainable farming methods, and farmer-focused marketing. It concludes that a transparent, efficient, and accessible input market is fundamental to lifting agricultural productivity, raising farm income, and sustaining the growth of Indian agriculture.

Introduction

Agricultural inputs underpin gains in productivity, farm profitability, and food security. A well-functioning input market makes certain that farmers obtain quality seeds, fertilizers, crop-protection products, machinery, irrigation equipment, and other essential resources at the right time, in adequate quantity, and at reasonable cost. Beyond mere supply, an efficient market also spreads useful information, reinforces extension support, and drives adoption of modern farming technology, thereby contributing to sustainable agricultural development. India possesses one of the largest agricultural sectors in the world, and millions of farmers depend on dependable input-supply systems for successful crop cultivation. The input market has been reshaped in recent years by policy reform, expanding private-sector participation, technological change, and the spread of digital platforms (Padmaja et al., 2020). These shifts have improved farmers' access to quality inputs and market information and have made input distribution more efficient, while emerging digital and agri-tech innovations are increasingly reshaping how inputs and services reach farmers (Kumar, 2025). Even so, the sector remains constrained by uneven distribution, escalating input costs, counterfeit products, limited farmer awareness, and regional disparities. This review discusses the significance, demand pattern, market structure, promotional strategies, key challenges, and future prospects of India's agricultural input market for sustainable agricultural growth.

Ravi Raj
MBA (Agri-Business Management) Student, College of Agribusiness Management, BAU, Sabour, Bihar

Agricultural Inputs: Meaning and Importance: Agricultural inputs include the goods, services, and technologies used to improve crop production and farm efficiency. They include seeds, fertilizers, crop protection products, farm machinery, irrigation equipment, bio-inputs, agricultural credit, extension services, and market advisory support. Their proper use increases productivity, improves produce quality, reduces production risks and promotes efficient resource use. Agricultural inputs are broadly classified into material inputs and supporting service inputs. Material inputs, such as seeds, fertilizers, pesticides, machinery, irrigation systems, and bio-inputs, are directly used in crop production. Supporting services, including agricultural credit, crop insurance, extension services, soil testing, and market information, help farmers make informed production and marketing decisions. Together, these inputs enhance farm productivity and support sustainable agricultural development.

Input Category	Contribution to Agriculture
Seeds	Strengthen crop establishment and enhance yield and grain quality
Fertilizers	Provide nutrients essential for plant growth and soil fertility
Crop protection inputs	Safeguard crops against pest, disease, and weed damage
Farm machinery	Cut labour dependence and raise operational efficiency
Irrigation equipment	Support efficient water use and boost productivity
Bio-inputs	Enhance soil health and promote sustainable cultivation
Advisory and extension services	Deliver technical know-how and market intelligence

Nature of Demand in Agricultural Input Markets : Demand for agricultural inputs is a derived demand, as farmers purchase seeds, fertilizers, crop protection products, machinery, and other inputs to increase crop production and farm income rather than for direct consumption. It depends on factors such as expected crop returns, market prices, weather conditions, government policies, and the availability of credit. Demand is highly seasonal, with peak requirements during the *Kharif*, *Rabi*, and *Zaid* cropping seasons. Manufacturers and distributors must therefore ensure the timely availability of quality inputs. Farmers' purchasing decisions are further influenced by product quality, price, extension support and awareness of improved technologies. Understanding these demand patterns helps businesses and policymakers develop effective marketing strategies and strengthen agricultural input distribution systems.

Market Structure and Competition in Agricultural Input Markets: India's agricultural input market comprises manufacturers, distributors, wholesalers, retailers, cooperatives, government agencies, and private agribusiness firms that ensure the timely supply of quality inputs to farmers. Policy reforms, technological advancements, and greater private-sector participation have strengthened competition, encouraged innovation, and improved input availability, particularly in the seed, fertilizer, crop protection, and farm machinery sectors. Agricultural inputs are distributed through a multi-tier marketing channel, from manufacturers to distributors or carrying and forwarding (C&F) agents, wholesalers, retailers, and finally farmers. Farmer Producer Organizations (FPOs), cooperatives and Agri-Clinics and Agribusiness Centres (ACABCs) also support

input distribution by providing quality inputs, technical guidance and extension services. Competition in this market is driven by product quality, price, brand reputation, dealer networks, and after-sales support, encouraging firms to strengthen customer trust and promote improved agricultural technologies.

Distribution Channel: Manufacturer → Distributor / C&F Agent → Wholesaler → Retailer / Agri-Input Dealer → Farmer

Promotional Strategies in Agricultural Input Marketing: Promotion is an essential part of agricultural input marketing as it creates awareness, builds farmers' trust, and encourages the adoption of improved technologies. Since effective input use requires technical knowledge, companies combine promotional activities with extension services to educate farmers about product features, application methods, and benefits. Field demonstrations, Kisan Melas, farmer meetings, dealer conferences, and training programmes remain effective because they provide direct interaction between companies, experts, and farmers.

Promotional Method	Value Delivered to Farmers
Field demonstrations	Build confidence by showcasing real performance results
Kisan Melas and exhibitions	Raise awareness of new technologies and products
Farmer training programmes	Improve correct and effective product usage
Dealer meetings	Strengthen supply networks and technical backup
Mobile apps and websites	Offer convenient access to product and advisory information
Social media and WhatsApp	Enable faster, direct communication with farmers

Digital communication has further strengthened promotional efforts. Agribus-iness firms use mobile applications, websites, social media, Whats App, YouTube, and SMS to provide product information, technical guidance, and crop advisories. Integrating traditional extension methods with digital platforms has improved farmers' access to information and made agricultural input marketing more effective and farmer-centric.

Challenges and Future Opportunities in Agricultural Input Markets

Despite significant progress, India's agricultural input market continues to face several challenges. Unequal access to quality inputs, especially in remote areas, delays in supply, rising input costs, and counterfeit products reduce farmers' productivity and income. Limited institutional credit, weak extension services, and low awareness of improved farming practices further restrict the adoption of quality inputs. Despite these challenges, the sector offers strong growth opportunities through digital agriculture, precision farming, biotechnology, and climate-smart practices. Strengthening collaboration among government agencies, private agribusiness firms, research institutions, extension organizations, and Farmer Producer Organizations (FPOs) will be essential for developing an efficient, transparent, and farmer-centric agricultural input market.

Conclusion

Agricultural input markets are indispensable to raising agricultural productivity, securing food supplies and lifting farmer income.

A well-developed input market ensures timely access to quality seeds, fertilizers, crop-protection products, farm machinery, and other resources needed for efficient crop production. Policy reform, private-sector participation, and technological progress have strengthened India's input sector in recent years, yet unequal access to quality inputs, rising costs, counterfeit products, and limited farmer awareness continue to weigh on its performance. Addressing these constraints through better infrastructure, stronger extension services, tighter regulation, and sustainable marketing practices will sharpen the efficiency of input markets. A transparent, farmer-oriented input system will be central to achieving sustainable agricultural development and strengthening the competitiveness of Indian agriculture.

References

Jay Bajrang Pratishtan. (n.d.). Project report on Agri-Input Supply Centre. Agri-Clinic and Agri-business Centre (ACABC) Scheme, Baraut, Uttar Pradesh.

Kumar, S. (2025). Innovations in agricultural inputs and services markets in India: A pathway to sustainable agricultural growth. *Indian Journal of Agricultural Economics*, 80(1): 91-112.

Panwar, A. and Sahoo, S. (2025). Digital buying behaviour among farmers: The impact of smartphone penetration on ecommerce adoption in rural India. *International Journal of Innovations in Science Engineering and Management*, 4(3): 131-137.

Padmaja, S. S., Balaji, S. J. and Pal, S. (2020). Agricultural input markets in India - Recent policy reforms and way forward: A review. *Indian Journal of Agricultural Sciences*, 90(6): 1047-1053.

Nutrient Stress in Kiwifruit: Causes, Impacts and Sustainable Management

Tamana, Garima Vashisth, Rupam Nehta, Ibajanai Kurbah and Sanjeev Kumar

Introduction

Actinidia chinensis Planch. (Chinese kiwifruit) is a fruit native to China being even more popular due to its economic, nutritional and health benefits. The fruits of *A. chinensis* are attractive because of their bright yellow flesh and regarded as sweeter and less sour than *A. deliciosa* when ripe (Pranamornkith et al. 2012). All parts of the plant including its fruits, leaves, vines and roots are used mainly as food and an additive in food products in addition to the traditional medical treatment. The plant is rich in triterpenoids, polyphenols, vitamin C, carbohydrates, amino acids and minerals. These components endow the plant with the large number of pharmacological properties which include antitumor, antioxidant, anti-inflammatory, immunoregulatory, hypolipemic, antidiabetic and cardiovascular protective ones which means that *A. chinensis* can be helpful in both prevention and treatment of the diseases related to cancer, oxidative stress and old age (He *et al.*, 2019). Nutrient stress is a situation involving insufficient presence of some important mineral nutrients in plant's tissues. In kiwifruit, the effects of nutrient stress can be aggravated by drought, high temperatures, waterlogging, unfavourable soil pH and lack of soil fertility. Owing to the relatively shallow root system, the plant is influenced more by environmental conditions and soil moisture than the nutrients degree in soil. Researches conducted recently proved that nutrient stress affects not only the plant's development but the plant's photosynthesis, metabolism, fruit development and their ability to withstand environmental stress (Bao *et al.*, 2024).

What is Nutrient Stress?

Balanced Mineral nutrition is highly important for the growth of plants, development, productivity and resistance to stress. There is a total of seventeen vital nutrients required for the development and growth of the plants. The major macro-nutrients include nitrogen (N), phosphorus (P) and potassium (K) which are essential minerals for the processes such as photosynthesis, metabolism, enzyme activation and reproduction (Ibrahim *et al.*, 2022). When one of these nutrients is not available or becomes exceedingly accessible, it means that the plant is experiencing nutrient stress. The nutrient stress occurring in the kiwi orchards is mainly due to nutrient-poor soils, incorrect fertilizer use, improper irrigation and harsh climate.

Tamana, Garima Vashisth and Sanjeev Kumar
Department of Basic Science, College of Forestry, Dr. YSP UHF, Nauni, Solan, Himachal Pradesh
Rupam Nehta
Department of Fruit Science, College of Horticulture, Dr. YSP UHF, Nauni, Solan, Himachal Pradesh
Ibajanai Kurbah
Department of Soil Science and Water Management, College of Forestry, Dr. YSP UHF, Nauni, Solan, Himachal Pradesh

It should also be noted, that this excess in fertilizers creates nutrient imbalance, makes the fertilizer usage less efficient and causes environmental pollution (Ding *et al.*, 2025).



Figure 1: Overview of NPK deficiency symptoms and their physiological effects in kiwifruit

Major Nutrient Deficiencies in Kiwifruit: Nitrogen is a key nutrient in kiwifruit development as it facilitates the expansion of leaves, the process of chlorophyll production and the creation of proteins. The absence of nitrogen gives the vines light green leaves (chlorosis), weak stems and small fruit. Excess nitrogen on the other hand results in heavy vegetative growth and therefore inhibits flowering or fruit formation. Phosphorus is also important since it enables the growth of roots and flowering. The lack of phosphorus hinders root development and flowering. Potassium is also an important element in the process of enzyme activity, water absorption and sugar transportation in the plant. Potassium deficient vines produce smaller fruits with lower sugar levels and show reduced tolerance to drought stress. The role of Calcium is to assist in the formation of strong cell walls as well as in preserving the firmness of fruits after harvest. Lack of Calcium leads to the weakening of fruit tissues resulting in the faster softening of fruit and a shorter storage period.

Magnesium is important for photosynthesis as it is a vital part of chlorophyll. The deficiency of magnesium is often manifested in interveinal chlorosis, which leads to a decrease in photosynthesis efficiency and limited carbohydrate supply. Among micronutrients, boron is of special importance because it ensures proper flowering, pollen germination, and fruit set. The results of some recent studies imply that excessive boron concentrations might cause oxidative stress in the kiwifruit and impede normal cellular functioning and metabolic processes by stressing the importance of the proper amount of boron in one's diet (Chalchisa *et al.*, 2025).

Environmental Factors that Increase Nutrient Stress: During periods of drought, moisture content in the soil will limit nutrient movement to roots and subsequently affect their uptake. This may cause the vines to show signs of nutrient deficiency, although the soil is in fact rich in nutrients (Bao *et al.*, 2024). Heat also has a negative effect on vine productivity. Heat stress reduces photosynthesis, stimulates respiration and enhances the formation of free radicals, which leads to oxidative injury. This negative change in physiology affects the plant's ability to take up and utilize the nutrients properly, thus having an adverse impact on the quality of fruit and yield as well (Bovio-Zenteno *et al.*, 2026). Waterlogging poses yet another significant problem by initiating oxygen-deprived conditions thereby impairing root function. Root due to poor aeration is unable to absorb essential nutrients which increases vulnerability to

environmental stress endured by the plant. Research conducted on Kiwifruit Vine Decline Syndrome shows that constant root stress as a result of waterlogging and other environmental conditions shuts down nutrient acquisition processes and puts the vines at risk of compromising their overall health (Guaschino *et al.*, 2026).

Effects on Yield and Fruit Quality: The presence of nutrients affects the quality and yield as well as marketability of kiwifruits. A lack of nutrients leads to the production of small fruits and inferior flesh quality due to the particular effect of the lack of nitrogen, potassium and calcium. Water deficiency compounds the problem because it restricts nutrient movement within the plant, resulting in further decrease in quality and weight. Proper nutrition should always be ensured to guarantee the production of high-quality fruits (high levels of vitamins and desirable firmness are among the important facets of quality). It has been shown that when the irrigation regime is combined with effective fertilization, the efficiency of nutrient use is increased, which leads to higher yields and better quality of fruits.

Sustainable Management Strategies: Essential nutrient stress management starts with regular soil testing and leaf analysis to help growers notice nutrient shortcomings before visual signs of deficiency become apparent. Moreover, being able to spot issues early ensures that they can rectify the problem in due time, which helps keep the vine growing vigorously, thus increasing productivity. Fertilizing according to the crop needs is important for avoiding shortages of nutrients and excessive fertilizer usage. The introduction of organic materials like compost also improves soil health. Proper management of irrigation is important for nutrient uptake. Maintaining appropriate soil moisture levels will help ensure the nutrients are absorbed efficiently, while minimizing leaching losses. Precision agriculture technologies such as remote sensing, soil moisture sensors and variable-rate fertilization systems allow farmers to manage nutrients more precisely, efficiently and sustainably. Long-term practices such as using cultivars that tolerate nutrient deficiency and ensuring good growth of healthy root systems provide greater resistance of kiwifruit vines to limitations of nutrients and stresses from the environment.

Future Perspectives

Future research is set to focus more on the molecular processes that allow plants to absorb nutrients, send signals in response to stress and adjust to changing environments. Advances in genomics together with technological improvements in precision agriculture and climate-smart orchard management will help minimize the negative environmental impacts caused by fertilizer use. Another important aspect of research is breeding kiwifruit varieties capable of overcoming nutrient deficiency and environmental stresses. All these improvements will help improve orchard resilience and promote sustainable kiwifruit production.

Conclusion

Nutrient stress continues to impose major

limitations on global kiwifruit production with regard to vine growth, yield, quality of fruit and its subsequent processing being impacted. Nutrient deficiency as well as excessive nutrient supply can have negative impact on normal growth of plants while environmental stresses such as drought, excessive air temperature and water logging can contribute to reduced uptake of nutrients. Use of sustainable nutrient management practices like balanced fertilization, regular monitoring of nutrients in soil and leaves, effective irrigation and precision agriculture techniques are very important for ensuring healthy orchards and high-quality fruits. The research in relation to plant nutrition and stress tolerance will make it possible to develop more effective management techniques which will lead to better results in terms of kiwifruit production in changing environmental conditions.

References

Bao, W. W., Chen, X., Li, R. N., Li, M., Xie, C. J., Dou, M. R., Zhang, K. Z., Wang, J., Gao, Z. X., Liu, Z. D. and Xu, Y. (2024). Comprehensive assessment of drought resistance and recovery in kiwifruit genotypes using multivariate analysis. *The Plant Journal*, 199 (1):100-114.

Bovio-Zenteno, E. M., Jia, T., Nazir, M. F., Dai, L., Xu, J., Zhao, Y., Zou, S. and Huang, H. (2026). Physiological, biochemical and molecular regulatory mechanisms of kiwifruit responses to heat stress: A review and future perspectives. *Plant Stress*, 19: 101209.

Chalchisa, G., Muzahid, A. N. M., … and Li, D. (2025). Kiwifruit sensitivity to boron: impact on physiological and molecular responses. *Frontiers in Plant Science*, 16: 1549854.

Ding, Y., Shang, C., Zhao, L., Jin, S., Li, C., Yin, S. and Ahammed, G. J. (2025). Effects of irrigation and fertilization management on kiwifruit yield, water use efficiency and quality in China: A meta-analysis. *Frontiers in Plant Science*, 16: 1534702.

Guaschino, M., Hargarten, H., Cook, C., Zhang, H., Honaas, L., Somera, T. and Spadaro, D. (2026). Exploring the Root Response to Multiple Stressors: Mechanisms Underlying Kiwifruit Vine Decline Syndrome Development. *Molecular Plant-Microbe Interactions*, 39(3): 489-507.

He, X., Fang, J., Chen, X., Zhao, Z., Li, Y., Meng, Y. and Huang, L. (2019). *Actinidia chinensis* Planch.: A Review of Chemistry and Pharmacology. *Frontiers in Pharmacology*, 10: 1236.

Ibrahim, M., Iqbal, M., Tang, Y. T., Khan, S., Guan, D. X. and Li, G. (2022). Phosphorus mobilization in plant-soil environments and inspired strategies for managing phosphorus: A review. *Agronomy*, 12(10): 2539-2563.

Pranamornkith, T., East, A. and Heyes, J. (2012). Influence of exogenous ethylene during refrigerated storage on storability and quality of *Actinidia chinensis* (cv. Hort16A): *Postharvest Biology and Technology*, 64(1): 1-8

Evaluating the Role of Chemical Herbicides in Contemporary Farming: Yield Optimization, Economic Profitability and Ecological Risks

Vikas Kashyap

Abstract

Unwanted vegetation poses a paramount biological threat to global crop production, competing intensely with cultivated species for key soil nutrients, moisture, solar radiation, and growing space. Integrating synthetic weedicides into contemporary agronomic systems has fundamentally reshaped crop protection by reducing reliance on laborious hand weeding, cutting operational expenditures, and supporting zero-tillage conservation systems. Nevertheless, continuous and improper application triggers substantial ecological friction, including the selection of resistant weed strains, chemical leaching into water tables, and disruption of non-target organisms. This manuscript provides an exhaustive evaluation of herbicide adoption in modern agriculture, exploring agronomic yield gains, key producing and consuming nations, financial efficiencies, environmental trade-offs, and holistic integrated management strategies.

Introduction

Securing consistent food production is an urgent global imperative as human populations approach an estimated 10 billion by mid-century. Achieving food sufficiency despite shrinking cultivable land per capita, changing rainfall regimes, and dwindling water reserves necessitates maximizing harvest efficiency per unit area. Among various biological stresses such as phytophagous insects, fungal pathogens and rodents weed infestations impose the most profound loss on agricultural output, causing potential yield reductions between 30% and 45% in staple cereal and oilseed crops when unmanaged. Traditionally, weed control relied on manual removal, animal-drawn implements, and deep mechanical cultivation.

Although effective, these conventional approaches demand excessive physical labor, consume valuable time, and are increasingly unviable due to escalating agricultural wages and seasonal labor deficits during crucial growth phases. The introduction and commercialization of chemical herbicides in the mid-twentieth century altered agricultural paradgms. Presently, chemical weed control constitutes the largest segment of global plant protection inputs, enabling high-density monocultures, direct-seeded rice (DSR) adoption, and conservation agriculture. Evaluating both the functional advantages and the ecological trade-offs of modern herbicide use is imperative for designing resilient crop management frameworks.

Classification and Biochemical Mechanisms of

Vikas Kashyap
MBA (Agri-Business Management) Student, College of Agribusiness Management, BAU, Sabour, Bihar

Action

Herbicides encompass specialized chemical compounds synthesized to inhibit or eliminate unwanted vegetation by interrupting crucial metabolic pathways. In scientific weed management, chemical formulations are categorized according to several primary parameters:

Timing of Application: Pre-plant incorporated (PPI), pre-emergence (administered prior to crop or weed germination), and post-emergence (applied to actively growing weeds).

Action Selectivity: Selective agents (suppressing specific weed species while sparing the host crop, e.g., 2,4-D, Clodinafop-propargyl) versus non-selective agents (extinguishing all green foliage, e.g., Glyphosate, Paraquat).

Physiological Mode of Action (MoA): Chemicals disrupt target enzymes or cellular machinery:

- ✓ **ALS Inhibitors (e.g., Sulfonylureas):** Inhibit acetolactate synthase, shutting down branched-chain amino acid biosynthesis.
- ✓ **EPSPS Inhibitors (e.g., Glyphosate):** Block 5-enolpyruvylshikimate-3-phosphate synthase, preventing aromatic amino acid generation.
- ✓ **Photosystem II Inhibitors (e.g., Atrazine, Metribuzin):** Arrest photosynthetic electron transfer inside chloroplasts.
- ✓ **Synthetic Auxins (e.g., 2,4-D, Dicamba):** Cause uncontrolled, fatal cell division and vascular collapse.

Global Market Overview: Leading Producers and Consumers

The global crop protection industry is predominantly led by chemical herbicides, spurred by expansive commercial farming, extensive cereal and oilseed cultivation, and widespread cultivation of genetically modified herbicide-tolerant (HT) crops. Primary production facilities are concentrated in major chemical manufacturing hubs, whereas consumption is concentrated in intensive agricultural regions across the Americas, Asia, and Europe.

Top five Herbicide Producing Nations

China: The global leader in agrochemical manufacturing and exports, producing immense volumes of technical-grade active ingredients like Glyphosate, 2,4-D and Paraquat.

United States: A pioneer in novel active ingredient discovery, formulation technology, intellectual property development, and high-tech manufacturing.

Germany: Base of prominent global life science enterprises advancing cutting-edge selective chemistry and environmentally optimized formulations.

India: A premier global hub for cost-effective synthesis and export of off-patent generic herbicides and key chemical intermediates.

Brazil: Maintains substantial synthesis capacity, local formulation plants, and packaging operations tailored to supply its large domestic agriculture market.

Top five Herbicide Consuming Nations:

United States: Top consumer globally, deploying extensive volumes of broad-spectrum and selective herbicides across vast maize, soybean, and cotton landscapes.

Brazil: Driven by intensive tropical cropping systems, double-cropping patterns (Safrinha), and widespread planting of herbicide-tolerant soybean varieties.

China: High consumption fueled by agricultural intensification, rapid rural-to-urban labor migration, and expanding direct-seeded rice adoption.

Argentina: Heavy reliance on non-selective chemical knock-down formulations to sustain vast zero-tillage soybean, corn, and wheat systems.

India: Experiencing accelerated herbicide adoption due to escalating manual labor expenses and a transition toward chemical weed control.

Rank	Leading Producing Countries	Leading Consuming Countries
1	China (Primary Agrochemical Exporter)	United States (Extensive Maize & Soybean Acreage)
2	United States (Advanced Molecular R&D)	Brazil (Continuous Tropical Cropping & Safrinha)
3	Germany (Proprietary Chemistry Innovation)	China (High Crop Intensity & Labor Transition)
4	India (Major Generic Manufacturing Hub)	Argentina (Broad-scale No-Till Soybean Systems)
5	Brazil (Domestic Synthesis & Packaging)	India (Escalating Labor Rates & Mechanization)

Agronomic and Economic Contributions of Herbicides

Yield Optimization and Protection against Competition: The core advantage of chemical weed management lies in rapid, uniform elimination of weed competition during critical early development stages (typically the initial 30 to 45 days post-sowing). Suppressing early competition for soil nutrients, moisture, and photosynthetically active radiation (PAR) allows crop canopies to establish rapidly and achieve maximum yield capacity.

Facilitation of Conservation Tillage and Soil Protection: Non-selective active ingredients (such as Glyphosate and Glufosinate) have enabled the widespread adoption of Zero-Tillage (ZT) and Reduced-Tillage systems. Conventional deep tillage disrupts soil aggregates, accelerates organic matter oxidation, and increases soil vulnerability to wind and water erosion. Chemical vegetation control permits direct seeding into undisturbed stubble, conserving soil moisture, maintaining structure, and promoting carbon sequestration.

Labor Rationalization and Financial Profitability : In smallholder farming economies, manual weeding costs during peak seasons can constitute 35% to 50% of overall variable production expenditure. Applying targeted herbicides significantly decreases human labor requirements while ensuring operational efficiency.

Operational Parameter	Manual / Physical Weeding	Chemical Herbicide Application
Labor Demand (Person-days ha^{-1})	25-40 person-days	1-2 person-days
Operational Speed	Slow (takes several days ha^{-1})	Rapid (covers multiple hectares per day)
Weather Constraints	Constrained by wet or muddy soil	Highly flexible (pre-emergence application possible)
Cost Profile	High ongoing labor cost	Lower input cost per unit area
Soil Impact	High soil disturbance & erosion risk	Preserves soil structure (enables no-till)

Operational Challenges and Ecological Vulnerabilities

Despite undeniable productivity benefits, heavy and continuous reliance on chemical weed control

introduces distinct operational and ecological liabilities:

Selection and Spread of Herbicide-Resistant Biotypes: Repeatedly applying herbicides with identical Modes of Action (MoA) exerts intense selection pressure on weed communities, resulting in the survival and spread of resistant biotypes. Globally, over 500 distinct instances of herbicide-resistant weeds are recorded across major cropping systems. Well-documented cases include *Phalaris minor* resistance to Isoproturon and Clodinafop in wheat-rice systems, and Glyphosate-resistant *Amaranthus palmeri*.

Contamination of Aquatic and Edaphic Ecosystems: Surface runoff and deep leaching carry persistent chemical residues into nearby water bodies and underground aquifers. Active ingredients exhibiting long soil half-lives or high mobility (e.g., Atrazine, Metolachlor) pose toxicological hazards to aquatic organisms, beneficial microflora, and non-target plant communities.

Off-Target Spray Drift and Injury to Non-Target Species: Droplet drift during high-pressure ground or aerial spraying can damage adjoining sensitive crops, natural habitats, and beneficial soil biota. Volatilization under atmospheric temperature inversions allows chemical plumes to travel significant distances, resulting in non-target crop injury.

Sustainable Management: Integrated Weed Management (IWM)

To ensure long-term crop protection while mitigating resistance risks and environmental impact, agricultural production systems must transition from sole chemical reliance toward Integrated Weed Management (IWM).

Mode of Action Diversification: Systematically rotating herbicide classes with varied target sites prevents the development of resistant weed biotypes.

Agronomic & Cultural Controls: Deploying cover crops, competitive crop varieties, higher planting densities, and diversified crop rotations naturally suppresses weed establishment.

Precision Delivery Systems: Employing drone sprayers, sensor-guided spot-sprayers, and smart nozzles reduces total chemical volume applied per hectare by treating weeds selectively.

Bio-herbicides and Plant Allelopathy: Utilizing natural plant extracts (such as Sorgaab from sorghum) and bio-herbicidal fungal preparations (mycoherbicides) as eco-friendly weed control components.

Conclusion

Chemical herbicides remain essential tools in modern agribusiness, offering unmatched efficiency in weed control, preserving crop yield potential, and enabling soil-conserving tillage practices. Nevertheless, unmonitored and continuous reliance on synthetic inputs poses serious threats to agricultural sustainability through herbicide resistance and ecological residues. Achieving long-term agricultural resilience requires balancing chemical precision with cultural, physical, and biological tactics under an Integrated Weed Management framework. By deploying smart application technologies, rotating chemical modes of action, and strengthening farmer advisory networks, the agricultural sector can

maximize economic productivity while preserving environmental health.

References

Acharya, S. S. and Agarwal, N. L. (2022). Agricultural marketing in India (7th ed.). Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi.

Del Buono, D. (2021). Can biostimulants be used to mitigate the effect of anthropogenic climate change on agriculture? It is time to respond. *Science of the Total Environment*, 751: 141763.

Government of India. (2023). Annual Report 2022-23. Ministry of Agriculture and Farmers Welfare, Department of Agriculture and Farmers Welfare, New Delhi.

Heap, I. (2024). The International Herbicide-Resistant Weed Database. Online resource available at: http://www.weedscience.org.

Indian Council of Agricultural Research. (2023). Handbook of Agriculture (8th ed.). ICAR Publications, New Delhi.

Swaminathan, M. S. (1996). Sustainable Agriculture: Towards an Evergreen Revolution. Konark Publishers Pvt. Ltd., Delhi, pp. 232.

Role of Fertilizers in Enhancing Agricultural Productivity: Balanced Nutrition, Economic Yields and Sustainability

Anand Kumar

Abstract

Fertilizers are critical agricultural inputs responsible for sustaining global food security, contributing to nearly 50% of world food production. As soil fertility depletes under continuous intensive cropping, balanced application of primary, secondary, and micronutrients becomes essential to optimize crop productivity and quality. However, imbalanced fertilizer usage particularly skewed Nitrogen-Phosphorus-Potassium (NPK) ratios causes soil degradation, nutrient leaching, and environmental pollution. This article examines the essential role of fertilizers in agricultural productivity, evaluates key nutrient management concepts, highlights modern innovations such as nano-fertilizers and customized blends, and outlines Integrated Nutrient Management (INM) strategies to ensure long-term soil health and economic crop returns.

Introduction

Meeting the food, fiber, and nutritional demands of a global population anticipated to surpass 9.7 billion by 2050 represents a major challe-nge for modern agriculture. With the expanding global population and concurrent reduction of arable land per capita, agricultural growth must rely on increasing yield per unit area rather than spatial expansion. Fertilizers serve as the cornerstone of modern yield enhancement, supplying essential mineral nutrients required for plant metabolism, vegetative biomass accumulation, and grain development. Since the Green Revolution of the 1960s, high-yielding crop varieties (HYVs) have depended heavily on synthetic mineral fertilizers to realize their genetic yield potential. Studies indicate that mineral fertilizers account for approximately 35% to 50% of the increase in crop yields achieved over the past half-century. However, continuous cropping without adequate nutrient replenishment exhausts soil reserves, giving rise to multi-nutrient deficiencies and declining fertilizer response ratios. Re-evaluating fertilizer management through balanced nutrition and sustainable practices is vital to maintain food security while preserving soil biological and chemical integrity.

Essential Plant Nutrients and their Functions

Higher plants require 17 essential elements to complete their vegetative and reproductive life cycles. Mineral fertilizers deliver these elements in plant-available inorganic forms:

Primary Macronutrients (N, P, K): Nitrogen (N) promotes vegetative growth, chlorophyll synthesis, and protein formation; Phosphorus (P) drives root

Anand Kumar
MBA (Agri-Business Management) Student, College of Agribusiness Management, BAU, Sabour, Bihar

development, energy transfer (ATP), and flowering; Potassium (K) regulates stomatal activity, water efficiency, and stress tolerance.

Secondary Macronutrients (Ca, Mg, S): Calcium (Ca) strengthens cell walls; Magnesium (Mg) forms the central atom of chlorophyll; Sulfur (S) is crucial for methionine and cysteine amino acid synthesis and oil formation in oilseeds.

Micronutrients (Zn, Fe, Mn, B, Cu, Mo, Cl): Required in trace amounts, micronutrients act as key enzymatic co-factors. Zinc (Zn) deficiency, for example, is widespread in cereal production systems across India, causing significant yield losses if left uncorrected.

Positive Impacts of Fertilizers on Crop Productivity

Yield Maximization and Cropping Intensity: Fertilizers replenish soil nutrient pools depleted by intensive harvests, allowing multiple cropping sequences within a single calendar year. Strategic top-dressing of nitrogen and basal placement of phosphorus and potassium ensure optimal root architecture, tiller survival in cereals, and improved seed fill capacity.

Enhancement of Input Use Efficiency and Water Productivity: Adequate crop nutrition enhances Water Use Efficiency (WUE). Adequate potassium levels maintain leaf turgor and stomatal regulation during moisture stress, enabling crops to extract subsoil moisture more effectively during dry spells.

Economic Returns and Farm Profitability: Judicious fertilizer application yields favorable Benefit-Cost (B:C) ratios, typically ranging between 2.5:1 and 4.0:1 for major field crops. Balanced fertilization enhances both grain volume and market quality attributes, such as protein content in wheat and oil concentration in mustard.

Nutrient Management Approach	Impact on Soil Health & Yield	Economic & Environmental Outcome
Unbalanced / Excess Urea Usage	Causes soil acidification, NPK imbalance (e.g. 8:2:1), lodging	High nutrient losses (leaching, volatilization), low ROI
Soil Test-Based Fertilization	Optimizes nutrient supply tailored to crop & soil deficit	Reduces input cost by 15-20%, maximizes target yield
Integrated Nutrient Management (INM)	Improves organic carbon, microbial activity & soil structure	Sustains long-term yield, buffers against climate stress
Foliar Nano-Fertilizer Application	Enhances leaf absorption, bypasses soil fixation constraints	High Nutrient Use Efficiency (>80%), minimizes runoff
Customized / Fortified Blends	Delivers balanced macro + micronutrients (e.g. Zincated Urea)	Corrects multi-nutrient deficiencies, improves food quality

Challenges Associated with Imbalanced Fertilizer Use

Despite the benefits of mineral fertilization, improper management and heavy subsidies on specific inputs (such as Urea) have led to severe agronomic and ecological issues:

Skewed NPK Consumption Ratios and Soil Degradation: The ideal national NPK application ratio for India is considered to be 4:2:1. However, in intensively cultivated regions, actual consumption ratios have drifted to 8:3:1 or higher. Over-application of Nitrogen without application of Nitrogen without adequate Phosphorous, Potassium

and micronutrients induces soil acidification, secondary nutrient exhaustion, and declining Partial Factor Productivity (PFP).

Environmental Pollution and Eutrophication: Nitrogen applied as Urea is prone to volatilization ammonia gas (NH_3), denitrification into nitrous oxide (N_2O, a potent greenhouse gas), and nitrate leaching (NO_3^-) into groundwater. Phosphate runoff into surface water bodies causes eutrophication, algal blooms, and oxygen depletion in aquatic habitats.

Modern Innovations and Strategic Management Frameworks

Addressing productivity bottlenecks and environmental risks requires adopting sustainable nutrient delivery technologies and management practices:

The 4R Nutrient Stewardship Framework: Applying the Right Source of nutrient, at the Right Rate, at the Right Time, and in the Right Place to maximize recovery efficiency.

Integrated Nutrient Management (INM): Combining inorganic mineral fertilizers with biofertilizers (e.g., Azotobacter, PSB), organic manures (FYM, compost), and green manure crops (e.g., Sesbania) to improve soil organic carbon and biological fertility.

Nano-Fertilizers and Slow-Release Coatings: Deploying Neem-Coated Urea (NCU) and foliar nano-fertilizers (e.g., Nano Urea, Nano DAP) reduces gaseous loss and surface runoff while increasing Nutrient Use Efficiency (NUE) significantly.

Soil Health Card (SHC) & Precision Farming: Using soil testing services, Leaf Color Charts (LCC), and sensor-guided variable rate applications matches fertilizer inputs to site-specific crop demand.

Conclusion

Fertilizers are indispensable inputs for sustaining agricultural productivity and ensuring national food security. However, transitioning from indiscriminate chemical usage to precision, soil-test-based nutrient management is essential for long-term sustainability. Emphasizing Integrated Nutrient Management (INM), adopting nano-fertilizers, and adhering to the 4R Stewardship principles will enable farmers to achieve higher yield returns, improve soil fertility, and safeguard ecosystems for future generations.

References

Acharya, S. S. and Agarwal, N. L. (2022). Agricultural marketing in India (7th ed.). Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi.

Bumb, B. L. and Baanante, C. A. (1996). World trends in fertilizer supply and demand to 2005. International Food Policy Research Institute (IFPRI), Washington, D.C.

Government of India. (2023). Annual Report 2022-23. Ministry of Agriculture and Farmers Welfare, Department of Agriculture and Farmers Welfare, New Delhi.

Indian Council of Agricultural Research. (2023). Handbook of Agriculture (8th ed.). ICAR Publications, New Delhi.

Ecological Mechanisms for Sustainable Pest Management

Rakholiya T. D. and Meet Dudhatra

Biological control is a natural ecological process in which predators, parasitoids and beneficial microorganisms suppress pest populations through interactions within the ecosystem rather than chemical intervention. By strengthening these natural processes, biological control provides sustainable, long-term pest suppression while conserving biodiversity, ecosystem services and environmental health.

Density-Dependent Biological Control

Density-dependent biological control is an important ecological mechanism in which the effectiveness of natural enemies increases as pest populations become more abundant. As pest density rises, prey or hosts become easier to locate, reducing the time and energy predators and parasitoids spend searching for food. The greater availability of prey also enhances the survival, reproduction and population growth of natural enemies, leading to increased predation and parasitism. This process, known as density-dependent mortality, acts as a natural negative feedback mechanism that suppresses pest populations before they reach outbreak levels or exceed the Economic Injury Level (EIL). For example, outbreaks of aphids in crops rapidly attract and support the multiplication of ladybird beetles (*Coccinellidae*), hoverflies (*Syrphidae*), green lacewings (*Chrysoperla* spp.) and parasitoid wasps such as *Aphidius* spp., which collectively reduce aphid populations through predation and parasitism, often restoring ecological balance without the need for chemical insecticides.

Tritrophic Interactions

Tritrophic interactions represent one of the most sophisticated ecological mechanisms underlying biological control, involving dynamic interactions among plants, herbivorous insects and natural enemies. These responses lead to the production of Herbivore-Induced Plant Volatiles (HIPVs), which function as chemical messengers that attract predators and parasitoids to infested plants. Guided by these volatile cues, natural enemies efficiently locate herbivorous pests and suppress them through predation or parasitism. Tritrophic interactions therefore strengthen ecosystem stability, conserve biodiversity and play a vital role in developing sustainable and ecologically resilient Integrated Pest Management (IPM) systems.

Host-Parasitoid Dynamics

Host-parasitoid dynamics represent one of the most precise and effective ecological mechanisms of biological control, in which parasitoids regulate pest populations through highly specialized interactions with their insect hosts.

Rakholiya T. D. and Meet Dudhatra
Research Scholar, Department of Entomology, College of Agriculture, JAU, Junagadh, Gujarat

Unlike predators, which consume several prey during their lifetime, a parasitoid requires only a single host to complete its immature development. Adult parasitoids are generally free-living insects that feed on nectar, pollen, honeydew, or other carbohydrate sources, whereas their immature stages develop either inside (endoparasitoids) or on the surface (ectoparasitoids) of a host insect. Most economically important parasitoids belong to the orders Hymenoptera (Braconidae, Ichneumonidae, Trichogrammatidae, Encyrtidae and Eulophidae) and Diptera (Tachinidae).

Mechanism of Host Location

The biological control process begins with the female parasitoid searching for a suitable host. Parasitoids possess highly sensitive antennae equipped with olfactory and gustatory receptors that enable them to detect hosts with remarkable accuracy. Host searching involves a combination of chemical, visual and tactile cues.

Major host-location cues include:

- ✓ Herbivore-Induced Plant Volatiles (HIPVs)
- ✓ Kairomones
- ✓ Host frass (faeces)
- ✓ Feeding damage on leaves, stems, or fruits.
- ✓ Host body odours and cuticular hydrocarbons.
- ✓ Honeydew secreted by sap-feeding insects.
- ✓ Host movement, colour, shape and size acting as visual cues.
- ✓ Vibrations and sound produced during feeding in certain concealed hosts.

These cues guide the parasitoid from long distances to the infested plant and finally to the exact location of the host.

Resources Provided by Complex Habitats

Diversified agricultural landscapes provide several ecological resources that are essential for biological control:

Nectar: Supplies carbohydrates that increase the longevity, flight activity and reproductive capacity of adult parasitoids, hoverflies, predatory wasps and lacewings.

Pollen: Provides proteins, amino acids and lipids required for egg production and survival of many beneficial insects.

Alternative prey or hosts: Maintain predator and parasitoid populations when target pests are scarce, ensuring their persistence in the ecosystem.

Shelter and refuges: Protect natural enemies from predators, adverse weather conditions and pesticide exposure.

Overwintering sites: Leaf litter, grasses, hedgerows and woody vegetation provide safe habitats for overwintering adults, pupae, or larvae, enabling early-season colonization of crops.

Favourable microclimate: Diverse vegetation moderates temperature, humidity and wind speed, creating environmental conditions that improve survival and activity of beneficial insects.

Cotton Ecosystem: Flowering plants such as marigold (*Tagetes spp.*), sunflower (*Helianthus annuus*), sesame (*Sesamum indicum*) and coriander (*Coriandrum sativum*) planted along cotton field margins provide nectar and pollen for parasitoids

such as *Trichogramma spp*. and predators including *Chrysoperla carnea* and *Coccinella septempunctata*. These natural enemies effectively suppress *Helicoverpa armigera*, aphids, jassids and white-flies.

Rice Ecosystem: Maintaining grasses and flowering vegetation along rice bunds supports predators such as spiders, dragonflies, damselflies and mirid bugs (*Cyrtorhinus lividipennis*), as well as parasitoids of planthoppers and stem borers. These habitats provide shelter and alternative prey, resulting in improved suppression of brown planthopper (*Nilaparvata lugens*), green leafhopper and yellow stem borer.

Cabbage and Cruciferous Crops: Flowering strips of buckwheat (*Fagopyrum esculentum*), sweet alyssum (*Lobularia maritima*), dill (*Anethum graveolens*) and coriander increase the abundance of parasitoids such as *Cotesia plutellae* and *Diadegma semiclausum*, along with predators like hoverflies and lacewings. Enhanced natural enemy activity significantly reduces infestations of the diamond-back moth (*Plutella xylostella*).

Maize Ecosystem: Intercropping maize with flowering legumes or maintaining vegetated field margins provides nectar and shelter for parasitoids such as *Cotesia marginiventris* and predators including ladybird beetles, lacewings and earwigs. This improves biological control of the fall army-worm (*Spodoptera frugiperda*) and maize stem borers.

Fruit Orchards: Ground cover vegetation and flowering plants in orchards enhance populations of parasitoids, predatory mites, hoverflies, lacewings and ladybird beetles. These beneficial insects naturally suppress aphids, scales, mealybugs, white-flies and spider mites while simultaneously support-ing pollinator diversity.

Ecological Engineering

Ecological engineering is a habitat-based approach to pest management that enhances the natural capacity of agroecosystems to regulate pest populations by creating favourable conditions for beneficial organisms. Instead of relying primarily on chemical pesticides, it focuses on designing cropping systems that provide food resources, shelter, breeding sites and alternative hosts or prey for predators, parasitoids and pollinators. Practices such as planting flowering strips and insectary plants, intercropping, maintaining cover crops, establishing beetle banks and habitat corridors, using banker plant systems and increasing crop diversity improve the abundance, survival, dispersal and reproductive success of natural enemies. By strengthening ecological interactions and promoting biodiversity, ecological engineering enhances biological control, suppresses pest outbreaks naturally. Climate and environmental factors play a crucial role in determining the effectiveness of biological control by influencing the survival and performance of natural enemies. Abiotic factors such as temperature, relative humidity, rainfall and photoperiod directly affect the development, longevity, fecundity, flight activity, host-searching efficiency and seasonal synchronization of predators and parasitoids with

their pest populations. Therefore, conserving a diverse community of climate-resilient natural enemies is essential for ensuring stable and sustainable biological control under changing environmental condition.

Conclusion

Biological control is fundamentally an ecological phenomenon driven by intricate interactions among plants, herbivores, predators, parasitoids and their environment. Strengthening these natural ecological processes not only reduces pesticide dependence but also enhances biodiversity, ecosystem resilience and agricultural sustainability. A deeper understanding of these mechanisms provides the scientific foundation for designing productive, environmentally sound and climate-resilient cropping system.

From Farm Gate to Fair Prices: Addressing Persistent Marketing Constraints

Jyoti Chaudhary, Sarita Devi, Kalpna Thakur and Rajat Singh

Abstract

Marketing of agricultural crops has always been a concern for the farmers. The farmers who put abundant of hard work in the production of crop fails to sell their crop at remunerative prices. Despite the continuous efforts by the government to bring farmers from the vulnerable states and getting fair prices for their produce. There are still pockets left in the country where the farmers are unable to sell their produce directly in the markets and fetch good prices for their produce. There are certain regions in the hilly area of the country where the farmers still depend upon the traders who would come and pick their produce and sell in the markets. Gohar block of Mandi district is one such region where farmer grow vegetables by putting lots of handwork but when it comes to marketing, they depend on traders the region being fragmented land holdings, small lot to sell which would cost them high transportation charges.

Introduction

Despite producing high-quality tomatoes, farmers in Himachal Pradesh's Gohar block continue to lose a significant share of their income because of persistent marketing challenges. Every thousands of farming families invest months of hard work, scarce resources, and considerable financial risk to cultivate one of the region's most important cash crops. Yet, when harvest season arrives, the excitement of a good crop is often overshadowed by a familiar anxiety: Will the market offer a fair price? For most tomato growers in Gohar and adjacent tomato growing villages, the answer depends less on production and more on marketing. Despite producing high-quality tomatoes, farmers often remain price takers rather than price makers. Their dependence on private traders and commission agents has created a marketing system in which producers bear the greatest risks while receiving the smallest share of the consumer's rupee. Every harvesting season, farmers invest heavily in quality seed, fertilizers, plant protection measures, irrigation, and labour with the hope of earning remunerative returns. Yet, when the crop reaches the market, fluctuating prices, dependence on private traders, and inadequate post-harvest infrastructure often reduce their profits. Over the last few decades, the Indian government has launched several schemes to solve the marketing problems of the farmers and to fix how crops are sold. Initiatives like regulated mandis (APMCs), the

Jyoti Chaudhary, Sarita Devi and Kalpna Thakur
College of Horticulture and Forestry, Thunag at Gohar (Gudhari), Mandi, Himachal Pradesh
Rajat Singh
College of Horticulture, Dr. YSP University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh

digital e-NAM platform, Farmer Producer Organizations (FPOs), and agricultural infrastructure funds paired with better rural roads and cold storage were all built with one goal in mind, helping farmers cut out middlemen, reach wider markets, and actually get paid what their hard work is worth. However, the reality on the ground tells a different story. In the hilly regions of Himachal Pradesh, many farmers continue to face serious barriers in marketing their produce. Poor road connectivity, inadequate transportation, limited storage facilities, lack of timely market information, and the highly perishable nature of tomatoes often force growers to sell their harvest immediately after picking. As a result, village traders remain the primary buyers despite offering prices well below those available in regulated wholesale markets.

A Tomato Hub with Untapped Potential

Gohar block has emerged as one of the important vegetable-producing regions of Himachal Pradesh. Besides tomatoes, farmers cultivate potato, peas, cabbage, cauliflower, beans, etc. throughout the year. Tomato cultivation is particularly concentrated in Gram Panchayats such as Naun, Gohar, Shalla, Tunna, and Chail Chowk, along with villages including Kharsi, Moviseri, Taraur, Bailla, Bassa, Majhothi (Devdhar), Kotla, Khunola, and Bassi. The region's favourable climate, fertile soils, and progressive farming practices have enabled growers to achieve excellent productivity and produce tomatoes of superior quality. Yet, success in production has not translated into higher incomes because marketing remains the weakest link in the value chain.

Dependence of farmers on Village traders

Transporting tomatoes to APMC markets involves additional expenses on vehicles, labour, packaging, and loading. For small and marginal farmers harvesting only a few crates, these costs often outweigh the expected gains. Long waiting times at markets, uncertainty about prices, and the risk of returning with unsold produce further discourage them. As enquired from most of the farmers the major issue is taking smaller lots to markets is an expensive affair. Also, farmers are more reluctant to invest their time in visiting the markets and selling the produce themselves as it is a time taking process.



Farmers sorting the produce and packing in the crates



Farmers waiting for traders to sell their produce

Village traders, on the other hand, visit farms and

roadheads directly, purchase tomatoes on the spot, and make immediate cash payments. Although this system offers convenience and saves transportation costs, it comes at a price. Farmers generally receive lower rates than those prevailing in wholesale markets, allowing intermediaries to capture a significant share of the profit.

Lack of awareness and market intelligence: Despite the various efforts of the government the farmers still lagging behind in terms of the price related information and price discovery. One of the most serious challenges is the lack of reliable market information. Most farmers do not know the prevailing wholesale prices before harvesting or selling their produce. Instead, they learn the day's price only when traders arrive in the village. Without access to real-time market intelligence, farmers have little opportunity to negotiate or decide whether transporting their produce to a regulated market would be more profitable. Adding to this uncertainty is the wide fluctuation in tomato prices. During the marketing season, prices ranged from around ₹500 crate^{-1} to as low as ₹250 crate^{-1}. Such sharp variations make farm incomes highly unpredictable and often fail to cover the rising costs of cultivation, harvesting, packaging, and transportation.Since tomatoes are highly perishable and storage facilities remain inadequate, growers have little choice but to sell immediately even when market prices unfavourable.

Strategic directions: Improving tomato marketing in Gohar as well as other hill regions of the state requires coordinated efforts from government agencies, research institutions, and farmer organizations. Better and affordable transportation, village-level collection centres, expanded cold storage facilities, and stronger Farmer Producer Organizations can significantly improve farmers' access to larger markets. Since the small and marginal land holdings and small lot to dispose off at the market yards will remain the unending saga. The only solution to bridge this gap is through creating the marketing cooperatives, Farmers Producers organisations which ultimately provide the farmers the platform to work collectively instead of struggling with these marketing problems individually. Equally important is ensuring that farmers receive real-time market information through digital platforms, mobile applications, and extension services. Training in grading, sorting, packaging and collective marketing can further strengthen farmers' bargaining power, while direct linkages with retailers, processors, and institutional buyers can reduce dependence on intermediaries.

Beyond Production: The farmers of Gohar have already demonstrated that they can produce high-quality tomatoes capable of competing in any market. What they now need is an equally efficient marketing system that rewards their hard work with fair and sustainable returns. Agricultural marketing is no longer simply an economic necessity it is essential for improving rural livelihoods and ensuring that the true value of agricultural production reaches those who create it. When marketing reforms finally bridge the gap between policy and practice.

Tractor Marketing in India: Growth Trends, Strategic Practices and Challenges

Shaurav Kumar

Abstract

India's tractor industry is the largest in the world by unit volume, accounting for nearly one-third of global production (Jain, 2006; Mandal and Maity, 2013). This review examines the growth and organization of the sector, as well as the actual marketing and sale of tractors, by utilising published industry figures and ground-level field research. It examines the long-term trends in domestic sales and exports, the consistent transition to higher-horsepower machines, the way in which market share is distributed among the leading manufacturers, and the factors that legitimately influence a farmer's brand selection. The review also investigates the practical application of rural marketing and the role that government mechanisation initiatives have played. Considering the challenges the business still confronts, such as low tractor penetration in many regions, demand concentrated in a few number of states, and poor dealer customer service. The main contention is that marketing centred around the farmer reliable equipment, accountable dealers, financing that is actually accessible, and advertising that addresses actual purchasing problems rather than just image is necessary for long-term prosperity.

Introduction

In India, tractors play a major role in farm mechanisation (Jain, 2006). Despite fluctuations related to the performance of the monsoon each year, domestic manufacturing started in 1961 with a meagre 880 units annually. Within 50 years, annual output had surpassed 350,000 units, growing at a compound annual growth rate of about 10% (Jain, 2006; Mandal and Maity, 2013; Singh *et al*., 2009). A tractor occupies a unique position in the market since it is both a functional agricultural asset and an expensive durable good whose acquisition depends on loan availability, dealer credibility, and brand reputation. Marketing tractors differs from marketing consumables like fertiliser or seed because of this. Evidence from production and sales data (Singh *et al*., 2009; Singh and Sahni, 2019), broad industry overviews (Bhalla, 2007, 2010), and field studies on consumer behaviour, brand satisfaction, and rural marketing practices (Verma, 2008; Singh *et al*., 2014; Sridevi and Premkumar, 2022) are all combined in this review.

Growth, Scale and Horsepower Trends: Before 1960, every tractor used in the country was imported. By 1997, annual production had crossed 255,000 units, and the national tractor population had passed the two-million mark (Jain, 2006; Singh *et al*., 2009). The industry's growth has never moved in a straight

Shaurav Kumar
MBA (Agri-Business Management) Student, College of Agribusiness Management, BAU, Sabour, Bihar

line it has passed through distinct phases: roughly 16 percent annual growth between 1994 and 1998, a flat stretch through 1999-2001, a contraction of about 13 percent from 2001 to 2003, and then a recovery from 2004 onward, helped along by stronger monsoons and wider access to bank credit (Bhalla, 2007; Jain, 2006). Domestic sales rose from about 241,757 units in 2004-05 to a peak of 633,846 units in 2013-14, working out to an overall compound annual growth rate of 5.83 percent across 2005-06 to 2015-16 (Singh and Sahni, 2019). Exports have generally grown even faster from roughly 20,076 units in 2004-05 to 33,813 units by 2006-07, a 29.78 percent CAGR, and on to 77,485 units by 2015-16, with Sri Lanka, Nepal, and the United States as the main buyers (Bhalla, 2007; Singh and Sahni, 2019). For a long stretch, the 31-40 HP bracket dominated the market, holding about 51 percent of volume in 2005-06 (Jain, 2006; Mandal and Maity, 2013). That picture has since shifted toward more powerful machines: by 2015-16, the 41-50 HP bracket had become the single largest segment at 45.41 percent, overtaking the 31-40 HP range, which had slipped to around 36 percent a change linked to growing demand for custom-hire work and haulage capacity (Singh and Sahni, 2019). At the other end of the scale, the sub-20 HP segment has also begun drawing interest from organised manufa-cturers, as small and marginal farmers move away from relying on bullock carts (Mandal and Maity, 2013).

Market Structure and Brand Competition: For many years, Mahindra and Mahindra (M&M) has dominated the Indian market. In 2007-08, it held 29.48 percent of the all-India share, surpassing TAFE Group at 23.64 percent and Escorts at 14.81 percent (Bhalla, 2010). By 2015-16, its production share had increased to 38.13 percent, with TAFE Group coming in second at 22.79 percent, followed by Sonalika (12.02 percent), Escorts (9.10 percent), and John Deere (8.23 percent) (Singh and Sahni, 2019). However, the true leader is mostly dependent on the region and horsepower segment: In certain years, TAFE Group has outsold M&M in the 31-40 HP range. M&M's strongest position tends to be in the south, west, and east of the country, while Escorts has occasionally led the 41-50 HP segment and Punjab Tractors Ltd. and John Deere have led the above-50 HP category (Bhalla, 2010).

Manufacturer	Approx. Share, 2007-08	Approx. Share, 2015-16
Mahindra & Mahindra	29.48%	38.13%
TAFE Group	23.64%	22.79%
Escorts Ltd	14.81%	9.10%
Sonalika (ITL)	9.75%	12.02%
John Deere India	4.48%	8.23%

Note: Compiled from Bhalla (2010) and Singh and Sahni (2019); figures are approximate and drawn from different reporting bases (unit sales versus production).

Farmer Buying Behaviour and Brand Satisfa-ction: A survey of 150 farmers in the Banswara district of Rajasthan revealed some startling gaps: 72 percent were purchasing a tractor for the first time, and 51 percent were unaware of the horsepower rating of their own tractor. Price was mentioned by just 10% of respondents, while durability (29%) and brand image (28%) both had a significant impact on their choice (Verma, 2008).

Eighty-four percent of purchasers found it easy to secure institutional financing, but the same study also revealed persistent dealer misbehaviour, such as withholding information and directing consumers toward models with higher commissions (Verma, 2008). Using Z-tests and a point-scoring system across fifteen technical factors, a separate satisfaction study of tractor owners in Kotkapura, Punjab, found that Swaraj had the highest owner satisfaction score (24.14 points), followed by HMT (21.56), Mahindra (16.97), John Deere (15.39), and Sonalika (10.22). According to Singh *et al.* (2014), brand preference was strongly correlated with a farmer's age, income, and tractor horsepower but not with their degree of education or the amount of their landholding.

Rural Marketing: The Mahindra Case: Only 45.7% of the 105 tractor users surveyed in Kovilpatti, Tamil Nadu, recognised the Mahindra brand; word-of-mouth was the most common way for people to learn about tractors (47.5%), far more so than television (17.1%) (Sridevi and Premkumar, 2022). Despite the fact that 40% had experienced engine repair issues and 51.4% thought the price was too expensive, 30.8% of respondents cited product quality as the primary reason for their purchase (Sridevi and& Premkumar, 2022). The pattern that shows up here is that a rural buyer's perception of a brand is mostly shaped by dealer behaviour and the machine's actual dependability rather than advertising.

Policy Support and Challenges: Over 90% of tractor purchases have historically been funded by public sector organisations, and government initiatives like the National Food Security Mission (2007), Rashtriya Krishi Vikas Yojana (2007), and Macro Management of Agriculture (2001) have encouraged both custom hiring and mechanisation (Singh *et al.*, 2009; Singh and Sahni, 2019). The availability of farm power increased from 0.48 kW per hectare in 1975-76 to 2.13 kW ha^{-1} in 2015-16, however the percentage of animal power decreased dramatically, from 85.5 percent to 10.6 percent (Singh and Sahni, 2019). Despite these advancements, there is still a significant gap: in order to fully mechanise India's arable land, an estimated 16.4 million tractors would be needed, compared to the country's existing fleet of less than five million (Mandal and Maity, 2013). Additionally, demand is still concentrated in about a dozen states, with Punjab and Haryana already approaching saturation (Bhalla, 2007; Singh and Sahni, 2019). Export growth has been uneven due to competition from used tractors and poor international market-building (Mandal and Maity, 2013). At the retail level, dealer misconduct and uneven after-sales service continue to be issues (Verma, 2008; Sridevi and Premkumar, 2022).

Conclusion

Over the course of four decades, India's tractor industry has grown at a rate of nearly ten percent annually, overcoming slowdowns caused by weak monsoons and tight credit, to become the largest tractor market in the world (Jain, 2006; Mandal and Maity, 2013; Singh *et al.*, 2009).

Durability, brand reputation, dealer behaviour, and word-of-mouth are what really determine marketing success rather than pricing or advertising (Verma, 2008; Sridevi and Premkumar, 2022; Singh *et al*., 2014). The industry's long-term outlook remains positive as long as manufacturers finally close the persistent gaps in dealer transparency and after-sales service. There is still a sizable mechanisation gap to close, policy support for rural finance and custom hiring, and a clear pivot toward both higher-horse-power and compact machines.

References

Bhalla, D. (2007). Tractor market in India: An overview. *Agricultural Engineering Today*, 31(3-4): 54-59.

Bhalla, D. (2010). Tractor industry in India: Market share analysis of various brands of tractors. *Agricultural Engineering Today*, 34(2): 17-32.

Jain, R. C. (2006, November 22-23). *Tractor industry in India: Present and future* [Paper presentation]. Roundtable Forum for Regional Agricultural Machinery Manufacturers and Distributors Associations, Seoul, South Korea.

Mandal, S. K. and Maity, A. (2013). Current trends of Indian tractor industry: A critical review. *Applied Science Reports*, 3(2): 132-139.

Verma, R. (2008). A study on factors influencing buying behaviour of tractor customers in Banswara district of Rajasthan. *Journal of Global Economy*, 4(3-4): 234-248.

Singh, R. S. and Sahni, R. K. (2019). Transformation of Indian agriculture through mechanization. *Economic Affairs*, 64(2): 297-303.

Singh, S., Singh, D. and Sahni, K. (2014). Customer satisfaction survey for various brands of tractors: A case study. *International Journal of Engineering Research & Technology*, 3 (7): 89-92.

Singh, S. P., Singh, R. S. and Singh, S. (2009). Tractor production and sales in India. *Agricultural Engineering Today*, 33(1): 20-32.

Sridevi, R. and Premkumar, S. (2022). The study of rural marketing strategies of Mahindra tractors. *International Journal of Advances in Engineering and Management*, 4(5): 2789-2793.

A Comprehensive Review of Precision Farming in Agribusiness Management

Nikhil Chopra

Abstract

Precision farming has shifted agribusiness to a data-driven model, prompting inquiry into technology economics, supply-chain design, and regulation. This review discusses key technologies like satellite guidance, remote sensing, IoT, variable rate application, UAVs, and AI decision support, assessing their regulatory impact in the EU, US, and India. Evidence from regions including the US Corn Belt and smallholder systems in Africa reveals a gap between large commercial farms and resource-poor smallholders. The review advocates for agribusiness strategies that integrate appropriate technology, service-based models, and transparent data governance to achieve equitable and sustainable results.

Introduction

Agriculture is under pressure to enhance productivity while minimizing environmental impact. Precision farming utilizes positioning systems, remote sensing, and data analytics to customize inputs for specific areas of a field, reflecting a management philosophy rather than merely a set of tools. The global precision agriculture market is expected to exceed ten billion USD by 2025, with growth of nine to thirteen percent annually due to falling technology costs and government initiatives, particularly in places like India. However, adoption is uneven, with satellite guidance widely used on large farms, while advanced technologies like variable rate systems still have limited reach. This review discusses three main areas: the technology stack of precision farming, regulatory frameworks around agricultural data, and case studies illustrating the interaction of technology and policy. Precision farming is viewed as a toolkit for farmers and policymakers, with rapidly diffusing technologies like satellite guidance contrasted against slower-adopting ones like integrated variable rate systems.

Core Technologies and Components of Precision Farming

Precision farming employs a multi-layered technology stack, consisting of positioning and data-acquisition tools at the field level, aggregation and analytics platforms in the middle, and management actions that implement insights into farm operations. A summary table outlines the main technology segments, their functions, and typical users.

Geospatial and Guidance Technologies: GNSS guidance and autosteer systems are leading precision technologies in commercial agriculture, dominating hardware revenue in North America.

Nikhil Chopra
MBA (Agri-Business Management) Student, College of Agribusiness Management, BAU, Sabour, Bihar

Table 1: Geospatial and Guidance Technologies

Technology Segment	Primary Function	Typical Adopter	Adoption Stage
GNSS/GPS guidance & autosteer	Reduces overlap in tillage, seeding and spraying passes	Large commercial farms	Mature
Variable Rate Technology (VRT)	Applies seed, fertiliser or chemical at site-specific rates	Medium-to-large mechanised farms	Growing, rarely exceeds one-fifth of farms globally
Remote sensing (satellite/drone imagery)	Monitors crop vigour, nutrient stress and pest incidence	All farm sizes via service providers	Rapidly scaling
IoT soil/weather sensors	Streams real-time soil moisture, temperature and weather data	Horticulture and irrigated cropping	Early-to-mid
Agricultural drones (UAVs)	Precision spraying, mapping and crop-health imaging	Custom Hiring Centres, FPOs, service providers	Early, subsidy-driven
AI/ML decision-support platforms	Converts sensor and imagery data into actionable farm advisories	Agri-tech intermediated smallholders and enterprises alike	Early, high growth trajectory

Table 2: Comparative overview of the regulatory and policy frameworks governing precision agriculture

Feature	European Union	United States	India
Core philosophy	Data governance via collective code of conduct	Market-led, technology-neutral innovation	State-built digital public infrastructure
Key instrument	EU Code of Conduct on Agricultural Data Sharing (2018); EU Data Act (2024)	FAA Part 107 (drones); voluntary industry data-privacy principles	Digital Agriculture Mission / AgriStack; Kisan Drone Scheme under SMAM
Data ownership stance	Farmer recognised as originator and controller of raw farm data	Contractual, platform-specific; limited statutory guidance	Farmer registries and consent layers built into public registries
Adoption support	Common Agricultural Policy eco-schemes reward precision input use	Private OEM financing and dealer-led extension (John Deere, Trimble)	Capital subsidies (up to 100% for institutions), Custom Hiring Centres, FPO-based rental models
Principal constraint	Non-binding code leaves enforcement and cross-border consistency weak	Uneven adoption between large commercial farms and small operations	High per-unit hardware cost relative to average landholding size

They effectively reduce overlap and skip in tillage, planting, and spraying, leading to significant savings in fuel, seed, and chemicals, which contributes to their rapid adoption.

Remote Sensing and Variable Rate Technology: Satellite and drone-based remote sensing allows for efficient monitoring of crop health, nutrient levels, and pest threats over extensive areas without intensive scouting. When integrated with Variable Rate Technology (VRT), which adjusts the application rates of inputs based on specific field zones, it optimizes resource use. However, VRT adoption remains limited to about 20% of farms, even in developed agricultural sectors, due to the necessary investment in equipment, software, and specialized knowledge.

IoT Sensors, Drones and AI-Based Decision Support: IoT sensor networks provide real-time measurements of soil moisture, temperature, and micro-climate variables, utilizing cloud platforms enhanced by AI and machine learning for actionable insights. Agricultural drones further this function-ality with precision spraying, crop-health imaging, and efficient field mapping, significantly reducing the time required for manual scouting. In India, government initiatives have made drones accessible to smallholder farmers by subsidizing costs and supporting Custom Hiring Centres, allowing farmers

to utilize this technology without capital expenditure.

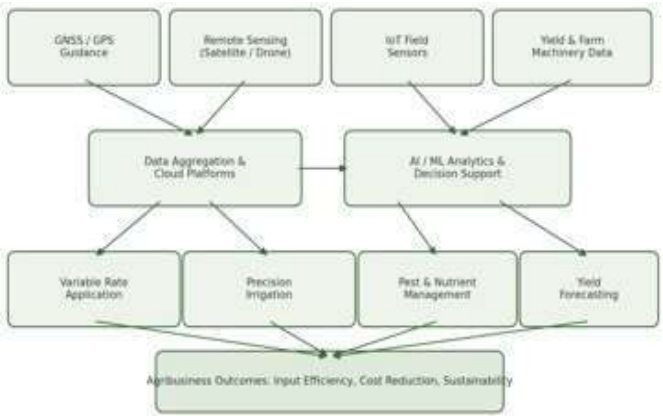


Fig. 1: Data-to-Decision Framework Linking Precision Farming Technologies to Agribusiness Outcomes. Sources: Illustrated by the author based on literature review.

Regulatory and Policy Frameworks Governing Precision Agriculture

Precision farming relies on ongoing farm-level data collection and exchange, making the regulatory framework around this data critical for its adoption. The literature identifies three main institutional models: the EU's negotiated code-of-conduct, the US's market-led contractual approach, and India's state-built digital public infrastructure.

Case Studies in Precision Farming Adoption

Variable Rate Technology in the United States Corn Belt: Studies indicate that guidance and autosteer technologies are adopted rapidly in grain-producing states, while Variable Rate Technology for seeding, nitrogen, and crop protection spreads more slowly due to its dependence on soil variability and farmers' data interpretation skills. Adoption tends to be higher among larger operations that can amortize costs over larger areas.

Smallholder Drone and Sensor Adoption in India: Field research in Punjab and other Indian states finds GPS-guided equipment, sensors, and drones adopted only gradually, with cultivators hesitant due to unfamiliarity and uncertain payback on small plots. Economic analyses of drone-based spraying nonetheless report cost savings and yield gains, and programmes such as Namo Drone Didi, which equips women-led self-help groups with drones and training, show how service-based delivery bridges the gap between smallholder economics and precision technology's capital intensity.

Barriers Facing Smallholders in Sub-Saharan Africa: Survey research in Nigeria's Oyo State reveals that precision agriculture adoption is linked to increased net farm income, despite challenges like high initial costs and technical knowledge gaps. A wider review in Kenya, Ghana, Ethiopia, and Pakistan highlights similar issues with awareness, credit access, and compatibility, indicating that successful technology transfer requires simultaneous investment in training and financing.

Supply Chain, Sustainability and Risk Management Implications

Precision farming is transforming the agribusiness supply chain by encouraging input suppliers to focus on analytics and advisory services. Equipment manufacturers are moving towards subscription-based software and cloud analytics, enhancing machinery sales. However, this approach increases operational risks due to reliance on continuous data connectivity. Managers must be prepared for potential breakdowns in data pipelines by having alternative agronomic guidance.

Sustainability benefits of precision farming include reduced use of fertilizers, water, and chemicals, aligning with stricter regulations like the EU's Common Agricultural Policy. Nevertheless, the environmental impact of the technology used, such as energy consumption and e-waste, is often overlooked in sustainability evaluations at the farm level.

Strategic Recommendations for Agribusiness Managers

Strategic priorities for agribusiness managers and policymakers to promote precision farming include:

- ✓ Emphasizing service-based delivery models, like Custom Hiring Centres and drone rentals, to serve smallholder markets.
- ✓ Investing in transparent, farmer-centered data governance to foster trust in data-sharing.
- ✓ Aligning technology with the scale and cropping system of farms, prioritizing low-cost tools for smallholders.
- ✓ Establishing public-private partnerships for shared digital infrastructure to enhance innovation while maintaining farmer data control.

Conclusion

Precision farming has evolved into a significant segment of global agribusiness, though its advantages are not uniformly accessible. While guidance systems are widely adopted across various farm sizes, technologies like Variable Rate Technology and AI decision-support tools remain predominantly with larger operations. Different regulatory frameworks in the EU, the US, and India influence the balance between fostering innovation and protecting farmers. Evidence from regions such as the US Corn Belt, Punjab, and smallholder systems in Nigeria indicates that the main barrier to wider adoption is not the technology itself, but rather the surrounding economic and institutional support, including financing, training, and data governance.

References

Assessing the economic and data management impacts of precision agriculture among smallholder farms in Nigeria. (2025). *Fountain Journal of Natural and Applied Sciences*.

Dah John, Hussin, N., Shahibi, M. S., Ahmad, M., Hashim, H. and Ametefe, D. S. (2023). A systematic review on the factors governing precision agriculture adoption among small-scale farmers. *Journal of Agricultural Extension and Rural Development*. https://doi.org/10.1177/00307270231205640

Lowenberg-DeBoer, J. and Erickson, B. (2019). Setting the record straight on precision agriculture adoption. *Agronomy Journal*, 111 (4): 1552-1569.

Press Information Bureau, Government of India. (2023). *Kisan Drone Scheme under the Sub-Mission on Agricultural Mechanization*.

The farm-level economic and environmental benefits of precision agriculture technology adoption: A meta-analysis of global evidence. (2025). *Sustainability*, 17(24), Article 11223.

The Digital Revolution in Agri-Input Marketing: Transforming Seed, Fertilizer and Crop-Protection Supply Chains

Sahil Siddharth

Abstract

From manufacturer to dealer to farmer, agricultural input marketing which includes seeds, fertilisers, crop-protection chemicals, and farm equipment has historically travelled through lengthy, intermediary-heavy chains. India and other developing agricultural economies have seen a structural change in the marketing and sales of these inputs over the past ten years due to the proliferation of inexpensive cellphones, low-cost mobile data, and government-backed digital infrastructure. The drivers of the digital revolution in agri-input marketing, the main platform models (B2C, B2B, and hybrid advisory-commerce), and its effects on pricing transparency, input authenticity, and farmer income are all examined in this article. It also addresses enduring obstacles, such as digital literacy, last-mile logistics, and trust deficiencies, and describes tactical solutions, such as public digital infrastructure, phygital (physical plus digital) retail models, and vernacular-language interfaces, that can make this shift more inclusive and sustainable.

Introduction

For many years, Indian farmers have purchased seeds, fertilisers, crop-protection products and other farm inputs mainly through local dealers. These dealers not only supplied agricultural inputs but also guided farmers in selecting suitable products for their crops. Although this traditional system served farmers well for many years, it often resulted in limited product choices, price differences and the availability of counterfeit inputs in some regions. Over the last decade, however, the rapid growth of smartphones, affordable internet services and government-supported digital initiatives has transformed agri-input marketing. Farmers can now compare products online, receive expert crop advisory services and order quality agricultural inputs directly through digital platforms. This digital transformation is making the agri-input supply chain more transparent, efficient and accessible for farmers across India. The digital transformation of agri-input marketing is not only changing the way agricultural inputs are sold but also improving the entire supply chain. It has increased price transparency, strengthened connections between farmers and input companies, and made crop advisory services more accessible. This article discusses the major drivers of digital transformation, different digital platform models, their benefits, existing challenges and the future prospects of digital agri-input marketing in India.

Drivers of Digital Transformation in Input Marketing

Sahil Siddharth
MBA (Agri-Business Management) Student, College of Agribusiness Management, BAU, Sabour, Bihar

Connectivity and Device Penetration: Millions of first-time rural users have joined the internet thanks to the sharp decline in mobile data prices since 2016 and the quick proliferation of low-cost smartphones. The number of smartphone users in rural India is expected to continue growing in the coming years, further supporting the adoption of digital agricultural services.

Digital Public Infrastructure: Government initiatives such as BharatNet, the Unified Payments Interface (UPI) and the Digital Agriculture Mission have created a strong digital foundation for agri-input marketing. These initiatives have improved internet connectivity, digital payments and farmer data management, making it easier for digital agri-input platforms to serve farmers across the country.

Private Capital and Start-up Activity: A number of agri-input and full-stack agritech startups have raised tens of millions of dollars in recent fundraising rounds to increase catalogue depth and last-mile logistics thanks to sustained venture capital interest.

Changing Farmer Expectations: Farmers' demands for price transparency, doorstep delivery, and after-sale responsibility have increased due to exposure to e-commerce in other industries; many traditional dealer networks are still unable to provide all these services efficiently.

Platform Models Reshaping the Input Value Chain

Direct-to-Farmer (B2C) Marketplaces: These platforms allow farmers to buy seeds, fertilisers and crop-protection products directly through mobile apps or websites while also providing crop advisory services. Founded in 2015, BigHaat is a farmer-focused digital marketplace that connects millions of farmers with agricultural input companies. The platform also helps companies understand farmers' demand and market trends. AgroStar reports involvement with several million farmers in places including Rajasthan, Uttar Pradesh, Maharashtra, and Madhya Pradesh. Its services are delivered through a combination of a farmer app, advisory centres and Saathi partner stores.

Business-to-Business (B2B) Wholesale Platforms: A second model digitises the upstream portion of the supply chain and focuses on the retailer instead of the farmer. By connecting thousands of rural retailers who in turn serve millions of farmers directly with manufacturers, AGRIM, for example, runs a marketplace that carries tens of thousands of stock-keeping units across seeds, pesticides, fertilisers, and equipment. This reduces unnecessary intermediaries, making the supply chain faster and more cost-effective.

Full-Stack Advisory-Commerce Platforms: Another rapidly growing model combines input supply with advisory services, credit and market linkages on a single platform. Founded in Bihar in 2012, DeHaat currently serves thousands of institutional purchasers and several hundred Farmer Producer Organisations, providing farmers in twelve agrarian states with millions of dollars' worth of combined advising, input, and market-linkage services. These platforms provide farmers with agri-

Table 1: Traditional versus Digital Agri-Input Marketing

Feature	Traditional Input Marketing	Digital Input Marketing
Market Reach	Limited to local dealer catchment area	Pan-regional/national reach via apps and web platforms
Price Discovery	Opaque, dealer-set, negotiated locally	Transparent, listed, comparable across sellers
Advisory Support	Informal, dealer-driven, product-biased	Data-based agronomy advice bundled with sale
Product Authenticity	Risk of spurious/counterfeit inputs	Traceable sourcing, verified sellers, digital invoices
Payment	Predominantly cash, informal credit	UPI, digital wallets, embedded agri-finance
Order & Delivery	Walk-in purchase, farmer bears logistics	Home/village delivery through logistics network
Data Generation	Negligible; no demand forecasting	Rich behavioural and agronomic data for manufacturers

cultural inputs, crop advisory, financial support and market linkages through a single digital platform.

Public Digital Marketplaces: In terms of output, more participating farmers can now reach consumers outside of their local market thanks to the government-run Electronic National Agriculture Market (eNAM), which has connected over a thousand mandis in most states. Although eNAM mostly deals with the selling of food rather than the purchase of inputs, it serves as an example of the wider normalisation of digital transactions in rural commerce and has indirectly increased farmer familiarity with app-based trading. This growing familiarity with digital platforms has also encouraged farmers to adopt digital agri-input services.

Benefits for Agribusiness Value Chains

Price and Quality Transparency: Online price lists and seller ratings help farmers compare products from different sellers and make better purchasing decisions. This also reduces the chances of unfair pricing and fake products.

Reducing Spurious Inputs: Digital invoices, verified sellers and product traceability help farmers identify genuine agricultural inputs. These measures reduce the risk of counterfeit seeds and fake crop-protection products entering the market.

Demand Forecasting for Manufacturers: Digital platforms help companies analyse farmers' purchasing patterns and cropping trends. This allows manufacturers to plan production and distribution more efficiently, reducing both shortages during the sowing season and excess inventory after the season.

Bundled Financial Access: Many digital platforms now provide short-term credit for farmers and working capital support for retailers. This helps farmers purchase quality agricultural inputs on time, even when they face temporary financial constraints.

Extension and consultancy at Scale: AI-based crop advisory services provide farmers with timely recommendations on crop management through the same digital platforms used to purchase agricultural inputs. This makes expert guidance more accessible and convenient.

Persistent Challenges and Constraints

The Residual Digital Divide: In 2025-2026, the rural internet subscriber density was just over 48 per 100 people, indicating that around half of the rural population still lacks regular access to the internet despite quick improvements. The effective user base of these platforms is further reduced by digital literacy, gaps in vernacular-language content, and lower smartphone ownership among female farmers. This could lead to a two-tier input market where better-connected, better-resourced farmers profit

disproportionately.

Last-Mile Logistics and Cost: It is still logistically costly to deliver heavy, low-margin and occasionally time-sensitive goods like fertiliser bags to scattered settlements, and local offline merchants continue to compete on price with digital platforms.

Grievance Redressal and Trust: Farmers who are used to dealing with a reputable local vendor who can be held directly responsible for a subpar batch of seed are frequently reluctant to transfer high-stakes purchases to an anonymous online vendor, especially when refund or replacement procedures are ambiguous or take a long time.

Disjointed Regulation: Digital agri-input commerce currently lacks a specific legal framework, leaving issues of platform liability, data ownership, and dispute resolution mostly unresolved, in contrast to the strictly regulated certification regimes governing seed selling itself.

Strategic Way Forward

Phygital Retail Models: By combining a digital ordering back-end with a reliable local pickup location, like the Saathi shop or DeHaat Center models, farmers can maintain the accountability they cherish while also utilising the efficiency and reach of digital ordering.

Vernacular, Voice-First Interfaces: By offering ordering and advice via regional-language voice assistants and WhatsApp-based tools, elderly and less literate farmers can join the digital world without needing to be fluent in the app.

Interoperable Public Digital Infrastructure: Lowering onboarding costs for both smaller platforms and cooperatives can be achieved by building input marketing on top of shared rails, such as AgriStack farmer records and UPI payments, instead of closed proprietary systems.

FPO-Led Aggregation: By using Farmer Producer Organisations to route digital input procurement, small landholders can jointly access platform loans and bulk prices, thereby mitigating the scale disadvantage that individual smallholders experience.

Light-Touch Regulatory Oversight: Without requiring EU-style pre-market certification, a minimum threshold for seller verification, return policy disclosure, and traceability on agri-input marketplaces would maintain market entry while shielding farmers from fake inputs.

Conclusion

Digital technologies are transforming agri-input marketing in India by making agricultural inputs more accessible, transparent and efficient. Farmers today can compare products, receive expert crop advice and purchase quality inputs through digital platforms. At the same time, challenges such as the digital divide, last-mile delivery and farmers' trust still need to be addressed. With better digital infrastructure, supportive government policies and active participation of agribusiness companies, digital agri-input marketing has the potential to improve farmers' livelihoods and contribute to the sustainable growth of Indian agriculture.

References

AGRIM. (2024). Series B funding round announce-

ment. As cited in Decentro. (2026). *17 top agritech startups in India in 2026*. https://decentro.tech/blog/agritech-startups/

AgroStar. (2026). *Company platform overview*. https://agrostar.in/

ANI. (2026, July 29). Rural internet penetration rises to 48.31 per 100 population under National Broadband Mission 2.0: Govt. https://aninews.in/news/business/rural-internet-penetration-rises-to-4831-per-100-population-under-national-broadband-mission-20-govt20260729141959/

Deccan Herald. (2024, September 9). Rise of digital farming in India. https://www.deccanherald.com/dhie/social-studies/2024/09/09/rise-of-digital-farming-in-india

Decentro. (2026). 17 top agritech startups in India in 2026. https://decentro.tech/blog/agritech-startups/

Foreign Affairs Forum. (2026, June 23). The digital village: How smartphones and artificial intelligence are remaking rural India. https://www.faf.ae/home/2026/6/23/the-digital-village-how-smartphones-and-artificial-intelligence-are-remaking-rural-india

NITI Aayog Frontier Tech. (2025, December 4). DeHaat's AI-enabled agriculture network driving market access and efficiency for 1.8 million farmers. https://frontiertech.niti.gov.in/story/dehaats-ai-enabled-agriculture-network-driving-market-access-and-efficiency-for-1-8-million-farmers/

Shah, B. A. (2025). Digital transformation in agricultural marketing: Advancing India's agri-trade ecosystem. *IBMRD's Journal of Management & Research*. https://ibmrdjournal.in/index.php/ibmrd/article/view/174290

StarAgri. (2026). Digital agri-commerce in India: The rise of tech-driven trading. https://www.staragri.com/digital-agri-commerce-in-india-the-rise-of-tech-driven-trading/

Microgreens: The Green Revolution on Your Plate

Sarvesh Kumar Sen and Kalyan Barman

Introduction

With global population touching sky high numbers, there a huge and growing demand for a more sustainable, accessible and nutritious food supply. Urban farming, especially controlled environment agriculture such as vertical farming, greenhouses, hydroponics, aquaponics have made quit a commendable progress not only in government but also in private sectors. Despite significant advances in agricultural techniques, malnutrition and micronutrient deficiencies remain the major widespread problem affecting billion of people worldwide. Rapid urbanisation and climate change with shrinkable arable land and increasing pressure on natural resources further complicate the ability of conventional food system to supple adequate quantities of nutritious food. Food is necessary to sustain human growth, development and survival by providing calories and essential nutrients. The contemporary field of food science and nutrition mirrors human evolution and advances have come about with the injection of information from various discipline such as medicine, biology and biochemistry. At present, nutrigenomics and nutrigenetics approaches have been used to advance research in this area. The change in this paradigm is a result of an accumulation of many years of scientific-based efforts.

Keeping this in mind, increased interest in understanding the various aspect of microbiome and its influence on individual health that leads to health promotion. Although the precise mechanism remains unclear, consumer interest in health promotion has been the driving force for healthier food with health enhancing properties. In this context new foods such as microgreens have emerged as food sources with ample of health benefits.

What are microgreens?

Microgreens are the young, tender seedlings of vegetables, herbs, cereals and legumes harvested shortly after germination have emerged as a promising functional food due to their exceptional nutritional profile and ease of production. On an average they are harvested within 10 to 14 days from seedling. Size varies from 1 to 3 inches. Microgreen consist of three parts including a central stem, cotyledon leaf or leaves and a pair of young true leaves. However, not all young vegetable greens are considered microgreens. Microgreens are different from baby greens in size and microgreens are harvested later than sprouts. Harvest time is primary distinction between sprouts, baby greens and microgreens. Baby greens are harvested at 2-4 inches spanning from 15 to 40 days whereas microgreens are picked as soon as their youngest leaves emerges. Additionally, the composition of sprouts can be used to distinguish them from microgreens.

Sarvesh Kumar Sen and Kalyan Barman
Department of Horticulture, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh

Table 1: Twenty-Five Commercially Grown Microgreens

Commercial name	Family	Genus and Species	Plant colour
Arugula	Brassicaceae	*Eruca sativa*	Green
Bull's blood beet	Chenopodiaceae	*Beta vulgaris*	Reddish green
Celery	Apiaceae	*Apium graveolens*	Green
China rose radish	Brassicaceae	*Raphanus sativus*	Purplish green
Cilantro	Apiaceae	*Coriandrum sativum*	Green
Garnet amaranth	Amaranthaceae	*Amaranthus hypochondriacus*	Red
Golden pea tendrils	Fabaceae	*Pisum sativum*	Yellow
Green basil	Lamiaceae	*Ocimum basilicum*	Green
Green daikon radish	Brassicaceae	*Raphanus sativus* L.*var. longipinnatus*	Green
Magenta spinach	Chenopodiaceae	*Spinacia oleracea*	Red
Mizuna	Brassicaceae	*Brassica rapa ssp. Nipposinica*	Green
Opal basil	Lamiaceae	*Ocimum basilicum*	Greenish purple
Opal radish	Brassicaceae	*Raphanus sativus*	Greenish purple
Pea tendrils	Fabaceae	*Pisum sativum*	Green
Peppercress	Brassicaceae	*Lepidium bonariense*	Green
Popcorn shoots	Poaceae	*Zea mays*	Yellow
Nutrient purple kohlrabi	Brassicaceae	*Brassica oleracea* L. *var. gongylodes*	Purplish green
Purple mustard	Brassicaceae	*Brassica juncea* L. *Czern*	Purplish green
Red beet	Chenopodiaceae	*Beta vulgaris*	Reddish green
Red cabbage	Brassicaceae	*Brassica oleracea var. capitata*	Purplish green
Red mustard	Brassicaceae	*Brassica oleracea* L. *Czern*	Purplish green
Red orach	Chenopodiaceae	*Atriplex hortensis*	Red
Red sorrel	Polygonaceae	*Rumex acetosa*	Reddish green
Sorrel	Polygonaceae	*Rumex acetosa*	Green
Wasabi	Brassicaceae	*Wasabia japonica Matsum*	Green

A sprout is made up of a stem, root and seed. On the other hand, microgreens are harvested without their roots. Microgreens are characterised to have delicate textures and unique flavours since they grow for a different amount of time. Another salient feature of microgreens is their range of hues. As a result, microgreens are used as a garnish for sandwiches, salads, soups and dishes. According to the local industry, in early 1980s, chefs in San Francisco, California, began using microgreens. Initially, there were not many varieties offered. Those available includes arugula, basil, beets, kale and cilantro. A study reported that there are 25 microgreens that are been commercially cultivated and consumed.

Cultivation, harvesting and marketing of micro-greens

A range of premium microgreens are grown on a commercial scale and occasionally people cultivate them on a smaller scale for domestic consumption. The growers also cultivate micro-greens in a mixed manner. One of the most crucial production methods for success is to have the right mix of microgreens at the right time of harvest. From seedling to harvest, each crops have a very different time frame. In order to harvest the full crop at once, growers are choosing crops with comparable growth rates while growing a variety of crops. Moreover, few farmers seed different crops separately and combine them after harvest. Depending on the need, microgreens can also be grown in containers, window sill and garden beds. Keeping in mind standard, sterile, loose, soil and many mixes they are

grown successfully with peat, vermiculite, perlite and bark. Seeding for microgreens either done in rows or as a broadcast method. Most growers seeding thickly as possible to maximise its production but not too thick because crowding encourages elongated stems and increases the risk of various diseases. Most crops require little or no fertilizer, as the seed provides adequate nutrition for the young crop. However, the application of various types of fertilizers particularly organic one mostly increases the yield of microgreens. Microgreens are harvested when the desired height is attained and first set of cotyledon leaves appear. These are ready for harvest when they reach the first true leaf stage, usually at about 5 cm tall and also depends on the type of crop. The time from seeding to harvest greatly varied for crops from 1 to 3 weeks. Harvested microgreens are highly perishable and are washed, cooled as quickly as possible using good handling practices for food safety. These are usually packed in polyethylene packages and cooled to recommend temperatures before supplying to the market or consumers. Microgreens are available in vegetable markets and grocery stores in umber of packaging materials, storage conditions and usually displayed under light. The effect of light exposure on quality and phytochemical concentrations of different vegetables has been studied extensively. Low-intensity fluorescent light increased fresh weight loss of Chinese kale, but prevented the loss of vitamin C during storage observed that continuous light exposure prevented loss of ascorbic acid and was beneficial in enhancing the amounts of carotenoids and tocopherols of baby lead spinach (*Spinacia oleracea* L.) it has been also reported that light exposure could cause detrimental effects on produce quality, so proper conditions are also necessary at market outlets to maintain the quality of microgreens.

Shelf life

Consumer awareness of microgreens distinctive colour, rich flavour and concentrated bioactive chemicals have led to a steady increase in their consumption in recent years. However, because of their short shelf life and quick decline in product quality, industrial production and marketing are constrained. Microgreens had a relatively short shelf life at room temperature due to their delicate and immature tissue structure. Perishable items have a short shelf life because of their quick post-harvest deterioration, which is determined by the crop. Due to the abrupt disruption of plant growth at a very early stage, they have a very short shelf life and are soon approaching the senescence stage after harvest. It has been demonstrated that rapid physiological, biochemical and molecular changes take place during leaf senescence. Since microgreens are harvested at the cotyledon stage, this process can result in degradation of the primary product. Lowering the temperature can result in slower respiration, which is directly related to a slower rate of cellular metabolism. The majority of fruits, vegetables and cut greens have been shown to exhibit this alteration of plant metabolic activity. Low temperatures cause slower metabolic rates, which

affect visual quality and can extend shelf life.

Bioactive components

Compared to mature plants or seeds, micro-greens have been discovered to contain higher concentrations of concentrated active chemicals. Because they are abundant in vitamins, trace elements, amino acids, antioxidants and other nutrients, they are highly prized for their health advantages. For instance, red cabbage microgreens had the highest concentration of vitamin C, while green daikon radish microgreens had the most vitamin E. Broccoli microgreens contain about 50 times more sulforaphane by weight than mature broccoli. Different microgreens vary in amounts of vitamins and carotenoids. Total ascorbic acid content ranges from 20.4 t0 147.0 mg/100 g fresh weight (FW), while B-carotene, lutein/zeaxanthin and violaxanthin concentrations ranged from 0.6 to 12.1, 1.3 to 10.1 and 0.9 to 7.7 mg/100 g FW. While as alpha-tocopherol and gamma- tocopherol ranged from 4.9 to 87.4 and 3.0 to 39.4 mg/100g g FW. Of the 25 microgreens examined, red cabbage, cilantro, garnet amaranth and green daikon radish had the highest levels of ascorbic acid, carotenoids, phylloquinone and tocopherols, respectively.

Future research prospective

There exists significant potential for cultivating microgreens from a range of crops to meet market demand. When coupled with the past advances, future development will contribute deeper understanding into the overall microgreens production and productivity. The microgreens are emerging fields with promising opportunities for the future research, driven by rising consumer demand. Selecting the types of crops, optimal harvesting methods and ensuring market readiness will be crucial for the industry's success. Progress in developing techniques that ensure shelf-life stability is also expected to boost the demand for these crops in the coming years. The physiological and biochemical changes that occur during the storage of microgreens warrant further investigation. Improve-ment in postharvest processing methods and pack-aging technology will aid in preserving quality for extended timeframes.

Conclusion

In today's market, microgreens are becoming increasingly popular due to shifts in lifestyle choices and growing health awareness among buyers. Microgreens offer a rich source of antioxidants, vitamins and minerals that contribute to enhancing human health. It is essential to have a comprehensive grasp of how to cultivate microgreens, as well as understanding their storage requirements post-harvest. This knowledge is vital for prolonging their shelf life and broadening their reach in the market. This analysis aims to enhance understanding of how to manage and process this emerging speciality crop.

Microbiome Engineering: The Future of Sustainable Plant Disease Management

Jesima Barveen U., Vinodhini A. and Sumitha S.

Introduction

In nature, plants are not alone. Millions of helpful microorganisms, including bacteria, fungi, viruses, and other microbes, surround every plant. These microbes inhabit plant tissues as well as the roots, leaves, stems and flowers. The plant microbiome is made up of all of them. The plant microbiome aids in plant growth, nutrient absorption, stress tolerance, and disease defense, much as the human gut microbiome is crucial to human health. Scientists have recently found that we can modify the plant microbiome to naturally suppress pathogens and increase crop productivity, rather than depending solely on chemical pesticides. One of the most promising strategies for sustainable agriculture is this new field known as microbiome engineering.

What is Microbiome engineering?

The deliberate alteration or control of beneficial microbial communities linked to plants in order to boost disease resistance, improve plant health, and boost agricultural productivity is known as microbiome engineering. Microbiome engineering seeks to establish a healthy microbial ecosystem in which pathogen establishment is naturally prevented by beneficial microbes, rather than focusing solely on the organism that causes the disease. In simply, plants that are healthy are shielded by microbes.

The Plant Microbiome: A Hidden Universe

Numerous microorganisms that reside on the roots, leaves, stems, flowers, and even inside the tissues of plants are all around them. The plant microbiome is a complex microbial community made up of viruses, fungi, bacteria, archaea, and other microscopic organisms. These microorganisms actively interact with plants and affect their growth, nutrition, immunity and capacity to tolerate environmental stress; they are not just passive residents. Nowadays, scientists view the plant and its microbiome as a single functional unit, sometimes known as the “plant holobiont,” highlighting the fact that a plant's health depends on both its genes and the micro-organisms that coexist with it.

How Plants are Protected by Beneficial Microbes

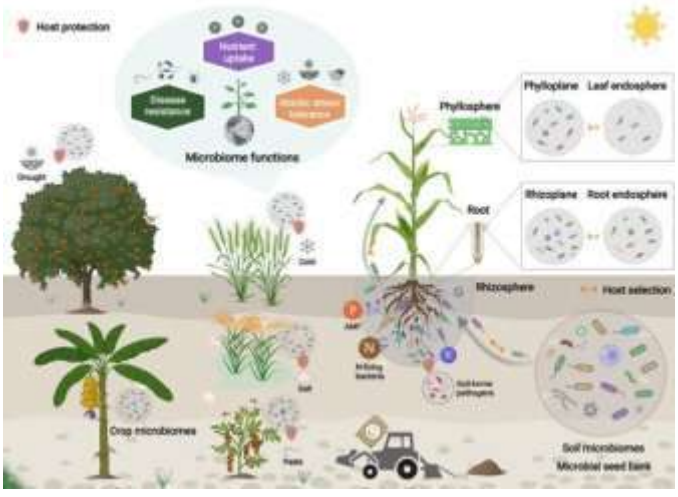
Plants are protected by beneficial microorganisms in a number of ways. In the area surrounding plant roots, a variety of bacteria and fungi compete with pathogens for nutrients and space, preventing the establishment of disease-causing organisms. Certain microorganisms produce hydrolytic enzymes, siderophores, volatile organic compounds and natural antibiotics that directly inhibit or kill pathogens. Others use Induced Systemic Resist-

Jesima Barveen U., Vinodhini A. and Sumitha S.
M.Sc. Scholar, Department of Plant Pathology, SRM College of Agril. Sciences, Baburayanpettai, Chengalpattu, Tamil Nadu

ance (ISR) to boost the plant's immune system, enabling it to react to pathogens more quickly. Some fungi, especially *Trichoderma* species, directly attack and break down the hyphae of pathogenic fungi as a form of mycoparasitism. These various mechanisms frequently function in tandem to provide long-lasting and broad-spectrum disease protection.

Microbiome Engineering in Organic Farming

Due to restrictions on the use of synthetic fertilizers and pesticides, organic agriculture mainly relies on natural biological processes. By increasing advantageous microbial populations in soil and on plant surfaces, microbiome engineering enhances organic farming. Without endangering the environment, healthy microbial communities enhance soil fertility, lower disease outbreaks, and increase nutrient availability. Because of this, microbiome engineering is a useful tool for advancing regenerative and organic agriculture.



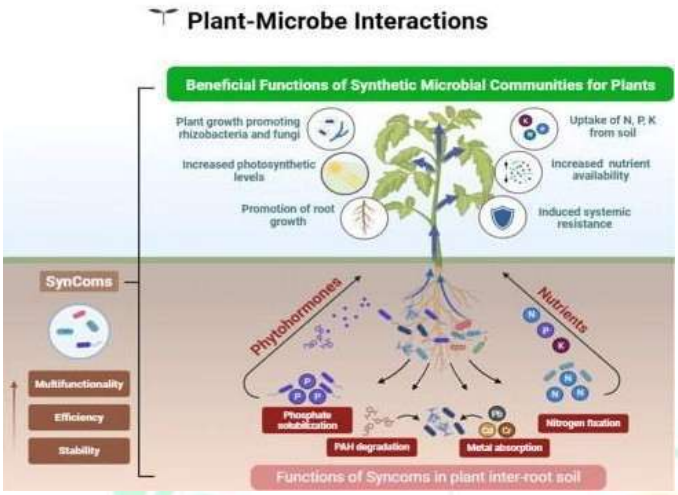
Recent Advances in Microbiome Engineering

Our knowledge of plant microbiomes has significantly increased thanks to recent developments in molecular biology and biotechnology. High-throughput sequencing technologies such as metagenomics and amplicon sequencing have enabled scientists to identify thousands of microbial species without the need for laboratory cultivation. Multi-omics approaches, including transcriptomics, proteomics, and metabolomics, help researchers understand how microbial communities function and interact with plants under different environmental conditions. Artificial intelligence and machine learning are increasingly being used to analyze massive microbiome datasets, identify beneficial microbial interactions and predict microbial combinations that can effectively suppress diseases. At the same time, advances in synthetic biology and CRISPR-based genome editing offer opportunities to improve beneficial microorganisms by enhancing traits such as root colonization, antimicrobial compound production, and environmental adaptability.

Synthetic Microbial Communities: A New Generation of Bioinoculants

The development of Synthetic Microbial Communities (SynComs) is one of the most exciting advances in microbiome engineering. Researchers put together carefully chosen collections of compatible microorganisms that carry out complementary tasks rather than using a single microbial strain. For instance, one bacterium might fix nitrogen in the atmosphere, another might solubilize phosphorus and still another might produce antibiotics to suppress fungal pathogens. When combined, these

microbes form a more robust and effective microbial community that can sustain plant growth in a variety of environmental circumstances. More and more people believe that SynComs will be the next generation of biopesticides and fertilizers.



Microbiome Engineering in Disease Management

Numerous investigations have shown how well microbiome engineering can manage significant plant diseases. Fusarium wilt in tomatoes, bacterial wilt in tobacco, take-all disease in wheat, rice blast, damping-off in vegetables, and root rot diseases in various crops have all been successfully mitigated by beneficial microbial communities. Beneficial microorganisms like *Bacillus subtilis*, *Trichoderma harzianum*, and *Fluorescent pseudomonas* species have demonstrated significant potential in onion cultivation to suppress basal rot caused by *Fusarium oxysporum* f. sp. cepae. These microbes enhance root development, nutrient uptake, and bulb yield in addition to lowering the incidence of disease.

Challenges to Field Application

Despite the tremendous potential that microbiome engineering has demonstrated in lab and greenhouse research, it is still difficult to apply these achievements in farmers' fields. The survival and efficacy of introduced microorganisms are influenced by a variety of factors, including soil type, climate, irrigation techniques, crop genotype, and pre-existing microbial communities. It's possible that beneficial microbes that thrive in controlled settings won't thrive in field settings. Furthermore, it is challenging to forecast long-term results due to the complexity and high dynamic nature of microbial interactions. Interdisciplinary research integrating microbiology, plant pathology, ecology, bioinformatics, and agricultural sciences is necessary to address these issues.

Future Perspectives

Precision agriculture, where microbial communities can be tailored to crop species, soil conditions, and local climates, is the future of microbiome engineering. Researchers hope to create crop-specific microbial formulations that can improve nutrient use efficiency, climate resilience, and long-term disease suppression. Sustainable crop management could be completely transformed by combining microbiome engineering with digital agriculture, remote sensing, artificial intelligence, and genomic selection. Microbiome engineering has the potential to lessen reliance on chemical pesticides and become a key component of climate-smart agriculture as our knowledge of microbial ecology advances.

Conclusion

By concentrating on enhancing the plant's

natural microbial partners rather than depending exclusively on chemical inputs, microbiome engineering represents a paradigm shift in the management of plant diseases. This novel approach provides sustainable solutions for disease control, increased crop productivity, and environmental conservation by utilizing beneficial microorganisms and comprehending their intricate interactions with plants. Rapid developments in genomics, synthetic biology, and computational sciences are speeding up the development of useful microbiome-based technologies, despite a number of ongoing scientific and technological obstacles. Microbiome engineering is anticipated to be crucial in creating resilient agricultural systems that can satisfy the rising demand for sustainable and safe food production worldwide in the upcoming decades.

References

Berg, G., Raaijmakers, J. M., *et al*. (2020). Microbiome definition re-visited: old concepts and new challenges.

Trivedi, P., Leach, J. E., *et al.* (2020). Plant-microbiome interactions: from community assembly to plant health.

Compant, S., Samad, A., *et al*. (2019). A review on the plant microbiome: ecology, functions and emerging trends in microbial application.

Toju, H., Peay, K. G., *et al.* (2018). Core microbiomes for sustainable agroecosystems.

Microalgae-Bacteria Consortia for Sustainable Farming

Vironika and Brajeshwar Singh

Introduction

Agriculture is increasingly looking towards biological inputs that can maintain crop productivity while reducing unnecessary dependence on chemical fertilizers. One promising approach involves microalgae-bacteria consortia, in which photosynthetic microorganisms and beneficial bacteria grow together and perform complementary functions. Microalgae and cyanobacteria use sunlight and carbon dioxide to produce biomass. Their bacterial partners recycle nutrients and release substances that may support algal and plant growth. A carefully selected consortium can therefore provide several useful functions that may not be available from a single microbial strain (Vironika and Singh, 2026). Commonly investigated organisms include green microalgae such as *Chlorella*, *Scenedesmus* and *Desmodesmus*; cyanobacteria such as *Nostoc*, *Anabaena* and *Calothrix*; and plant-growth-promoting bacteria such as *Azospirillum* and *Pseudomonas*. Cyanobacteria are photosynthetic bacteria rather than true algae, but they are often discussed with microalgae because of their similar cultivation requirements and agricultural applications.

How does the Microbial Partnership Work?

During photosynthesis, microalgae and cyanobacteria use sunlight and carbon dioxide and release oxygen and carbon-rich compounds into their surroundings. Sugars, amino acids and other algal metabolites can support associated bacterial populations. In return, bacteria decompose organic material and release carbon dioxide, vitamins and mineral nutrients that may support algal growth. Some bacterial partners can also fix atmospheric nitrogen, mobilize poorly available nutrients and produce siderophores or plant-growth-regulating compounds. Thus, the consortium operates through the exchange of nutrients and metabolites between its members.

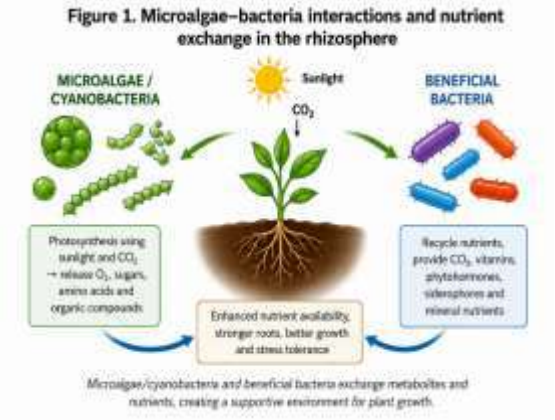


Fig. 1: Microbial cooperation and exchange of nutrients between microalgae, cyanobacteria, beneficial bacteria and crop roots

After being introduced into soil, these microorganisms interact with plant roots and the native soil microbiome. Their biomass contributes

Vironika
Research Scholar, Division of Microbiology, Faculty of Basic Sciences, SKUAST-J, Chatha, Jammu, UT of J&K
Brajeshwar Singh
Professor and Head, Division of Microbiology, Faculty of Basic Sciences, SKUAST-J, Chatha, Jammu, UT of J&K

organic material, while extracellular polysaccharides produced by many cyanobacteria can help micro-organisms attach to soil particles and root surfaces. Together, these processes may create a biologically active environment around the developing root system.

Role in Crop Growth and Soil Fertility

Recent research has shown that microalgal and bacterial combinations can influence both crop development and soil properties. In a three-year maize field experiment, *Nostoc linckia* was applied alone and in combination with *Azospirillum lipoferum* and *Pseudomonas fluorescens*. Several treatments improved chlorophyll measurements and increased the fresh and dry biomass of maize leaves and roots. The treatment containing 0.3 g L^{-1} *N. linckia* together with *A. lipoferum* produced particularly favourable results. Some treatments also increased total soil nitrogen by about 21-40% and nitrate-plus-nitrite nitrogen by approximately 27-59%. However, the degree of improvement varied between the three growing seasons, indicating that weather and field conditions strongly affect inoculant performance (Solomon *et al*., 2025). Microalgal inoculation can also influence the microorganisms already present in cultivated soil. Jose *et al*. (2024) evaluated a consortium containing the cyanobacteria *Nostoc* and *Calothrix* together with the green microalga *Desmodesmus armatus* in chilli plants. The treatment improved plant growth and yield and increased soil fertility indicators. Metagenomic analysis further revealed greater microbial diversity and changes in the composition of bacterial and fungal communities in inoculated soil. This suggests that the consortium supported crop growth partly by reshaping the native soil microbiome (Jose *et al*., 2024). These findings show that microalgal inoculants do not function only as sources of nutrients. They may also stimulate soil biological activity and influence the wider microbial community surrounding plant roots.

Support under Drought Stress

Cyanobacteria are also being investigated for their ability to support plants under water-limited conditions. Their extracellular substances may help maintain favourable microsites around soil particles and roots, while their metabolites can influence plant growth and stress responses (Vironika and Singh, 2026). Kollmen *et al*. (2025) studied living nitrogen-fixing cyanobacteria in wheat and *Arabidopsis thaliana*. *Nostoc calcicola* increased wheat dry biomass by around 30% under hydroponic conditions and by 44% in a pot experiment. Under controlled drought conditions, *Nostoc muscorum* and *N. calcicola* increased the dry biomass of *Arabidopsis* by approximately 57% and 32%, respectively. These results indicate that selected cyanobacterial strains may act as biofertilizers while also supporting plant growth during water stress (Kollmen *et al*., 2025). However, results obtained in hydroponic systems and pot experiments should be interpreted carefully. Their effectiveness must still be confirmed through multi-location field trials under different soils and climatic conditions.

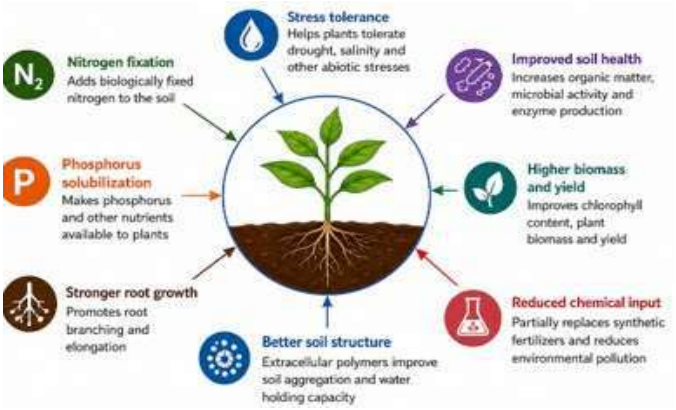


Fig. 2: Major agricultural benefits associated with microalgae-bacteria and cyanobacterial consortia

Application in Agriculture

The most suitable application method depends on whether the preparation contains living microorganisms, harvested biomass and cell extracts. These forms should not be treated as interchangeable because they act differently after application.

Seed treatment: Microalgal extracts can be applied to seeds before sowing to expose the developing seedling to bioactive compounds. Supraja *et al.* (2020) tested mixed microalgal extracts as seed primers in tomato. Extract concentrations of 40-80% produced complete germination within three days and promoted early plant growth. Because the experiment used algal extracts, the response was mainly associated with soluble compounds rather than permanent microbial colonization of the roots.

Soil and root-zone application: Living cells or microbial biomass may be applied directly to soil when the intended purpose is nutrient cycling, rhizosphere activity and interaction with native soil microorganisms. In maize, soil-applied *Nostoc linckia* together with *Azospirillum lipoferum* or *Pseudomonas fluorescens* improved plant biomass and selected soil-nitrogen indicators over three growing seasons (Solomon *et al.*, 2025). Similarly, the cyanobacteria-green microalgae consortium used in chilli improved plant performance and altered the native soil microbiome following its addition to the cultivation substrate (Jose *et al.*, 2024). Living cyanobacteria were also applied in wheat pot experiments, where *Nostoc calcicola* increased plant dry biomass by 44%. This provides evidence that living cyanobacterial cultures can function as soil-applied biofertilizers under controlled conditions (Kollmen *et al.*, 2025).

Foliar application: Microalgal extracts or suspensions may also be sprayed on leaves when the preparation is intended mainly as a biostimulant. In tomato, foliar application of a 60% mixed microalgal extract produced the best yield response among the concentrations examined by Supraja *et al.* (2020). The treatment was also associated with increased chlorophyll content and plant growth. Foliar application should therefore be described mainly as a method for delivering algal metabolites or biomass-derived compounds. It should not automatically be assumed to establish a microbial population in the rhizosphere.

Seed coating and irrigation delivery: Seed coating and delivery through irrigation water are promising approaches for microbial formulations. However, their effectiveness depends on microbial survival, compatibility with coating materials or irrigation systems, and the ability of the organisms to reach the intended plant surface. These methods require crop-

specific testing before they can be recommended widely. They should therefore be presented as developing application options rather than universally established practices.

Challenges in Field Application

Despite encouraging results, microalgae-bacteria consortia do not always perform consistently. Their survival and activity can be influenced by temperature, rainfall, soil pH, salinity, crop genotype and competition from native microorganisms. The seasonal variation reported in the maize field experiment illustrates the importance of testing inoculants for more than one growing season (Solomon *et al*., 2025). Maintaining a stable microbial composition during production and storage is another challenge. One organism may multiply faster than its partners and disturb the balance of the consortium. Contamination, loss of viability and unsuitable storage conditions may also reduce product effectiveness. Microbial strains intended for agricultural use must therefore be correctly identified and assessed for safety. Suitable carriers, packaging and quality-control standards are required to maintain their activity until application.

Conclusions and Future Perspectives

Microalgae-bacteria consortia offer a promising biological approach for sustainable farming. They can improve nutrient cycling, plant growth, soil activity and stress tolerance. However, their performance depends on the microbial partners, crop and growing conditions. Therefore, they should complement integrated nutrient management rather than completely replace mineral fertilizers. Future research should develop stable, crop-specific formulations and validate them through long-term, multi-location field trials. With proper selection and field testing, these consortia may become useful inputs for resource-efficient and climate-resilient agriculture.

References

Jose, S., Malla, M. A., Renuka, N., Bux, F. and Kumari, S. (2024). Cyanobacteria-green microalgae consortia enhance soil fertility and plant growth by shaping the native soil microbiome of *Capsicum annuum*. *Rhizosphere*, 30: 100892.

Kollmen, J., Juvigny-Khenafou, N. P. D., Wastian, K., Yavuz, S., Engl, A. *et al*. (2025). Co-cultivation of wheat and *Arabidopsis thaliana* with nitrogen-fixing cyanobacteria: a strategy to enhance plant growth and drought tolerance. *Journal of Applied Phycology*, 37: 4181-4196.

Solomon, W., Mutum, L., Janda, T. *et al*. (2025). Microalgae-bacteria interaction: a catalyst to improve maize (*Zea mays* L.) growth and soil fertility. *Cereal Research Communications*, 53: 1037-1049.

Vironika and Singh, B. (2026). Microalgae-bacteria consortia as next-generation biostimulants for maize and cereal-based farming: microbial interactions, climate-stress mitigation and field translation. *Maydica Journal*, 8(7): 1169-1190.

Digital Plant Pathology

Shraddha Karcho

Introduction

Plant diseases are among the major constraints affecting global agricultural productivity, food security and farm profitability. Traditional plant disease diagnosis mainly depends on visual observation of symptoms and laboratory-based confirmation, which can be time-consuming, labor-intensive and difficult to apply over large agricultural areas. In many cases, visible symptoms appear only after the disease has progressed significantly, reducing the opportunity for timely management. The emergence of digital plant pathology is transforming this traditional approach by integrating advanced technologies such as drones, remote sensing, hyperspectral imaging, artificial intelligence (AI) and machine learning into plant disease detection and management. These technologies enable rapid, non-destructive and large-scale monitoring of crop health and can help identify disease-associated changes before symptoms become clearly visible to the human eye (Mahlein, 2016; Sankaran *et al.*, 2016). Drone-based imaging provides high-resolution aerial information that allows researchers and farmers to monitor disease distribution across fields, while hyperspectral imaging captures detailed spectral signatures associated with physiological and biochemical changes in infected plants (Sankaran *et al.*, 2016; Thomas *et al.*, 2016). When these large and complex datasets are analyzed using AI and deep learning algorithms, disease symptoms can be automatically detected, classified, and mapped with increasing accuracy (Singh *et al*., 2016). The integration of these technologies offers new opportunities for early disease diagnosis, precision disease management and targeted application of crop protection measures. Thus, digital plant pathology represents an important transition from conventional, symptom-based diagnosis toward data-driven and predictive approaches, supporting more efficient, sustainable and precise crop disease management in modern agriculture (Mahlein, 2016; Singh *et al*., 2016).

Concept and Importance

Digital plant pathology is an emerging interdisciplinary field that applies digital technologies, advanced imaging systems, remote sensing, artificial intelligence (AI), machine learning (ML), and data analytics to the detection, diagnosis, monitoring, and management of plant diseases. It represents a shift from conventional plant pathology, which largely depends on visual symptoms, microscopic examination, and laboratory-based diagnosis, toward rapid, automated, data-driven approaches. Digital plant pathology uses information generated from smartphones, digital cameras, drones, satellites, multispectral and hyperspectral sensors, and other

Shraddha Karcho
Assistant Professor (Plant Pathology), Raja Bhoj College of Agriculture, Waraseoni (JNKVV, Jabalpur), Madhya Pradesh

sensing platforms to obtain detailed information about plant health. These technologies can detect subtle changes in plant physiology, morphology and biochemical composition that may occur during pathogen infection, sometimes before visible symptoms develop (Mahlein *et al*., 2016; Sankaran *et al.*, 2016). AI and deep learning algorithms further support automated image analysis and disease recognition by processing large datasets and identifying patterns that may be difficult to recognize through conventional methods. Digital technologies can also be integrated with geographic information systems (GIS), Internet of Things (IoT) devices, and weather-based disease forecasting systems, creating a comprehensive framework for real-time crop health monitoring and precision plant disease management.

Role of Digital Technologies in Modern Plant Disease Management

Digital technologies are increasingly important in modern plant disease management because they improve the speed, accuracy, and scale of disease detection. Conventional disease diagnosis often requires field inspection and laboratory confirmation, which can delay management decisions. In contrast, digital imaging and sensor-based technologies allow rapid monitoring of large crop areas and provide early indications of disease development. Drones equipped with RGB, multi-spectral, or hyperspectral cameras can collect high-resolution data over extensive fields, helping identify disease hotspots and variations in crop health (Mahlein *et al.*, 2016). AI and ML technologies play a major role in converting these large datasets into useful diagnostic information. Deep learning models, particularly convolutional neural networks (CNNs), can analyze plant images and recognize disease-associated patterns, supporting automated identification and classification of diseases (Mohanty *et al.*, 2016). The integration of digital disease detection with precision agriculture can enable farmers to apply fungicides or other control measures only where and when they are required. This site-specific approach can reduce unnecessary pesticide use, lower production costs and minimize environmental impacts. Digital plant pathology has the potential to transform disease management from a reactive approach based on visible symptoms into a proactive, predictive, and precision-based system. By combining advanced sensing technologies with AI-driven analysis, it can support sustainable crop production, improve disease management efficiency, and strengthen global food security (Mahlein *et al*., 2016).

Integration of Drones, Hyperspectral Imaging and AI

The integration of drones, hyperspectral imaging, and artificial intelligence (AI) represents one of the most promising developments in modern digital plant pathology. Each technology provides a different type of information about crop health, and their combination creates a powerful system for detecting, diagnosing, and monitoring plant diseases. Drones, or unmanned aerial vehicles (UAVs), prov-

ide flexible and high-resolution data collection over agricultural fields. Hyperspectral sensors mounted on drones capture reflected light across numerous narrow wavelength bands, providing detailed information about the physiological and biochemical condition of plants. AI and machine learning algorithms then process these complex datasets to identify disease-associated patterns and distinguish healthy plants from infected ones (Mahlein *et al.*, 2016).

Combining Remote Sensing with Intelligent Disease Diagnosis

Remote sensing technologies enable the detection of changes in plants caused by pathogen infection without requiring direct physical contact with the crop. Disease development can alter leaf pigments, water content, cellular structure, and other physiological characteristics, resulting in changes in the spectral reflectance of infected plants. Hyperspectral imaging can detect these subtle spectral variations, sometimes before disease symptoms become clearly visible to the human eye. When this information is combined with AI-based analysis, large volumes of spectral and image data can be automatically interpreted to identify potential disease symptoms. Machine learning and deep learning models can be trained using datasets containing images or spectral signatures of healthy and diseased plants. These models can classify disease conditions, estimate disease severity, and identify spatial patterns of infection. The combination of remote sensing and intelligent diagnosis therefore reduces dependence on manual field scouting and allows disease assessment to be conducted more rapidly and objectively (Sankaran *et al*., 2010; Mohanty *et al*., 2016).

Development of Precision Plant Pathology Systems

The integration of drones, hyperspectral sensors, and AI is contributing to the development of precision plant pathology systems. These systems are designed to provide accurate information about the location, severity, and progression of diseases within agricultural fields. Instead of treating an entire field uniformly, digital disease maps can identify specific areas where infection is concentrated. Farmers and plant health professionals can then use this information to implement targeted disease management strategies. These outputs can be integrated with geographic information systems (GIS) and precision agriculture equipment to support site-specific application of fungicides or other crop protection measures. Such approaches have the potential to reduce unnecessary chemical applications, lower production costs, and minimize environmental contamination while maintaining effective disease control (Sankaran *et al*., 2010; Mohanty *et al*., 2016).

Real-Time and Large-Scale Disease Surveillance

One of the major advantages of integrating these technologies is the possibility of conducting rapid and large-scale disease surveillance. Traditional field scouting is often restricted by the availability of trained personnel, time and accessibility of agricultural fields. In contrast, drones can

rapidly survey large areas and repeatedly collect data at different stages of crop development. This allows plant disease progression to be monitored over time and supports the identification of emerging disease outbreaks (Mahlein *et al*., 2016).

When drone-based imaging is combined with AI-powered automated analysis, disease surveillance can become faster and more scalable. Repeated observations can help track changes in disease distribution and severity, while AI models can assist in identifying areas requiring immediate field inspection or intervention. In the future, integration with Internet of Things (IoT) sensors, weather data, satellite imagery, and disease forecasting models may enable near-real-time disease monitoring and early warning systems. Such integrated digital platforms could shift plant disease management from a largely reactive approach toward proactive and predictive disease management (Sankaran *et al*., 2010; Mohanty *et al*., 2016). By combining high-resolution data acquisition, advanced spectral sensing, and intelligent data analysis, these systems can improve early disease detection, enhance disease surveillance, support precision management, and contribute to more sustainable crop production.

Applications in Crop Disease Management

Digital plant pathology technologies, including drones, hyperspectral imaging, remote sensing, and artificial intelligence (AI), are increasingly being applied to improve crop disease management. These technologies provide rapid, accurate, and non-destructive methods for detecting and monitoring plant diseases at both individual plant and field scales.

Early Detection and Disease Forecasting: Digital imaging and hyperspectral sensors can identify subtle physiological and biochemical changes associated with pathogen infection before clear visual symptoms appear. AI and machine learning models can analyze these changes and provide early indications of disease development. When combined with weather information and historical disease data, these technologies can also support disease forecasting and early warning systems, allowing timely management decisions.

Disease Mapping and Monitoring: Drone-based RGB, multispectral and hyperspectral imaging can be used to identify and map disease-affected areas across large agricultural fields. AI-based analysis can classify infected regions and estimate disease severity, producing digital disease maps. Repeated drone surveys also allow changes in disease distribution and progression to be monitored throughout the growing season.

Precision Application of Fungicides and Other Interventions: Digital disease maps can support site-specific disease management by identifying areas that require treatment. Instead of applying fungicides uniformly across an entire field, precision agriculture systems can guide targeted applications to disease hotspots. This approach can improve the efficiency of disease control while reducing unnecessary chemical applications.

Reduction of Crop Losses and Pesticide Use: Early

detection and targeted intervention can help prevent diseases from spreading and reduce crop losses. Precision application of fungicides and other control measures can also decrease excessive pesticide use, lowering production costs and minimizing environmental impacts. Thus, digital plant pathology contributes to more efficient, economical, and sustainable crop disease management.

Future Prospects of Digital Plant Pathology

The future of digital plant pathology is closely linked with advances in artificial intelligence (AI), remote sensing, the Internet of Things (IoT), robotics, and smart farming technologies. The integration of these technologies is expected to make plant disease detection faster, more accurate, automated, and predictive. Future digital plant pathology systems may enable continuous monitor-ing of crop health and provide farmers with timely information for disease prevention and management.

AI-Powered Autonomous Disease Detection: Advanced AI and deep learning algorithms are expected to improve the automated detection and classification of plant diseases. Future systems may analyze images and spectral data collected by drones, robots, and smart cameras to detect infections at an early stage with minimal human involvement. This can support rapid diagnosis and large-scale disease surveillance.

Integration with IoT and Smart Farming: The integration of digital plant pathology with IoT-based sensors can enable continuous monitoring of environmental and crop conditions. Sensors measuring temperature, humidity, leaf wetness, soil moisture, and other parameters can be combined with disease detection data to identify conditions favor-able for pathogen development. Such interconnected systems can provide farmers with real-time inform-ation for improved crop management.

Real-Time Disease Prediction and Decision Support: Future platforms are likely to combine AI, weather data, remote sensing, and historical disease records to predict disease outbreaks before they become widespread. Decision-support systems could provide alerts and recommend appropriate management actions, helping farmers respond quickly and efficiently to emerging disease threats.

Development of Autonomous Agricultural Systems: The long-term goal of digital plant pathology is the development of autonomous agricultural systems capable of detecting diseases, assessing their severity, and initiating targeted interventions with minimal human involvement. Autonomous drones and agricultural robots may identify infected plants and apply treatments precisely to affected areas. Such systems could reduce labor requirements, pesticide use, and crop losses while improving the sustainability and efficiency of modern agriculture. These advance-ments could play an important role in achieving sustainable crop production and strengthening global food security.

Conclusion

Digital plant pathology is emerging as a transformative approach to modern crop disease

management by combining drones, hyperspectral imaging, remote sensing, artificial intelligence and advanced data analytics. These technologies enable rapid, non-destructive, and large-scale detection of plant diseases, often providing valuable information before symptoms become clearly visible. The integration of high-resolution aerial imaging with hyperspectral sensing and AI-based analysis can improve disease identification, mapping, monitoring, and severity assessment. The future of digital plant pathology lies in the integration of these technologies with IoT-based sensors, smart farming platforms, autonomous drones, and agricultural robots. Such interconnected systems could enable real-time disease prediction, early warning, automated decision-making, and targeted disease management. Although challenges such as high costs, data quality, technological complexity, and the need for reliable AI models remain, continued advancements in digital technologies are expected to overcome many of these limitations.

References

Mahlein, Anne-Katrin. (2016). Plant Disease Detection by Imaging Sensors Parallels and Specific Demands for Precision Agriculture and Plant Phenotyping. *Plant Disease*, 100(2): 241-251.

Sankaran, Sindhuja, *et al*. (2010). A Review of Advanced Techniques for Detecting Plant Diseases. *Computers and Electronics in Agriculture*, 72(1): 1-13.

Thomas, S. *et al.* (2016). Plant Disease Detection Using Hyperspectral Imaging. *Plant Disease*, 100(12): 2465-2475.

Singh, A. *et al*. (2016). Machine Learning for High-Throughput Stress Phenotyping in Plants. *Trends in Plant Science*, 21(2): 110-124.

Mohanty, S. P., David, P. Hughes and Marcel Salathé. (2016). Using Deep Learning for Image-Based Plant Disease Detection. *Frontiers in Plant Science*, 7 : 1419.

Mahlein, Anne-Katrin, *et al*. (2012). Hyperspectral Imaging for Small-Scale Analysis of Plant Diseases. *Plant Methods*, 8: 17.

Phosphorus Management for Sustainable Agriculture: Soil Processes, Use Efficiency and Future Strategies

Akshay B. Jadhao, Swati P. Zade, Snehal S. Shilewant and M. S. Deshmukh

Abstract

Phosphorus (P) is an essential macronutrient that plays a vital role in plant growth, energy transfer, root development, flowering, and seed formation. However, its availability in soil is often limited because of fixation by iron, aluminum, and calcium compounds, resulting in low phosphorus-use efficiency. Efficient phosphorus management is therefore essential for improving crop productivity, maintaining soil fertility, and reducing environmental impacts. This technical paper presents the sources, forms, and behavior of phosphorus in soils, its role in crop growth, factors affecting phosphorus availability, and practical strategies for improving phosphorus-use efficiency through integrated nutrient management, biofertilizers, precision fertilization, and sustainable phosphorus management practices.

Introduction

Phosphorus (P) is one of the three primary macronutrients required for plant growth and is essential for energy transfer, photosynthesis, root development, flowering and seed production. Although agricultural soils contain considerable amounts of total phosphorus, only a small fraction is available for plant uptake because phosphorus rapidly becomes fixed by iron and aluminum in acidic soils and calcium in alkaline soils. Consequently, phosphorus-use efficiency remains low, limiting crop productivity and increasing fertilizer requirements. Improving phosphorus availability through balanced fertilization, organic amendments, phosphate-solubilizing microorganisms, and precision nutrient management is essential for sustainable crop production. This technical paper highlights the importance of phosphorus in agriculture, its sources and forms, soil dynamics, fixation mechanisms, crop response, and practical strategies for enhancing phosphorus-use efficiency and sustaining agricultural productivity.

Importance of Phosphorus in Agriculture

Phosphorus is indispensable for normal plant growth and development. It stimulates root proliferation, enhances nutrient and water uptake, supports energy transfer through ATP, improves flower-

Akshay B. Jadhao
M.Sc. Scholar, Department of Soil Science, College of Agriculture, VNMKV, Parbhani, Maharashtra
Swati P. Zade
Assistant Professor, Department of Soil Science, College of Agriculture, VNMKV, Parbhani, Maharashtra
Snehal S. Shilewant
Junior Research Assistant, Department of Soil Science, College of Agriculture, VNMKV, Parbhani, Maharashtra
M. S. Deshmukh
Associate Professor, Department of Soil Science, College of Agriculture, VNMKV, Parbhani, Maharashtra

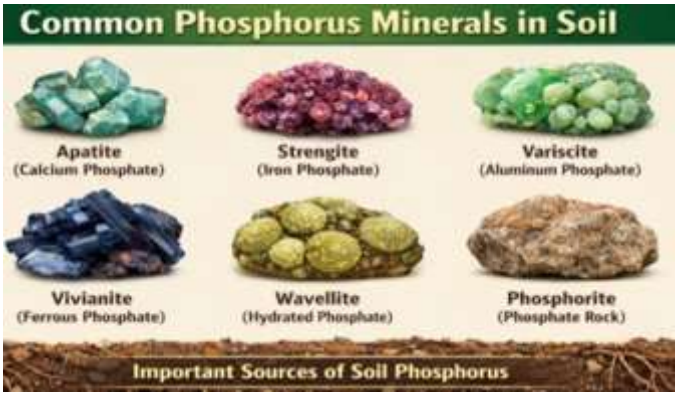
ing and seed formation and increases crop productivity. Adequate phosphorus nutrition also accelerates crop maturity, improves produce quality, and enhances tolerance to environmental stresses.

Sources, Forms and Fractions of Phosphorus

Phosphorus is the tenth most abundant element in the Earth's crust and occurs mainly in apatite minerals, which serve as the primary source of phosphatic fertilizers. The total phosphorus content of Indian soils ranges from 100 to 2,000 mg kg^{-1} (Tandon, 1987). Soil phosphorus exists in inorganic and organic forms. Inorganic phosphorus constitutes approximately 54-84% of total phosphorus and occurs mainly as iron, aluminum, and calcium phosphates. Organic phosphorus accounts for 20-80% of total soil phosphorus and includes inositol phosphates, nucleic acids, phospholipids, and phosphoproteins. These organic forms become available to plants through microbial mineralization.

Phosphates of Fe and Al

Mineral	Formula	Source
Plumbogumite	$M.Al_3(PO_4)_2(OH)_5.H_2O$	Well drained soil
Variscite	$AlPO_4.2H_2O$	Well drained soil
Strengite	$FePO_4.2H_2O$	Well drained soil
Vivianite	$Fe_3(PO)_4.8H_2O$	Waterlogged soil
Wavellite	$Al_8(OH)_3.5H_2O$	Dropping of sea birds
Crandallite	$CaAl_3(PO_4)_2.5H_2O$	Islands



Phosphate Fixation

Phosphate fixation is the process by which soluble phosphorus added to the soil through fertilizers is converted into less soluble or insoluble forms, thereby reducing its availability for plant uptake. The phenomenon was first recognized by Thomas Way (1850) and is also referred to as phosphorus reversion. Phosphate fixation is not merely an adsorption process but involves a combination of adsorption, chemisorption, and precipitation reactions between phosphate ions and soil minerals. As a result, only a small fraction of applied phosphorus remains in the soil solution for plant absorption, while the remainder becomes fixed in stable mineral forms. Soil pH is the most important factor controlling phosphate fixation. In acidic soils (pH < 7.0), soluble phosphate reacts with iron (Fe^{3+}) and aluminum (Al^{3+}) oxides and hydroxides to form sparingly soluble iron and aluminum phosphates. In neutral to alkaline and calcareous soils (pH ≥ 7.0), phosphate precipitates with calcium (Ca^{2+}) to form progressively less soluble calcium phosphate minerals, such as dicalcium phosphate, octacalcium phosphate, and hydroxyapatite. These reactions significantly reduce phosphorus availability and consequently lower phosphorus-use efficiency.

Precipitation of phosphate in acid and calcareous soils

Acid Soils

$Al^{3+} + H_2PO_4^- + 2H_2O \rightarrow AlPO_4.2H_2O \rightarrow \rightarrow Al(OH)_2H_2PO_4 + 2H^-$

Here, $Al^{3+} + H_2PO_4^- + 2H_2O$ = Dihydrogen phosphate (Soluble)

$AlPO_4.2H_2O$ = Aluminum hydroxy phosphate (Slightly soluble)

$Al(OH)_2H_2PO_4 + 2H^- =$ Variscite (Insoluble)

In acid soils, when phosphorus added either through fertilizers or organic matter decomposition, the resulting iron and aluminium phosphate are insoluble and unavailable to plant.

Calcareous soils

$Ca(H_2PO_4)2 \rightarrow Ca_2(HPO_4)2 \rightarrow Ca_3(H_2PO_4)2$

$3[Ca_3(H_2PO_4)2].CaCO_3$

Decreasing solubility $\rightarrow \rightarrow \rightarrow$

In calcareous soil, this reaction occurs when Phosporus added to soil, leading to the formation of insoluble calcium phosphate, such as hydroxyapatite and these compounds are also unavailable to plant.

Factors Affecting Phosphate Fixation

Phosphate fixation is influenced by several soil properties that determine phosphorus availability.

Nature of Soil Components: Soils rich in amorphous Fe and Al oxides, kaolinite clay, and $CaCO_3$ have a higher phosphorus-fixing capacity. Lateritic soils fix more phosphorus than black (Vertisol) soils. Exchangeable cations increase phosphorus adsorption, while competing anions (OH^-, SO_4^{2-}, SiO_4^{4-}, MoO_4^{2-}) reduce it.

Soil pH: In acidic soils, phosphorus reacts with Fe and Al to form insoluble phosphates, whereas in alkaline and calcareous soils, it precipitates as calcium phosphates, reducing its availability.

Organic Matter: Organic matter decreases phosphorus fixation by releasing organic acids that chelate Fe and Al, compete for adsorption sites, and increase phosphorus solubility.

Temperature: Higher soil temperature enhances phosphorus adsorption and fixation, thereby reducing phosphorus availability.

Overliming: Excessive lime application increases the formation of insoluble calcium phosphates, leading to greater phosphorus fixation in calcareous soils.

Phosphorus-Related Root System Architecture

The root system plays a fundamental role in phosphorus (P) acquisition because phosphorus is relatively immobile in soil. Under phosphorus-deficient conditions, plants adapt by increasing root length, lateral root formation, root hair density, and root surface area, thereby enhancing soil exploration and phosphorus uptake. Root growth is closely linked with shoot photosynthesis, as photosynthates produced in leaves provide the energy required for root development and nutrient absorption (Osaki *et al.*, 1997). Manipulation of root architecture and beneficial associations with arbuscular mycorrhizal fungi can significantly improve phosphorus acquisition and crop productivity (Chang et al., 2004; Lambers, 2022).

Phosphorus Use Efficiency

Phosphorus Use Efficiency (PUE) is defined as the amount of biomass or economic yield produced per unit of phosphorus absorbed or applied (Hammond *et al.*, 2009). Since only 10-20% of applied phosphorus fertilizer is utilized by crops during the first growing season due to fixation react-

ions, improving PUE is essential for sustainable crop production. Integrated nutrient management, phosphate-solubilizing microorganisms, arbuscular mycorrhizal fungi, precision fertilizer application, and nano-phosphorus fertilizers have been shown to enhance phosphorus availability, fertilizer-use efficiency, and crop yield (Dotaniya, 2014; Lambers, 2022; Mansouri *et al.*, 2025).

Phosphorus Use Efficiency = {(Grain yield under treated plots- Grain yield under control plot)/ Nutrient applied (kg ha^{-1}) X 100}

Phosphorus-Related Root Activity

Roots are essential for phosphorus (P) uptake by absorbing nutrients and interacting with beneficial rhizosphere microorganisms. Root exudates, phosphatase enzymes, root hairs, and mycorrhizal fungi improve phosphorus solubility and uptake, particularly under phosphorus-deficient conditions (Raghothama, 1999; Lambers, 2022).

Impact of Phosphorus on Crop Productivity

Adequate phosphorus promotes root growth, photosynthesis, flowering, grain filling, seed quality, and early crop maturity, leading to higher yields. In contrast, phosphorus deficiency causes stunted growth, poor root development, dark green or purplish leaves, delayed maturity, and reduced productivity.

Improving Phosphorus Use Efficiency (PUE)

Phosphorus-use efficiency can be improved through balanced application of phosphatic fertilizers (DAP, SSP), integrated nutrient management, phosphate-solubilizing bacteria (PSB), arbuscular mycorrhizal fungi (AMF), organic manures, optimum soil pH (6.5-7.5), and precision fertilizer application (Hammond et al., 2009; Mansouri *et al.*, 2025).

Future Research Strategies

Future research should focus on soil phosphorus testing, phosphorus recycling, precision nutrient management, best management practices (BMPs), and climate-smart technologies to enhance phosphorus-use efficiency while reducing environmental losses (Scholz *et al.*, 2025; McDowell and Haygarth, 2025).

Toxicity and Environmental Issues

Toxicity Sources

- ✓ Phosphate rock may contain radioactive elements (uranium and radium) and heavy metals, particularly cadmium (Cd).
- ✓ The production of phosphatic fertilizers generates phosphogypsum, a by-product that may pose environmental risks if not properly managed.

Environmental and Health Impacts

- ✓ Continuous use of phosphatic fertilizers can lead to the gradual accumulation of cadmium in agricultural soils.
- ✓ Cadmium may enter the food chain through crop uptake, posing potential risks to human and animal health.
- ✓ Phosphate fertilizer application is considered one of the major anthropogenic sources of cadmium in the environment.
- ✓ Phosphate mining and fertilizer manufacturing can contribute to soil degradation, water pollut-

ion, air contamination and ecosystem disturbances.



Conclusion

Phosphorus is an essential nutrient for sustainable crop production, playing a vital role in plant growth, root development, energy transfer, and yield formation. However, its availability is often limited by soil fixation, resulting in low phosphorus-use efficiency. Integrated phosphorus management through balanced fertilization, organic amendments, biofertilizers, and precision nutrient management can improve phosphorus availability, enhance crop productivity, maintain soil fertility, and reduce environmental impacts. Sustainable phosphorus management is therefore crucial for ensuring long-term agricultural productivity and conserving finite phosphate resources.

References

Brady, N. C. and Weil, R. R. (2017). The Nature and Properties of Soils (15th ed.). Pearson Education.

Chang, T. T., Osaki, M., Matsui, H. and Tadano, T. (2004). Root growth and nutrient acquisition under phosphorus deficiency. *Plant and Soil*, 261: 117-126.

Dotaniya, M. L. (2014). *Soil Science: An Elementary Textbook*. Kalyani Publishers, New Delhi.

Hammond, J. P., Broadley, M. R. and White, P. J. (2009). Genetic responses to phosphorus deficiency. *Journal of Experimental Botany*, 60: 289-301.

Lambers, H. (2022). Phosphorus acquisition and utilization in plants. *Annual Review of Plant Biology*, 73: 17-42.

Manschner, P. (2012). Marschner's Mineral Nutrition of Higher Plants (3rd ed.). Academic Press.

Mansouri, H., Ait Said, H., Noukrati, H., *et al*. (2025). Development, efficiency and impact factors of phosphorus nanofertilizers in agriculture. *Journal of Plant Nutrition and Soil Science*, 188: 894-912.

Morel, C., Tunney, H., Plénet, D. and Pellerin, S. (2000). Transfer of phosphate ions between soil and roots. *Plant and Soil*, 222: 181-190.

Osaki, M., Shinano, T. and Tadano, T. (1997). Root-shoot interactions under phosphorus deficiency. *Plant and Soil*, 196: 153-160.

Raghothama, K. G. (1999). Phosphate acquisition. *Annual Review of Plant Physiology and Plant Molecular Biology*, 50: 665-693.

Scholz, R. W., *et al*. (2025). Overcoming recycling barriers to transform global phosphorus management. *Nature Reviews Earth & Environment*.

Integrated Management of Soil Borne Diseases in Vegetable Crops

Vishal D. Pawar and Kishor T. Thakare

Abstract

Vegetable crops play a vital role in nutritional security and farm income, but their productivity is severely affected by soil borne diseases. These diseases are caused by fungi, bacteria and nematodes that survive in the soil for long periods and infect plants through roots and collar regions. Pathogens such as *Fusarium, Rhizoctonia, Pythium* and *Sclerotium* cause wilting, root rot, damping-off and stem rot in vegetable crops, leading to heavy yield losses. Farmers often rely on chemical fungicides for disease control; however, continuous use of chemicals results in environmental pollution, pathogen resistance and deterioration of soil health. Integrated Disease Management (IDM) offers an effective and sustainable approach by combining cultural, biological and chemical practices. This article discusses major soil borne diseases of vegetables, their symptoms, factors favouring disease development and integrated management strategies for sustainable vegetable production.

Introduction

Vegetable cultivation is an important component of Indian agriculture, providing income, employment and nutritional security to millions of farmers. However, vegetable crops are highly susceptible to soil borne diseases due to intensive cultivation, frequent irrigation and continuous cropping. Soil borne diseases are difficult to manage because the pathogens survive in soil for many years in the form of spores, sclerotia or dormant mycelium. These pathogens attack plants at early growth stages, causing seed rot, damping-off, root rot and wilting. Yield losses due to soil borne diseases in vegetables may range from 20 to 80 percent depending on crop, pathogen and environmental conditions. Therefore, effective and sustainable management of soil borne diseases is essential for profitable vegetable production.

Major Soil Borne Diseases of Vegetable Crops

Several soil borne pathogens cause serious diseases in vegetable crops. Important diseases include:

***Fusarium* Wilt:** Caused by *Fusarium oxysporum*, resulting in yellowing, wilting and vascular discoloration.

Damping-Off: Caused by *Pythium* and *Rhizoctonia* species, leading to seedling death before or after emergence.

Root Rot: Caused by *Rhizoctonia solani*, resulting in root decay and stunted plant growth.

Stem and Collar Rot: Caused by *Sclerotium rolfsii*, characterized by white mycelial growth and sclerotia

Vishal D. Pawar
Assistant Professor, Plant Pathology Section, College of Agriculture, Nagpur, Maharashtra
Kishor T. Thakare
Young Professional-II, Hiwara, Gondia, Maharashtra

near the soil surface.

These diseases are commonly observed in tomato, brinjal, chilli, cabbage, cauliflower, okra and cucurbits.



Symptoms of Soil Borne Diseases

Typical symptoms observed in vegetable crops include:

- ✓ Poor seed germination and seedling mortality
- ✓ Yellowing and wilting of leaves
- ✓ Brown or black discoloration of roots
- ✓ Reduced root system and stunted growth
- ✓ Premature drying and plant death

Early identification of symptoms is crucial for effective disease management.

Factors Favouring Development of Soil Borne Diseases

Several environmental and agronomic factors favour the development of soil borne diseases:

- ✓ Continuous monocropping of vegetables
- ✓ Poor soil drainage and waterlogging
- ✓ Excessive irrigation and high soil moisture
- ✓ Imbalanced fertilizer application
- ✓ Low organic matter content in soil

Integrated Management of Soil Borne Diseases

Integrated Disease Management (IDM) involves the combined use of different management strategies to reduce disease incidence effectively and sustainably.

Cultural Management

- ✓ Cultural practices form the foundation of soil borne disease management:
- ✓ Crop rotation with non-host crops
- ✓ Use of disease-free and certified seeds
- ✓ Proper field drainage and raised bed cultivation
- ✓ Removal and destruction of infected plant debris
- ✓ Solarization of nursery beds

Seed Treatment

- ✓ Seed treatment is one of the most economical and effective methods:
- ✓ *Trichoderma spp.* @ 4-10 g kg^{-1} seed
- ✓ *Pseudomonas fluorescens* @ 10 g kg^{-1} seed
- ✓ Carbendazim or Thiram @ recommended doses
- ✓ Seed treatment protects seedlings during early growth stages.

Biological Control

- ✓ Biological control agents play an important role in suppressing soil borne pathogens:
- ✓ Soil application of *Trichoderma* mixed with FYM or compost
- ✓ Promotion of beneficial soil microorganisms
- ✓ Enhancement of soil microbial diversity
- ✓ Biological methods improve soil health and provide long-term disease suppression.

Chemical Management

Chemical control should be used judiciously as a supportive measure:

- ✓ Soil drenching with recommended fungicides

- ✓ Avoid overuse of chemicals
- ✓ Rotation of fungicides to prevent resistance

Role of Organic Matter

Incorporation of organic matter such as farmyard manure, compost and green manure improves soil structure, increases beneficial microbes and reduces disease severity.

Benefits of Integrated Disease Management

Adoption of IDM practices provides several benefits:

- ✓ Effective and long-term disease control
- ✓ Reduced dependency on chemical fungicides
- ✓ Improved soil health and fertility
- ✓ Enhanced crop yield and quality
- ✓ Sustainable vegetable production

Role of Farmers and Extension Services

Training and awareness programs for farmers play a vital role in successful adoption of IDM practices. Extension services should promote low-cost, eco-friendly technologies and encourage farmers to adopt integrated approaches for disease management.

Conclusion

Soil borne diseases are a major constraint in vegetable crop production, causing significant yield losses. Integrated management of soil borne diseases using cultural, biological and chemical methods provides effective and sustainable control. Adoption of IDM practices not only reduces disease incidence but also improves soil health and farm profitability. Farmers are encouraged to adopt integrated approaches for long-term management of soil borne diseases in vegetable crops.

References

Agrios, G. N. (2005). Plant Pathology. 5th Edition. Elsevier Academic Press.

Harman, G. E., Howell, C. R., Viterbo, A., Chet, I. and Lorito, M. (2004). *Trichoderma* species - opportunistic plant symbionts. *Nature Reviews Microbiology*, 2(1): 43-56.

Shinde, R., Verma, S. and Sarkar, Po.K. (2021). Eroded and Compacted Soils and Their Reclamation. In: Kumar *et al*. (Eds.), Problematic Soils and Their Management. New India Publishing Agency, New Delhi. pp. 79-106.

Genome Editing Tools for Vegetable Crop Improvement

S. Teja and V. Boomika

Abstract

Genome editing has quickly become a game-changing technology in plant science. It lets scientists change DNA sequences very precisely to make targeted mutations and better crop varieties. Genome editing is easier, more accurate and has fewer risks of affecting the wrong genes than classical mutation breeding, which is slow and often unpredictable. Researchers can now edit almost any part of the genome by using tools like CRISPR/Cas9, TALENs, and Zinc Finger Nucleases. Editing is possible even in crops with complicated genetic backgrounds and having few options for breeding. This is especially important for vegetables because they are important for human health and nutrition because they are full of vitamins, minerals, and fiber. Genome editing speeds up functional genomics research in addition to breeding. This helps scientists find out what genes do with more accuracy than ever before. In the future, genome editing could help improve vegetables in a way that is environmentally friendly, uses fewer chemicals and leads to healthier diets. However, there are still problems with regulation and public acceptance. These tools represent a new era in vegetable science, where new ideas at the genetic level led to better crops and better food for everyone.

Introduction

Vegetables are an important part of people's diets because they are full of vitamins, minerals, fiber, and bioactive compounds that keep people healthy. However, growing vegetables is still hard because of pests, diseases, climate stress, and losses after harvest that can lower yield and quality. Many better varieties have come from traditional breeding, but the process is slow, takes a lot of work, and doesn't always work for crops with complicated genomes. The advent of genome-editing technologies signifies a pivotal moment in crop science. Genome editing lets you make exact, predictable changes to specific parts of the DNA, as opposed to random changes that happen in conventional mutation breeding. Scientists can use tools like CRISPR/Cas9, TALENs, and Zinc Finger Nucleases to cut, add, or change genes with amazing precision. These new technologies not only speed up research in functional genomics, but they also make it possible to grow vegetables that are more nutritious, durable, and easy for farmers to work with. Genome editing is already showing its potential by making tomatoes that can resist viruses and cucumbers that can better handle powdery mildew. As rules change and more people learn about these technologies, they

S. Teja
Department of Vegetable Science, ASPEE College of Horticulture, NAU, Navsari, Gujarat
V. Boomika
Department of Fruit Science, ASPEE College of Horticulture, NAU, Navsari, Gujarat

promise to change how we improve vegetables. They will provide long-term solutions that use fewer chemicals, make food safer, and lead to healthier diets.

Types of genome editing tools

Zinc Finger Nucleases (ZFNs)

ZFNs are artificially engineered restriction enzymes that combine a zinc finger DNA-binding domain with the FokI nuclease catalytic domain. Each zinc finger recognizes a 3-base pair sequence and arrays of fingers can be designed to target specific DNA sites. When two FokI domains dimerize at the target they create a double-strand break, enabling gene editing. ZFNs are versatile but can cause off-target effects due to sequence context, leading to genome instability. They have been used experimentally in crops like wheat, maize, tobacco, and rice to introduce herbicide tolerance and site-specific gene integration, though no commercial vegetable varieties currently rely on ZFNs (Brock *et al*., 2025). In tomato target gene NF-Y, L1L4, NF-YB6 responsible for biosynthesis of seed storage proteins and fatty acids then mutants showed varied metabolite profiles and high amounts of OA as compared to wildtype (Gago *et al*., 2017)

Transcription Activator-Like Effector Nucleases (TALENs)

TALENs are the second generation of site-specific nucleases, designed as an alternative to ZFNs. They combine a DNA-binding domain made of TALE repeats (from *Xanthomonas* bacteria) with the FokI nuclease. Each TALE repeat recognizes a single nucleotide, giving TALENs higher specificity and flexibility compared to ZFNs. By assembling repeat variable di-residues (RVDs), researchers can target virtually any DNA sequence and induce double-strand breaks. TALENs have been successfully applied in crops such as rice, soybean, wheat, and potato to improve traits like oil quality, disease resistance and storage stability. Their advantages include easier design and fewer off-target effects, though limitations such as sensitivity to cytosine methylation and sequence requirements at target sites remain (Kim). In potato target gene *Vinv* is edited by using TALEN (SDN1) to produce mutants with improved cold storage and processing traits. (Clasen *et al*., 2016)

CRISPR/Cas9

CRISPR/Cas9 is a powerful genome-editing system adapted from the natural bacterial immune defence against viruses. It uses two components: the Cas9 nuclease and a guide RNA (sgRNA) that directs Cas9 to a specific DNA sequence near a PAM site. Once bound, Cas9 makes a precise cut, enabling targeted mutations or gene replacements. Compared to ZFNs and TALENs, CRISPR/Cas9 is simpler, cheaper and highly versatile with the ability to edit multiple sites at once. It has been widely applied in crops, including vegetables, to improve disease resistance, stress tolerance and nutritional quality. While off-target effects remain a challenge, improved design strategies and breeding can minimize risks, making CRISPR/Cas9 the most widely adopted genome-editing tool in plant science today.

(Kim *et al.*, 2021).

Crop	Target Gene	Trait/Outcome	Reference
Tomato	*SlMlo1*	Resistance to powdery mildew	Nekrasov et al., 2017
Tomato	*SlAGO7*	Altered leaf morphology	Brooks et al., 2014
Tomato	*SlPelo*	Male sterility for hybrid breeding	Xu et al., 2015
Cucumber	*eIF4E*	Resistance to cucumber vein yellowing virus	Chandrasekaran et al., 2016
Potato	*StALS1*	Herbicide tolerance	Butler et al., 2015
Potato	*StGBSS*	Reduced amylose content	Andersson et al., 2017
Cabbage	*BoPDS*	Albino phenotype	Lawrenson et al., 2017
Lettuce	*LsBIR2*	Altered growth regulation	Woo et al., 2015

Fig. 1: Application of CRISPR-Cas9-based editing of genes in vegetables (Kim *et al.*, 2021)

Base Editing

Base editing is a newer genome-editing approach that allows precise single-base changes in DNA without creating double-strand breaks. It uses a modified Cas9 nickase fused with a deaminase enzyme, guided by an sgRNA to the target site. Two main types are cytosine base editors (CBEs), which convert C-G to T-A and adenine base editors (ABEs) which convert A-T to G-C. This technology has been applied in crops like rice, maize, wheat and potato to introduce point mutations with high efficiency. More advanced systems, such as dual base editors (STE ME) can perform multiple base conversions simult-aneously, offering powerful tools for fine-tuning traits and studying regulatory regions. Base editing is especially valuable for improving vegetable crops where subtle gene changes can enhance nutrition, stress tolerance or disease resistance (Kim *et al.*, 2021)

Prime Editing

Prime editing is a recent breakthrough designed to overcome the limitations of earlier genome-editing tools. It uses a Cas9 nickase fused with a reverse transcriptase and guided by a prime editing RNA (pegRNA) to directly write new genetic information into the target site. Unlike CRISPR/ Cas9, it does not rely on double-strand breaks and can introduce precise substitutions, small insertions, or deletions. Prime editing enables up to 12 types of base conversions and has been successfully demonstrated in rice and wheat, though efficiency in plants is still relatively low. Its potential lies in creating highly accurate edits without linkage drag, making it a promising tool for future vegetable improvement once technical challenges are addressed (Kim *et al.*,2021).

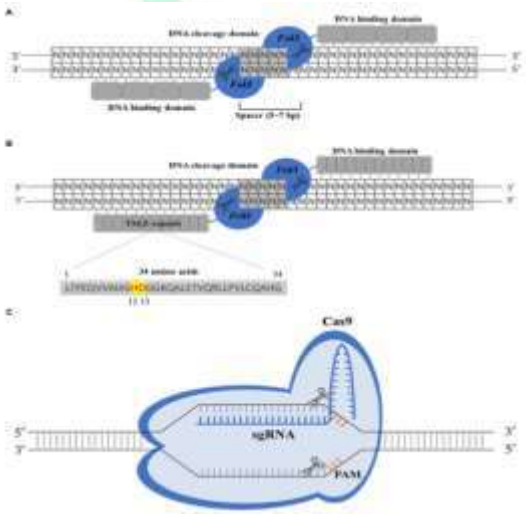


Figure 2: Genome-editing technologies using site-specific nucleases include ZFNs, TALENs and CRISPR-Cas9 systems (Kim *et al.*, 2021)

Challenges of Genome editing tools (Kim et al., 2021)

- ✓ Limited genomic resources
- ✓ Complex and polyploid genomes
- ✓ Low transformation and regeneration efficiency
- ✓ Off-target mutations
- ✓ Delivery bottlenecks for Cas proteins and guide RNAs
- ✓ Trait complexity

- ✓ Regulatory and public acceptance barriers
- ✓ Intellectual property restrictions
- ✓ Limited field validation and trait stability

Conclusion

Genome editing tools have made it possible to make precise changes in vegetable crops that make them more resistant to disease, better for nutrition and able to handle stress. Even though there are problems like off-target effects, complicated genomes and low transformation efficiency, CRISPR/Cas and more advanced editors like base and prime editing are still very useful tools. These technologies can speed up breeding and provide strong, high-quality vegetables for sustainable agriculture if they are improved and tested in more places.

References

Brock, N., Kaur, N. and Halford, N. G. (2025). Advances in genome editing in plants within an evolving regulatory landscape, with a focus on its application in wheat breeding. *Journal of Plant Biochemistry and Biotechnology*, 34(3): 599-614.

Das, T., Anand, U., Pal, T., Mandal, S., Kumar, M., Radha, … and Dey, A. (2023). Exploring the potential of CRISPR/Cas genome editing for vegetable crop improvement: An overview of challenges and approaches. *Biotechnology and Bioengineering*, 120(5): 1215-1228.

Kim, Y. C., Kang, Y., Yang, E. Y., Cho, M. C., Schafleitner, R., Lee, J. H. and Jang, S. (2021). Applications and major achievements of genome editing in vegetable crops: A review. *Frontiers in Plant Science*, 12: 688980.

Gago, C., Drosou, V., Paschalidis, K., Guerreiro, A., Miguel, G., Antunes, D. and Hilioti, Z. (2017). Targeted gene disruption coupled with metabolic screen approach to uncover the LEAFYCOTYLEDON1-LIKE4 (L1L4) function in tomato fruit metabolism. *Plant Cell Reports*, 36: 1065-1082.

Clasen, B. M., Stoddard, T. J., Luo, S., Demorest, Z. L., Li, J., Cedrone, F., Tibebu, R., Davison, S., Ray, E. E., Daulhac, A., *et al.* (2016). Improving cold storage and processing traits in potato through targeted gene knockout. *Plant Biotechnology Journal*, 14: 169-176.

Topsoil to Trouble: Unravelling the Nutrient Crisis behind Soil Erosion

Navjot Kaur and Rekha Bhandari

Abstract

Soil erosion is one of the most critical threats to global agricultural sustainability and ecosystem health. It triggers a cascade of ecological disruptions - stripping away nutrient-rich topsoil, impairing microbial communities, contaminating water bodies and accelerating climate change through carbon losses. This article reviewed literature to examine the causes, consequences and management strategies related to soil erosion, with a particular emphasis on its impact on nutrient cycling. Special attention is given to the Indian subcontinent, including the state of Punjab, where agricultural intensity exacerbates erosion risks.

Introduction

Food hunger, climate change and land degradation are coming together at a rate never seen before. Over 2 billion people worldwide suffer from hidden hunger and 66% of the world's population is at risk of being deficient in one or more important mineral elements, according to FAO (2022). An estimated 12% of global yearly anthropogenic green-house gas (GHG) emissions are attributed to agricultural operations, which also account for half of all anthropogenic N2O emissions. To make matters worse, 23.5 million people were displaced in 2016 alone due to water and climate-related disasters, while 26% of the world's population lives in poverty. There were 258 million foreign migrants by 2017, many of them were motivated by resource scarcity associated with environmental deterioration. Soil is the underlying issue at the heart of these situations. At the core of these crises lies a fundamental problem like soil degradation.

FAO (2022) reports that 33% of the world's soils are already degraded, with nutrient imbalances identified as one of the primary driving causes.

What is Soil Degradation?

Soil degradation is defined as a change in soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries (FAO, 2020). On the global scale, degraded land arises from several interconnected processes:

Soil erosion: The dominant cause, comprising water erosion (68%) and wind erosion (16%)

Chemical degradation: Accounting for 12% of global degraded area

Physical degradation: Responsible for the remaining 4%

Water erosion, as the largest single contributor, merits particular attention as it directly governs the loss of topsoil nutrients, disrupts the physical structure of the land and degrades down-

Navjot Kaur and Rekha Bhandari
Research Scholar, Department of Soil Science, PAU, Ludhiana, Punjab

stream water quality.

Soil Erosion

Soil erosion is a gradual process of movement and transport of the upper layer of soil (topsoil) driven by agents such as water, wind and mass movement, causing long-term deterioration of the land. The process unfolds in three sequential stages (Hagen, 1991):

Detachment: The topsoil is physically dislodged from its original position by the kinetic energy of raindrops or the shear force of wind.

Transport: Detached particles are carried away from their original location via runoff, wind currents, or gravity-driven mass movements.

Deposition: The transported material is eventually deposited in another area, often in valleys, reservoirs, riverbeds, or coastal zones.

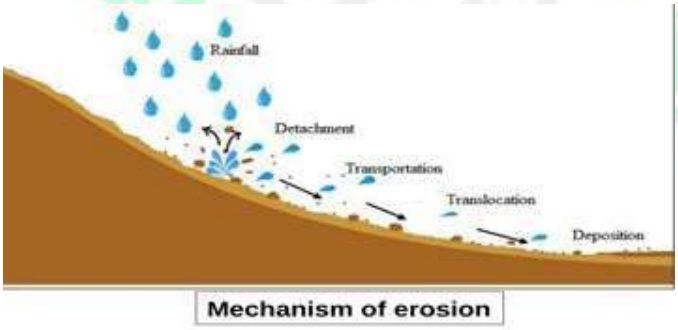


Fig. 1: Mechanism of soil erosion showing detachment, transportation and deposition stages (Hagen, 1991)

Factors Affecting Soil Erosion (Hagen, 1991)

Soil erosion intensity is governed by a complex interplay of natural and anthropogenic factors:

Climate: Rainfall intensity, temperature fluctuations and wind speed are primary drivers. The erosive capacity of runoff increases fourfold when the degree of slope doubles.

Topography: Erosion is directly proportional to the square root of slope length. A fourfold increase in slope degree multiplies erosive capacity by four.

Soil Type: Properties such as infiltration rate, permeability, soil depth, and particle size determine how susceptible a soil is to detachment and transport.

Vegetation: Root systems and plant cover significantly reduce erosion by stabilising soil particles and intercepting rainfall.

Land Use: Agricultural practices, deforestation, and urban expansion drastically alter erosion rates across landscapes.

Agents and Processes of Soil Erosion

Soil erosion is driven by a range of natural and human agents (Hagen, 1991).

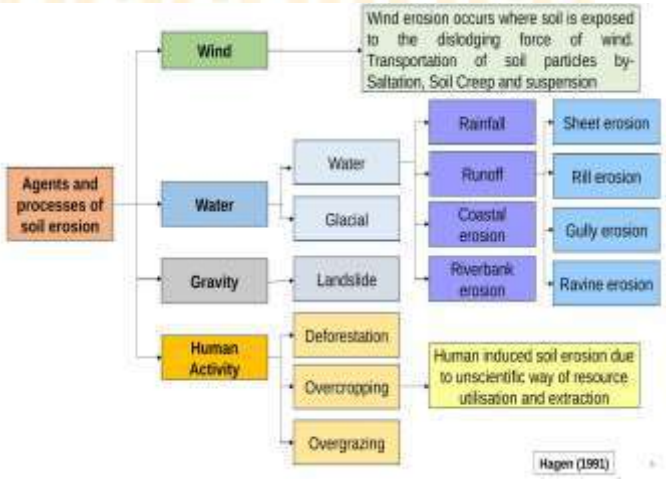


Fig. 2: Agents and processes of soil erosion (Hagen, 1991)

Water erosion operates through rainfall-induced sheet erosion, runoff-driven rill and gully erosion, glacial action, riverbank erosion, coastal erosion and ravine formation. Wind erosion transports particles via saltation, soil creep and suspension. Gravity initiates landslides and mass wasting.

Human activities including deforestation, over-cropping and overgrazing are increasingly major contributors to soil erosion globally.

Soil Erosion in India

India faces one of the most severe soil erosion crises in the world. According to ICAR - Indian Institute of Soil and Water Conservation, Dehradun (2022), land degradation affects 120 M ha in India, of which water erosion alone accounts for 82.6 M ha approx. 68% of the total degraded area.

The fate of eroded material in India

Table 1: Fate of gross erosion and associated losses in India (ICAR, 2022)

Fate of Erosion	Total (Mt)	% of Total Gross erosion rate	Tonnes ha^{-1}
Deposition in reservoirs	1,743	34%	6.7
Displacement within country	2,197	43%	5.3
Discharged to Oceans	1,170	23%	3.6
TOTAL	5,110	100%	15.6

Soil Erosion Status in Punjab

Punjab, often called the 'Granary of India', is not immune to soil erosion threats despite its predominantly flat terrain. According to Pal et al. (2016): 87% of Punjab's total geographical area experiences annual soil loss below 5 Mg ha^{-1}, which is within tolerable limits. 4.02% of the area suffers severe annual soil loss above 15 Mg ha^{-1}, broken down as:

Moderately severe (0.88%): Soil loss of 15-20 Mg ha^{-1}

Severe (1.72%): Soil loss of 20-40 Mg ha^{-1}

Very severe (1.42%): Soil loss of 40-80 Mg ha^{-1}

Estimated Nutrient Loss under Different Land Uses

Table 2: Estimated nutrient loss under different land uses in India

Land Use	Nitrogen (kg ha^{-1} yr^{-1})	Phosphorus (kg ha^{-1} yr^{-1})	Potassium (kg ha^{-1} yr^{-1})
Agriculture Land	20-60	5-20	15-40
Forest Land	2-10	0.5-2	1-5
Grasslands/Pastures	5-15	1-4	3-10
Orchards/Plantations	10-25	2-8	5-15
Bare Land	55-65	20-25	20-40

Impact of Soil Erosion on Nutrient Cycling

Nutrient cycling is the process by which essential elements nitrogen, phosphorus, potassium and others are taken up by plants, returned to the soil through decomposition and recycled within the ecosystem. Soil erosion fundamentally disrupts this natural cycle through four key mechanisms:

- ✓ Depletion of organic matter and topsoil fertility
- ✓ Reduced plant growth and organic matter return
- ✓ Disruption of Soil Microbial Communities
- ✓ Nutrient loss to water bodies and eutrophication

Erosion Management Strategies

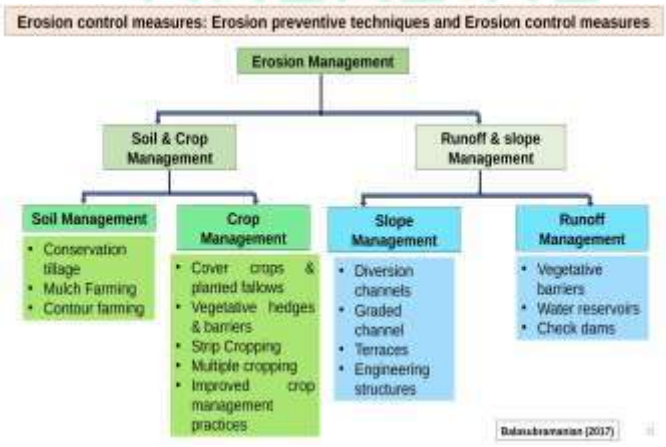


Figure 3: Classification of erosion management strategies (Balasubramanian, 2017)

Soil and Crop Management

Soil management practices include conservation tillage, mulch farming, and contour farming. Crop management strategies encompass the use of cover crops and planted fallows, vegetative hedges

and barriers, strip cropping, multiple cropping systems and improved crop management practices.

Runoff and Slope Management

Slope management involves structural interventions such as terracing, diversion channels, graded channels and engineering structures designed to reduce slope length and runoff velocity. Runoff management measures include of vegetative barriers, water reservoirs and check dams that trap sediment and regulate water flow.

Conclusions

Soil erosion-induced disruption of microbial communities, nutrient cycling or carbon cycles further degrades long-term soil health and productivity. Conservation techniques such as terracing, check dams, conservation tillage and fish-scale pits have showed strong effectiveness across diverse rainfall and slope conditions. Ultimately, soil erosion demands an integrated land management, policy support, and community engagement to secure soil fertility and ecosystem resilience for future generations.

References

Balasubramanian, A. (2017). Soil erosion - causes and effects. University of Mysore Technical Report.

FAO. (2020). State of knowledge of soil biodiversity - Status, challenges and potentialities. Food and Agriculture Organization of the United Nations.

Morgan, R. P. C. (2005). Soil Erosion and Conservation (3rd ed.) Blackwell Publishing.

FAO. (2022). World Food and Agriculture - Statistical Yearbook. Food and Agriculture Organization of the United Nations.

Hagen, L. J. (1991). A wind erosion prediction system to meet user needs. *Journal of Soil and Water Conservation*, 46(2): 106-111.

ICAR-Indian Institute of Soil and Water Conservation, Dehradun, Uttarakhand. (2022). Annual Report.

Lal, R (1998). Soil erosion impact on agronomic productivity and environment quality. *Critical Reviews in Plant Sciences*, 17(4): 319-464.

Pal, S., Sidhu, S., Tiwari, A. K., Sarkar, D. and Sharda, V. N. (2016). Soil erosion in Punjab. *Current Science*, 110(10): 1687.

Mashua: A Colourful Tuber with Health and Agricultural Benefits

P. P. Sudharshan, M. Kalirajan and M. Rajasekar

Introduction

Mashua (*Tropaeolum tuberosum*) is a traditional root crop, native to the Andean regions of South America, where it has been cultivated for centuries alongside potato, oca and ulluco. Mashua is known for its colourful tubers and its high ability to adapt to adverse climatic conditions. It is appreciated as a nutritious food as well as a medicinal plant. The crop is a rich source of carbohydrates, vitamin C, dietary fibre and bioactive compounds responsible for its health-promoting properties. Although it is important in the Andes, mashua is still underutilised in many parts of the world. Due to increasing interest in climate-resilient and nutrient-dense crops, mashua is emerging as a promising alternative food source that can contribute to sustainable agriculture and nutritional security.

Scientific Classification

Kingdom: Plantae

Order: Brassicales

Family: Tropaeolaceae

Genus: Tropaeolum

Species: *T. tuberosum* Ruiz & Pav

Botanical Description

Mashua (*Tropaeolum tuberosum* Ruiz & Pav.) is a perennial herbaceous climbing plant cultivated mainly for its edible underground tubers. The plant has long trailing stems, which may reach a maximum length of 2-4 m. The alternate leaves are peltate, palmate-lobed and reminiscent of the common nasturtium. Bright coloured, showy, tubular flowers are available in a range of colours are yellow, orange and red. It yields long meaty tubers in a range of colours such as yellow, orange, red, purple and mottled. Mahua is a good performer in poor soils and adverse weather and thrives in cold, high-altitude areas.



Plants Morphology

Stems & habitat: It is fast- growing climbing or trailing vine which can grow up to 4 m. Stems are hairless, cylindrical and slender.

P. P. Sudharshan and M. Kalirajan
M.Sc. Scholar, Department of Vegetable Science, SRM College of Agricultural Sciences, Baburayanpettai, Chengalpattu, Tamil Nadu

M. Rajasekar
Assistant Professor, Department of Vegetable Science, SRM College of Agricultural Sciences, Baburayanpettai, Chengalpattu, Tamil Nadu

Leaves: The leaves are alternate, bright green and smooth. They are peltate, with the leaf stalk attaching near the centre of the leaf blade. They are divided into 5-7 rounded lobes in a palmate arrangement. The leaves are borne on long petioles.

Flowers: Flowers are succulent, slender and twining or trailing. They are highly branched and can reach up to 2-4 m length and allow the plant to climb on nearby vegetation.

Roots and tubers: The plant develops a fibrous root system which produces enlarged underground tubers. Tubers are long, fleshy and range in size, shape and color, ranging from cream and yellow to orange, red and purple. These tubers are the plant's main storage and edible organs.

Cultivation

Mashua is mostly cultivated in the Andean countries of South America, like Peru, Bolivia, Ecuador, and Colombia, it is an important traditional food crop. In India, mashua remains largely unknown and is not commercially. Because of its ability to thrive in cool climate and poor soils, the crop has potential for cultivation in India's hill regions.

Health Benefits

Mashua is a tuber loaded with nutrients such as Vitamin C, dietary fibre, antioxidants and health-promoting phytochemicals. It is traditionally used in Andean medicine and is known for its antibacterial, anti-inflammatory and antioxidant properties. Regular consumption can help boost the immune system, enhance digestion, decrease oxidative stress and support general wellness. Its bioactive components also have potential to help in prevention of illness and health.

Future Prospects

Mashua has good potential to become a major crop in the future because of its flexibility, nutritional value and inexpensive needs. The agriculture sector is facing problems due to climate change and decreasing natural resources. There is increasing relevance for crops such as mashua that can grow in harsh conditions. It is also intriguing to people seeking better food options because of its sustainable nutritional content and health promoting characteristics.

Conclusion

Mashua (*T. tuberosum*) is a unique crop, highly adaptable, nutritious and underutilised with a great potential for sustainable agriculture and nutritional security. Farmers and consumers find it appealing due to its ability to withstand harsh weather conditions, its nutrient-rich composition and its medicinal benefits. The growing interest in climate-resilient crops could make mashua a major contributor to diversification of diets and foods security in its traditional areas and in new areas of cultivation.

References

Luera-Quiñones, S. et al. (2025). Mashua (*Tropaeolum tuberosum* Ruiz & Pavón): Nutritional composition, bioactive compounds, and applications in functional foods. *Foods*, 14(24): 4198.

Aguilar-Galvez, A., García-Ríos, D., Ramírez-Guzmán, D., Lindo, J., Chirinos, R., Pedreschi, R. and Campos, D. (2023). *In vitro* and *in vivo* biotransformation of glucosinolates from mashua (*Tropaeolum tuberosum*) by lactic acid bacteria. *Food Chemistry*, 404: 134631.

Coloma, A., Flores-Mamani, E., Quille-Calizaya, G., Zaira-Churata, A., Apaza-Ticona, J., Calsina-Ponce, W. C., Huata-Panca, P., Inquilla-Mamani, J. and Huanca-Rojas, F. (2022). Characterization of nutritional and bioactive compounds in three genotypes of mashua (*Tropaeolum tuberosum* Ruiz and Pavón) from different agroecological areas in Puno. *International Journal of Food Science*, 2022: Article 7550987.

Vera, W., *et al*. (2025). Applications and functional potential of mashua (*Tropaeolum tuberosum*): A review of nutritional composition, bioactive compounds, and health-promoting properties. *Foods*. https://pmc.ncbi.nlm.nih.gov/articles/PMC12692520/

Grau, A., Paredes-Andrade, N. J. and Sørensen, M. (2024). Traditional uses, processes, and markets: The case of mashua (*Tropaeolum tuberosum* Ruíz & Pav.). In M. P. Cereda & O. F. Vilpoux (Eds.), *Traditional Starch Food Products* (Vol. 4, pp. 269-278). Academic Press. https://doi.org/10.1016/B978-0-323-90844-3.00009-3

Benefits of Silicon for Plant Health

Komal, Kanik Kumar Bansal and Gurpreet Kaur

Abstract

Silicon (Si) is the second most abundant element in the Earth's crust and is increasingly recognized as a beneficial element for plant growth. Although not classified as an essential nutrient for most crops, silicon enhances plant tolerance to various biotic and abiotic stresses. Plants absorb silicon as monosilicic acid and deposit it as phytoliths in tissues, improving structural strength and defense mechanisms. Silicon improves photosynthesis, water-use efficiency, nutrient uptake, and resistance to drought, salinity, heavy metals, heat stress, diseases, insects, and nematodes. Recent advances in silicon nanoparticles have further increased the efficiency of silicon application in agriculture. Additionally, silicon contributes to soil health and climate-resilient farming through improved soil structure and carbon sequestration. This review summarizes the major benefits of silicon in plant health and highlights its potential role in sustainable agriculture.

Introduction

Silicon constitutes nearly 28% of the Earth's crust and is absorbed by plants in the form of monosilicic acid. For many years, silicon was considered a non-essential element because plants could complete their life cycle without it. However, extensive research has demonstrated that silicon significantly improves plant growth and stress tolerance, leading to its recognition as a beneficial or quasi-essential element. Recent studies show that plants can increase silicon uptake under stress conditions such as drought or salinity, almost as if they sense trouble and reach for this protective tool (PeerJ, 2026). After uptake, silicon is transported through specialized transport proteins and deposited in plant tissues as silica bodies known as phytoliths. These deposits strengthen plant structures and enhance resistance to environmental stresses. With increasing challenges such as drought, salinity, climate change, and pest outbreaks, silicon has emerged as an important component of sustainable crop production.

Role of Silicon in Plant Growth and Development

Strengthening Plant Structure: Silicon accumulates in cell walls, increasing their rigidity and mechanical strength. This reinforcement reduces lodging, improves stem strength, and creates a physical barrier against pathogen invasion. Silicon deposition also enhances cuticle thickness, reducing water loss and improving protection against external stress.

Improvement in Photosynthesis and Nutrient Uptake

Silicon-treated plants often exhibit higher

Komal, Kanik Kumar Bansal and Gurpreet Kaur
Faculty of Agriculture, Guru Kashi University, Talwandi Sabo, Bathinda, Punjab

chlorophyll content and improved photosynthetic efficiency. Silicon protects chloroplast membranes from oxidative damage and enhances the uptake of essential nutrients such as nitrogen, phosphorus, potassium, and calcium. It also stimulates root development, leading to better water and nutrient absorption.

Silicon-Mediated Tolerance to Abiotic Stresses

Drought Stress: Silicon improves drought tolerance by maintaining plant water status and enhancing antioxidant defense systems. It promotes the accumulation of osmoprotectants such as proline and supports efficient stomatal regulation. Studies have shown that silicon application increases root growth and water-use efficiency, helping plants survive under limited water availability.

Salinity Stress: Salinity negatively affects crop productivity by causing ion toxicity and osmotic stress. Silicon reduces sodium uptake, improves potassium balance, and protects photosynthetic machinery from salt-induced damage. Silicon-treated crops frequently show higher biomass and yield under saline conditions.

Heavy Metal Stress: Silicon reduces the toxicity of heavy metals such as cadmium, lead, and arsenic by decreasing their uptake and translocation within plants. It promotes sequestration of toxic metals in cell walls and vacuoles, thereby protecting vital metabolic processes and improving plant growth.

Heat Stress: High temperatures disrupt photosynthesis and cellular metabolism. Silicon enhances heat tolerance by stabilizing cellular membranes, increasing antioxidant activity, and maintaining photosynthetic efficiency under elevated temperatures.

Silicon-Mediated Resistance to Biotic Stresses

Fungal Diseases: Silicon acts as both a physical and biochemical defense against fungal pathogens. Silicon deposits strengthen plant tissues and reduce pathogen penetration. Additionally, silicon stimulates defense-related enzymes and compounds, enabling plants to respond more rapidly to infections.

Insect Pests: Silicon accumulation in leaves increases tissue hardness and abrasiveness, reducing insect feeding and survival. Silicon also activates jasmonic acid-mediated defense pathways, enhancing the production of compounds that deter herbivorous insects.

Nematodes: Research has shown that silicon application can reduce root-knot nematode infestation by strengthening root tissues and activating defense responses. Silicon-treated plants often exhibit lower gall formation and improved root health.

Silicon Nanoparticles in Agriculture: Recent advances in nanotechnology have led to the development of silicon nanoparticles (SiNPs). Due to their small size and large surface area, SiNPs provide improved uptake efficiency and enhanced stress protection at lower application rates. Studies indicate that nano-silicon improves drought and salinity tolerance by enhancing antioxidant activity, maintaining membrane stability, and regulating stress-responsive genes.

Although promising, further studies are required to evaluate their long-term environmental impacts.

Silicon and Sustainable Agriculture: Beyond plant protection, silicon contributes to soil health by improving soil aggregation, water retention, and microbial activity. Silicon-rich phytoliths can store carbon for long periods, contributing to carbon sequestration and climate change mitigation. Silicon fertilizers derived from industrial by-products and agricultural residues such as rice husk ash offer environmentally friendly and cost-effective options for sustainable farming systems.

Conclusion

Silicon has emerged as a valuable tool for improving plant health and productivity. Its ability to strengthen plant structures, enhance photosynthesis, improve nutrient uptake, and increase resistance to biotic and abiotic stresses makes it highly relevant for modern agriculture. Furthermore, advances in nano-silicon technology and its role in soil sustainability highlight its potential in climate-smart farming. Continued field-based research will help optimize silicon use across different crops and production systems, contributing to resilient and sustainable agriculture.

References

ACS Omega. (2024). Silicon-mediated improvement in drought and salinity stress tolerance of black gram (*Vigna mungo* L.).

Agriculture. (2025). Silicon as a tool to manage *Diaphorina citri* and soil and leaf chemistry in Tahiti lime.

Discover Applied Sciences. (2025). Exploring the role of silicon in enhancing sustainable plant growth and stress mitigation.

Eghlima, G., Moradi, P. and Mastinu, A. (2024). Nano-silicon foliar application improves drought tolerance. *Horticulturae*, 10(8): 806.

Etesami, H. (2025). Silicon as a beneficial element for plant growth in challenging environments. *Agronomy Journal*, 117(2): 412-438.

Ma, J. F. and Yamaji, N. (2006). Silicon uptake and accumulation in higher plants. *Trends in Plant Science*, 11(8): 392-397.

Mitani-Ueno, N., and Ma, J. F. (2021). Linking transport system of silicon with its accumulation in different plant species. *Soil Science and Plant Nutrition*, 67(2): 245-251.

Mukarram, M., Choudhary, S., Khan, M. M. A. and Corpas, F. J. (2024). Silicon-mediated heavy metal tolerance in crop plants. *Plant, Cell and Environment*, 47(4): 1205-1224.

PeerJ. (2026). Nano-scale silicon intervention for improving abiotic stress resilience in rice: Mechanistic insights and practical applications.https://doi.org/10.7717/peerj.12880103

Thakral, V., Kumar, S. and Bhardwaj, R. (2024). Silicon-mediated mechanisms of abiotic stress tolerance in crop plants. *International Journal of Molecular Sciences*, 25(7):, 3891.

Role of Seed Marketing in Agricultural Practices

Shubham Sahil

Abstract

Seed is the primary input driving agricultural yield and the key carrier of genetic innovation. However, high-yielding and resilient varieties can only transform farm productivity when supported by an efficient seed marketing system. This article explores how strategic seed marketing spanning demand forecasting, quality assurance, optimal pricing, rural distribution, farmer education, and digital advisory bridges the gap between seed breeders and smallholder farmers. It addresses persistent structural constraints like fake seeds, supply delays, and climate uncertainty while offering actionable frameworks for agribusiness professionals.

Introduction

Agriculture is the backbone of the Indian economy, supporting nearly half of the national population and ensuring food security for 1.4 billion people. With shrinking arable land, climate risks, and surging food demand, enhancing crop productivity is a vital national mandate. Among all agricultural inputs, quality seed is the most fundamental 'carrier of technology' determining genetic yield potential, crop health, and economic returns. Developing high-yielding seeds alone does not guarantee agricultural progress. Seeds must reliably reach farmers through an efficient marketing framework. Seed marketing bridges the gap between scientific breeding and field application, ensuring quality seeds arrive at the right time, location and price point. Modern seed marketing goes beyond simple distribution to include market research, promotional education, digital advisory, and comprehensive post-sales service.

Understanding Seed Marketing & Quality Inputs

Seed marketing is the strategic process of planning, pricing, promoting, and distributing certified seeds to farmers while delivering value and satisfaction. Its primary objectives include ensuring timely seed delivery, promoting high-yielding hybrids, raising crop profitability, and fostering long-term brand trust. Quality seeds are proven to increase agricultural output by 15-20% on their own, with greater gains when paired with balanced agronomy. Key attributes of superior seed include high genetic purity, vigorous germination, pest/ disease resistance, uniform maturity, and tolerance to environmental stress. Adopting certified seeds directly boosts farm incomes compared to traditional farm-saved seeds.

Core Components of Seed Marketing

An effective seed marketing framework comprises seven interconnected operations designed to deliver value to rural communities:

Market Research and Demand Analysis: Evaluat-

Shubham Sahil
MBA (Agri-Business Management) Student, College of Agribusiness Management, BAU, Sabour, Bihar

ing agro-climatic conditions, regional cropping patterns, farmer preferences, and purchasing power to introduce tailored seed varieties.

Product Development and R&D: Investing in plant breeding, field evaluation, and biofortification to create climate-resilient, disease-resistant hybrids.

Quality Assurance and Certification: Conducting seed testing and certification to guarantee high germination, physical purity, and disease-free seed lots.

Competitive and Inclusive Pricing: Structuring affordable pricing models, seasonal discounts, and dealer incentives that encourage adoption among smallholders.

Distribution and Supply Chain Management: Leveraging distributors, retail dealers, FPOs, and cooperatives to guarantee timely pre-sowing seed delivery across remote rural markets.

Farmer Education and Promotion: Conducting field demonstrations, village meetings, Kisan Melas, and multimedia campaigns to build confidence in modern seed technologies.

Technical Support and After-Sales Service: Deploying field officers to advise on seed treatment, sowing methods, nutrient management, and resolving field complaints.

Structure of Seed Distribution Channels

The seed supply chain in India relies on three primary distribution channels to ensure physical availability, affordability, and accessibility across diverse agro-ecological zones:

Government / Public Channel: Operated through State Departments of Agriculture, National Seeds Corporation (NSC), State Seeds Corporations (SSCs), and Krishi Vigyan Kendras (KVKs). This channel plays a crucial role in distributing subsidized seeds of high-volume, self-pollinated crops (wheat, paddy, pulses) and ensuring food security in marginalized or remote regions.

Private Sector Channel: Comprises private seed corporations, distributor networks, wholesale dealers and village agri-input retailers. Driven by high R&D investment, this channel focuses primarily on high-value hybrid seeds (maize, cotton, vegetables) and leverages extensive marketing networks, brand building, and promotional demonstrations.

Cooperative and FPO Channel: Functions through Primary Agricultural Credit Societies (PACS), district cooperative marketing federations, and Farmer Producer Organizations (FPOs). This community-centric channel bridges last-mile gaps by supplying certified seeds alongside subsidized micro-credit and extension support directly at the village level.

Impact of Seed Marketing on Agricultural Productivity

Seed marketing plays a pivotal role in transforming agricultural output across several structural dimensions:

Accelerating Technology Adoption: Converts laboratory innovations into field-level crop adoption through live demonstrations and advisory.

Ensuring Sowing Timeliness: Prevents yield loss caused by late planting by maintaining robust invent-

ory and agile logistics.

Enhancing Farm Incomes: Delivers higher crop yields and premium grain quality, driving farmer profitability and reinvestment.

Strengthening Food Security: Maximizes food output per unit of land, supporting national food buffers and market stability.

Mitigating Climate and Production Risks: Distributes stress-tolerant seeds (drought, flood, heat) that safeguard yields during adverse weather.

Promoting Sustainable Farming: Encourages resource-efficient crop varieties requiring less water and chemical protection.

Modern Trends in the Seed Sector

Technological integration and changing farmer demographics are reshaping agribusiness marketing models across India:

Digital Marketing and Mobile Advisory: Utilizing WhatsApp, mobile apps, YouTube, and localized SMS for crop guidance and direct farmer engagement.

Precision Farming Integration: Pairing seed selection with soil sensors, satellite imagery, and drone analytics for optimal resource use.

Direct-to-Farmer and E-Commerce: Expanding online ordering and direct delivery models that reduce intermediary markups.

Public-Private Partnerships (PPP): Collaborating between ICAR, SAUs, and private seed firms to accelerate technology transfer.

Key Challenges in Seed Marketing

Despite rapid sector growth, seed marketing faces significant operational hurdles that require targeted intervention:

Low Awareness and Traditional Practices: Many smallholders rely on saved seed due to information gaps or risk aversion.

Spurious and Counterfeit Seeds: Substandard seed sales damage crop yields and erode farmer trust in commercial brands.

Rural Logistics and Storage Constraints: Inadequate warehousing in remote hubs causes seed quality deterioration and supply bottlenecks.

Price Sensitivity and Financial Bottlenecks: High upfront hybrid seed costs disincentivize cash-constrained farmers without micro-credit.

Strategic Action Plan for Agribusinesses

To overcome challenges and elevate marketing effectiveness, seed companies and policy leaders should pursue six strategic priorities:

Expand Last-Mile Retail Networks: Partner with FPOs, rural cooperatives, and local agri-dealers to ensure timely village access.

Deepen Demonstration Programs: Establish frontline demonstration plots to provide visible, local proof of hybrid performance.

Implement QR Traceability: Deploy QR code tracking on seed packages to eliminate fake seeds and build brand authenticity.

Strengthen Technical Advisory: Deploy agri-extension professionals to deliver season-long guidance from sowing to harvest.

Develop Climate-Smart Offerings: Focus marketing strategies on stress-resilient varieties tailored to

changing weather patterns.

Facilitate Input Financing: Collaborate with rural banks and fintechs to offer timely credit for purchasing certified seeds.

Conclusion and Core Takeaways

Seed is the initial and most vital link in the agricultural production chain. Connecting scientific breeding with practical farming through efficient seed marketing ensures that productivity gains reach smallholders effectively. By embracing digital tools, strengthening quality control, and placing farmer success at the center of agribusiness strategy, the seed sector can drive sustainable agricultural growth and long-term food security.

Summary of Core Implications for Agribusiness

- ✓ Quality seed is the foundation of crop productivity (15-20% yield gain).
- ✓ Efficient marketing ensures timely availability and last-mile accessibility.
- ✓ Farmer education and field demonstrations drive modern technology adoption.
- ✓ Digital tools, QR traceability, and extension services build brand trust.
- ✓ Farmer-centric strategies enhance farm income, resilience, and national food security.

References

Acharya, S. S. and Agarwal, N. L. (2022). Agricultural marketing in India (7th ed.). Oxford & IBH Publishing.

Government of India. (2023). National Seed Policy and Seed Sector Development. Ministry of Agriculture and Farmers Welfare.

Indian Council of Agricultural Research. (2023). Handbook of Agriculture (8th ed.). ICAR Publications, New Delhi.

Kotler, P., Keller, K. L., Chernev, A. and Sheth, J. (2024). Marketing management (16th Global ed.). Pearson Education.

National Seed Corporation Limited. (2023). Annual Report 2022-23. NSC, Government of India.

Seed Association of India. (2023). Indian Seed Industry: Growth and Prospects. https://seedassociationindia.com

Bridging Agri-Inputs to End Consumers: Shaping Resilient and Sustainable Food Ecosystems

Muskan Kumari

Abstract

The global agrarian supply chain is experiencing a significant structural transition, shifting from isolated, production-driven chemical input manufacturing to an integrated, consumer-orientated agro-food network. Historically, fundamental farm inputs such as high-yielding seeds, synthetic plant nutrition, and crop protection chemicals were managed as disconnected upstream tools aimed exclusively at maximizing gross output. At present, evolving consumer awareness regarding food safety, chemical residue elimination, fully traceable supply chains, and environmental stewardship is reformulating how agricultural inputs are synthesized, commercialized, and deployed at the field level. This manuscript provides a comprehensive evaluation of the direct link connecting farm inputs to end-consumer markets, detailing the strategic roles of biological formulations, digital provenance tracking, Farmer Producer Organizations (FPOs), and direct-to-consumer ag-tech models in constructing durable, sustainable food systems.

Introduction

Global food production frameworks operate under a critical dual objective: supplying adequate food, fiber, and nutrition for a human population expected to approach 10 billion by mid-century, while simultaneously arresting soil degradation, freshwater depletion, and ecological imbalance. In traditional agricultural economics, agribusiness value chains functioned in rigid silos. Upstream input providers concentrated exclusively on elevating per-hectare volume yields through synthetic chemical fertilizers and synthetic pesticides, while downstream post-harvest aggregators, food processors and grocery retailers acted independently at the consumer endpoint.

Contemporary consumers, however, increasingly demand complete visibility into agricultural origin, cultivation methodology, and supply chain handling. Heightened concern over chemical residue accumulation, soil organic degradation, agricultural greenhouse gas emissions, and dietary nutritional density has established a direct feedback loop linking consumer market preferences with upstream input choices. Establishing a seamless connection between agricultural inputs and consumer retail markets creates a closed-loop value ecosystem where sustainable field practices directly improve human health, corporate brand value, and environmental sustainability.

Transforming Upstream Agri-Inputs: Aligning

Muskan Kumari
MBA (Agri-Business Management) Student, College of Agribusiness Management, BAU, Sabour, Bihar

Manufacturing with Green Demand

Building a sustainable food system originates at the seed and soil level. Rising market demand for residue-free produce is driving substantial innovation across core input sectors:

Climate-Resilient and Biofortified Germplasm: Plant breeders are actively prioritizing biofortified crop varieties (such as zinc-dense wheat and iron-rich pearl millet) alongside climate-hardy hybrids engineered to withstand prolonged drought, soil salinity, and extreme heat without forfeiting nutritional value.

Biological Soil Nutrition and Microscopic Inoculants: Transitioning from heavy reliance on synthetic chemical fertilizers toward mycorrhizal fungi, bio-inoculants, and botanical biostimulants restores soil organic matter, stimulates soil microflora and reduces nitrate contamination in ground water aquifers.

Targeted Biopesticides and Residue Control: Integrating microbial biopesticides, natural botanical extracts, and pheromone disruption systems curtails chemical residue levels on harvested crops, ensuring full compliance with stringent Maximum Residue Limits (MRLs) demanded by premium domestic and international retail markets.

Midstream Infrastructure: FPO Aggregation, Ag-Tech, and Traceability Platforms

Translating sustainable input adoption into premium consumer value requires robust midstream aggregation networks and digital verification infrastructure:

Farmer Producer Organizations (FPOs) as Aggregation Pillars: FPOs consolidate smallholder input requirements to procure certified seeds and bio-formulations at wholesale costs, while simultaneously enforcing standardized post-harvest protocols to satisfy commercial retail specifications.

Digital Traceability and Blockchain Provenance: Implementing QR-code tracking systems from seed packaging to supermarket shelves allows end consumers to scan product labels and verify farm-level practices, organic credentials, and chemical residue compliance in real time.

Precision Agronomy and Smart IoT Integration: Utilizing drone-assisted application systems, satellite crop monitoring, and soil sensors guarantees that agricultural inputs are applied strictly on a variable-rate basis, minimizing total chemical loading while optimizing crop uniformity.

Value Chain Dimension	Traditional Supply-Driven Paradigm	Sustainable Consumer-Centric Paradigm
Agri-Input Selection	Focus on max volume output; heavy synthetic chemical reliance	Focus on bio-inputs, stress resilience & residue-free safety
Agronomic Extension	Ad-hoc, unmonitored chemical application schedules	Precision agronomy, soil testing & Integrated Input Management
Market Connectivity	Fragmented intermediaries with opaque price discovery	Direct-to-consumer ag-tech platforms & FPO retail linkages
Quality Verification	Visual grading at wholesale mandis; zero input tracking	QR-code digital provenance from seed/soil to consumer plate
Consumer Value	Variable food safety; unverified environmental footprint	Certified residue-free produce, high nutrition & eco-transparency

Downstream Value Creation: Empowering Far-

mers and Consumers

Satisfying Consumer Demand for Safe and Ethical Food: Urban consumer segments demonstrate an increasing willingness to pay a financial premium for independently verified residue-free, organic, or sustainably cultivated food. Aligning farm-level input deployment with these retail market preferences enables agribusinesses to secure brand loyalty, enhance dietary nutrition, and support overall public health goals.

Elevating Farmer Income and Agribusiness Profitability: Adopting sustainable input management reduces long-term cultivation expenditure by optimizing resource conversion efficiency. Additionally, traceable produce secures higher market realizations, ensuring smallholders capture an expanded share of the final consumer price while buffering against climate-induced production volatility.

Strategic Action Roadmap for Agribusiness Stakeholders

To accelerate the development of an integrated, sustainable food system, industry leaders and agricultural policymakers should implement five strategic imperatives:

Accelerate R&D in Bio-Inputs and Nano-Technologies: Direct public and private capital toward advanced biopesticides, nano-nutrients, and microbial inoculants.

Expand Digital Value Chain Platforms: Scale digital ag-tech platforms that connect upstream input distribution networks directly with FPOs and commercial retailers.

Standardize National Traceability Protocols: Establish official regulatory guidelines for QR-code provenance, residue-free testing, and eco-labeling.

Strengthen Agricultural Extension and Advisory: Conduct comprehensive farmer training on Integrated Nutrient Management (INM) and Integrated Pest Management (IPM).

Incentivize Sustainable Input Adoption: Provide micro-credit facilities and financial incentives for growers adopting climate-smart biological inputs and micro-irrigation.

Conclusion

Building the future of sustainable food systems requires dismantling historical barriers separating upstream agricultural input manufacturing from downstream consumer retail markets. Aligning input chemistry, biological innovations, and precision farming with consumer expectations for safe, traceable, and eco-friendly produce empowers agribusinesses to drive a transformative paradigm shift. Re-engineering the agricultural supply chain from 'Agri-Inputs to Consumer' guarantees environmental preservation, elevates smallholder livelihoods, and secures global food sustainability.

References

Acharya, S. S. and Agarwal, N. L. (2022). Agricultural marketing in India (7th ed.). Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi.

Indian Council of Agricultural Research. (2023). Handbook of Agriculture (8th ed.). ICAR Publications, New Delhi.

Government of India. (2023). Annual Report 2022-23. Ministry of Agriculture and Farmers Welfare, Department of Agriculture and Farmers Welfare, New Delhi.

Kotler, P., Keller, K. L., Chernev, A. and Sheth, J. (2024). Marketing management (16th Global ed.). Pearson Education.

Swaminathan, M. S. (1996). Sustainable Agriculture: Towards an Evergreen Revolution. Konark Publishers Pvt. Ltd., Delhi, pp. 232.