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Root System Architecture Plays a Pivotal Role in Alleviating Phosphorus Deficiency Stress in Legumes

Somsole Bharath, Uttarayan Dasgupta, Darshan G. P., Umashankar, Neeraj Kumar and Chellapilla Bharadwaj

The bioavailable form of phosphorus, known as inorganic phosphate (Pi), is indispensable for the proper growth and development of plants. Within cells, it serves as a fundamental component of nucleic acids, the carriers of genetic information. Pi is also a crucial constituent of ATP, the primary energy currency utilized by cells. Additionally, cellular membranes, which delineate various compartments within the cell and separate the cell's interior from its external environment, rely on phospholipids, another form of Pi, for their structural integrity. Moreover, phosphate plays a pivotal role in numerous enzymatic reactions involved in both anabolic and catabolic pathways. Second only to nitrogen, phosphorus is a major limiting factor for plant productivity. In soil, the majority of phosphate exists in insoluble inorganic or organic complexes, rendering it inaccessible for direct uptake by plant roots. Consequently, many agricultural lands world-wide face either inherent phosphorus deficiency or are currently experiencing scarcity of Pi. To achieve optimal crop yields, these lands necessitate substantial quantities of phosphate fertilizers. How-ever, the availability of phosphate reserves, notably phosphate rocks, is limited globally, exacerbating the challenge. In response to phosphorus deficiency, plants have evolved a repertoire of molecular, biochemical, physiological and morphological adaptations. In this article we would like to emphasize on the prominence of root system architecture and how does the plants plasticize the root architecture to overcome the phosphorus deficiency stress.

The integral role of root system architecture in plant resilience

To cope with low phosphorus stress, plants remodel their root system architecture through coordinated changes in root growth, branching and spatial arrangement (Fig. 1). Phosphate is predominantly found in the upper layers of soil, gradually diminishing in concentration as soil depth increases. As it remains stationary, plants adapt their flexible root system architecture to efficiently acquire nutrients, such as phosphorus, from the soil. Root system architecture refers to the spatial arrange-ment of all root components, including root hairs. Nutrient availability can influence various aspects of root system architecture, including root length, diameter, quantity, angle, and density (Fig. 2). In conditions of low phosphate availability, primary

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root length in dicot plants like *Arabidopsis* may be suppressed due to disruption of the root's growth region. It is hypothesized that the root tip detects signals of low phosphate and triggers the activation of the low phosphate root (LPR) protein, which subsequently alters hormonal levels, thereby affecting the structure of the root's growing tip (Lynch, 2011).

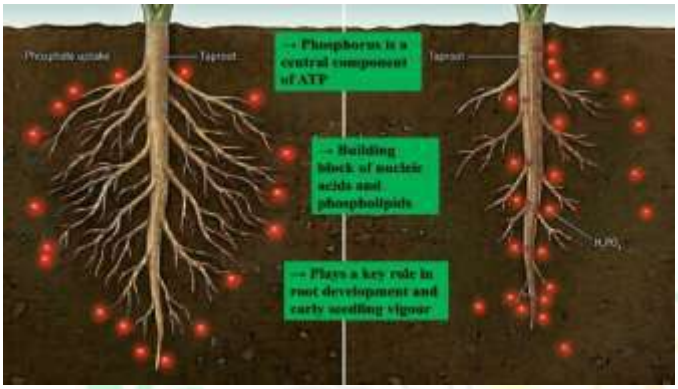

Figure 1: Role of phosphorus and root system architecture responses demonstrating increased lateral root elongation under phosphorus deficiency (left) compared to phosphorus sufficient conditions (right)

In leguminous plants such as white lupin and chickpea, primary root length inhibition due to phosphate deficiency is well-documented. This deficiency not only affects primary root growth across various plant species but also stimulates lateral root elongation in plants like *Arabidopsis*, rice, chickpea, and white lupin. In chickpea, low phosphorus tolerant genotypes typically maintain greater primary root extension and develop a more prolific lateral root system under phosphorus deficiency. Consistent with this pattern, a recent hydroponic study in chickpea landraces reported that genotypes showing better performance under low phosphorus conditions had greater primary root length, total root length, total surface area, root volume, root dry weight and root mass ratio at the seedling stage (Bharath *et al*., 2025a; Bharath *et al.*, 2025b). These findings indicate that phosphorus efficient genotypes express stronger root system response under stress, which supports better adaptation to low phosphorus conditions (Figure 3). This enhanced root proliferation increases soil exploration, allowing plants to intercept limited phosphate more efficiently from the upper soil layers. As a result, tolerant genotypes show improved adaptive root architecture, better nutrient foraging capacity, and superior growth performance under low phosphorus conditions compared with sensitive genotypes. Moreover, an increase in lateral root density accompanies this elongation. Such modifications in root system architecture prove beneficial for nutrient acquisition from the top soil, thereby enhancing plant survival in low phosphate conditions.

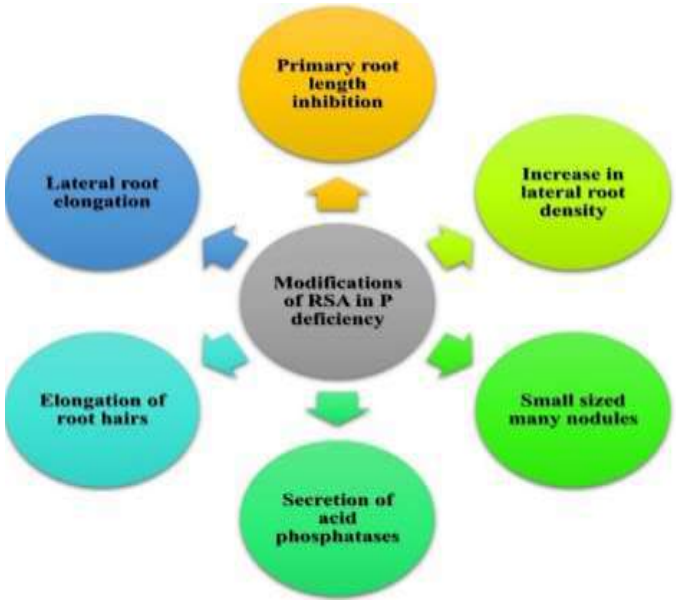

Figure 2: Representing the modifications of root system architecture in P deficiency

Studies on common bean indicate that genotypes proficient in phosphate utilization exhibit greater secondary root growth compared to inefficient genotypes, with minimal shoot growth observed. Experiments suggest that signals of phosphate deficiency originate within the phosphate-deficient zone of the rhizosphere, triggering secondary root growth in regions where phosphate is available. Similar responses have been noted in barley, where deficiencies in nutrients like nitrate, ammonium, and potassium also induce secondary root growth in nutrient-rich areas. This implies that plants promote secondary root growth in regions abundant in nutrients to optimize nutrient uptake, particularly in response to nutrient deficiencies. These newly formed root branches consist of non-respiring xylem and sclerenchyma tissues, thus minimizing energy expenditure while maximizing nutrient absorption (Lynch and Brown, 2001).

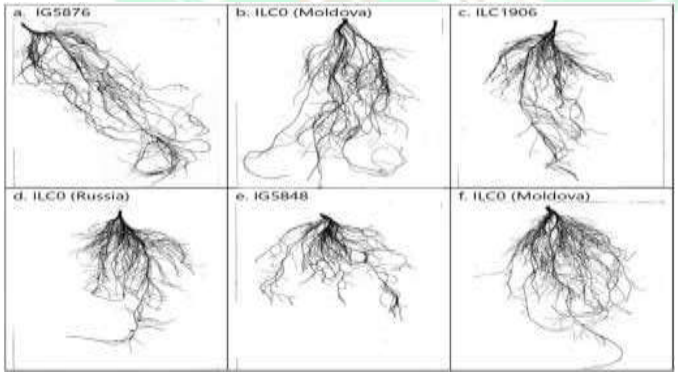

Figure 3. Representative root system images of *Cicer arietinum* L. genotypes grown under low phosphorus (a, b, c) and sufficient phosphorus (d, e, f), illustrating variation in root length and lateral root development. The image clearly shows differences in root length, branching and root spread among genotypes, reflecting contrasting responses to phosphorus availability. Source: Bharath *et al.* (2025). *Indian Journal of Agricultural Sciences*, 95(8): 931-937.

Leguminous plants like white lupin exhibit a unique root adaptation known as cluster roots when facing phosphorus deficiency. The formation of these cluster roots is influenced by the internal phosphorus levels of the plant. Surrounding the cluster roots, the rhizosphere becomes enriched with exudates, promoting the solubilization and uptake of phosphorus. However, it's worth noting that cluster root formation has not been observed in several members of the Leguminosae family, such as chickpea.

Phosphorus deficiency prompts the formation and elongation of root hairs in various plant species. Interestingly, this elongation of root hairs appears to be specific to phosphorus deficiency, as deficiencies in other nutrients like boron, manganese and sulphur do not affect root hair length. Root hairs are elongated epidermal cells that greatly increase the root's surface area. Plants can produce root hairs with minimal metabolic cost, making this morphological adaptation an efficient strategy for enhancing phosphate acquisition. It is well-established that root hairs play a crucial role in phosphate uptake, with plants exhibiting longer root hairs able to acquire more phosphate. However, there is limited information available on chickpea root architecture under phosphorus deficiency.

Experiments by researchers found that chickpea varieties with longer and denser root hairs absorb nutrients, including phosphorus, more effectively than those with shorter hairs. Additionally, root hairs play a role in soil acidification.

This acidification may be facilitated by root exudates containing secondary metabolites like oxalic acid and citric acid, which help release inorganic phosphate from bound forms. Roots also secrete acid phosphatases (APases) to break down phosphate from organic complexes, making it accessible to the roots. Leguminous plants, including chickpea, feature specialized root structures called "root nodules", forming a symbiotic relationship with *Rhizobia* bacteria to enhance plant nutrition and soil fertility. Phosphorus deficiency can hinder nodule development, affecting nitrogen fixation. Nodules have a higher demand for phosphate compared to shoots, and mild phosphorus deficiency may result in smaller nodules but increased nodule numbers. It's unclear if phosphorus partitioning is influenced by bacterial demand or plant adaptation.

Conclusions and future perspectives

Legume varieties exhibit substantial genetic diversity and root system architecture, offering valuable scope for improving phosphorus acquisition efficiency. Future breeding efforts should focus on root traits that enhance phosphorus foraging under low phosphorus conditions, including lateral root proliferation, root angle, root elongation, root development and the cluster root formation where relevant. Identifying and characterising germplasm with favourable root phenotypes should be the first step toward developing nutrient efficient varieties. Integrating phenotyping with genomic tools will further accelerate the use of these traits in breeding programmes aimed at improving productivity under phosphorus limited conditions.

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Computer Vision Techniques for Real-Time Wheat Yield Prediction

Theja Lakshmi T. and Anjelo F. Denis

Abstract

Wheat is one of the world's most important cereal crops, contributing significantly to food security and agricultural economies. Accurate real-time wheat yield prediction supports farm management, market planning, and national food policy decisions. Traditional yield estimation methods are labor-intensive, time-consuming, and often less accurate under variable field conditions. Recent advances in computer vision, remote sensing, and artificial intelligence have enabled non-destructive and high-throughput yield prediction systems using RGB images, UAV imagery, satellite data, and deep learning models. This review examines major computer vision techniques used for real-time wheat yield prediction, including image acquisition systems, feature extraction, machine learning, and deep learning approaches such as CNN, Mask R-CNN, YOLO, and U-Net. The integration of multispectral sensors, hyperspectral imaging, and weather-based decision support systems is also discussed. Critical analysis highlights strengths, limitations, and research gaps across recent studies. Challenges such as occlusion, lighting variability, limited annotated datasets, and model transferability remain significant barriers to field-scale deployment. Future research should focus on multimodal data fusion, edge-AI systems, and farmer-friendly low-cost solutions. The review concludes that computer vision offers strong potential for precision agriculture and sustainable wheat production, especially when combined with robust agronomic validation and policy support.

Introduction

Wheat is a major staple crop globally and plays a central role in food and nutritional security. Accurate pre-harvest yield prediction is essential for crop management, input planning, storage decisions, and trade policy. Conventional methods rely on manual sampling and destructive measurements, which are slow and expensive. Computer vision provides a non-invasive alternative by using images from field cameras, drones, and satellites to estimate plant traits such as spike number, canopy cover, plant height, biomass, and grain formation. These traits are directly associated with final yield. Recent advances in artificial intelligence have improved the speed and precision of yield estimation. This review focuses on computer vision techniques for real-time wheat yield prediction and evaluates current methods, practical applications, and future research needs.

Thematic Sections

Image Acquisition Platforms: Ground-based RGB

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cameras provide close-range crop monitoring with low cost. UAVs capture high-resolution canopy images and support ear counting and biomass estimation. Satellite platforms such as Sentinel-2 and Landsat provide large-scale monitoring through vegetation indices like NDVI and EVI.

Feature Extraction for Yield Prediction: Important visual traits include spike density, spikelet count, leaf area index, canopy temperature, and chlorophyll status. Traditional image processing used segmentation and thresholding, while modern systems rely on deep feature extraction using convolutional neural networks.

Deep Learning Models: CNN models improve feature learning for wheat trait prediction. Mask R-CNN is effective for spike detection under overlapping conditions. YOLO models provide real-time object detection suitable for mobile and edge systems U-Net supports segmentation of spikes and canopy regions. SlypNet demonstrated high precision using Mask R-CNN and U-Net for spikelet-based yield prediction.

Multispectral and Remote Sensing Integration: Combining RGB with multispectral and radar imagery improves robustness. Sentinel-2 combined with weather forecasting improved county-scale yield prediction accuracy. Radar data are especially useful under cloudy conditions.

Critical Analysis and Discussion

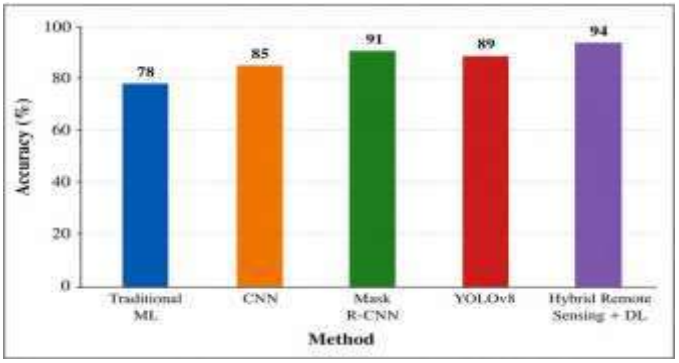
Most studies report high accuracy under controled experimental conditions but lower generalization across regions and seasons. Deep learning models require large labeled datasets, which are often unavailable. Smallholder farming systems also face challenges related to device cost and internet access. RGB-based systems are affordable but sensitive to lighting variation. UAV systems provide better accuracy but increase operational cost. Satellite systems scale well but may miss field-level variability. Therefore, hybrid systems combining field imaging with remote sensing are more promising. Research gaps include explainable AI, real-time edge deployment, standard benchmark datasets, and stronger integration with agronomic decision-making.

Table 1: Comparison of Recent Studies

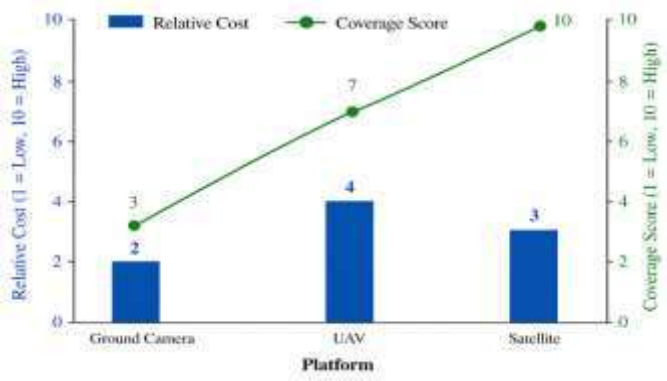
Study	Year	Method / Data Used	Main Finding
Maji et al.	2022	Mask R-CNN + U-Net	High precision spikelet prediction
Zhang et al.	2024	Landsat + MODIS + Machine Learning	Improved county and pixel-level prediction
Li et al.	2024	Sentinel-2 + Weather + Deep Learning	Better in-season yield prediction
Ashfaq et al.	2025	Climate + Satellite + AI	Strong national-scale prediction

Table 2. Advantages and Limitations

Technology	Advantage	Limitation
RGB Camera	Low cost and easy to use	Sensitive to lighting changes
UAV Imaging	High-resolution field monitoring	Expensive operation
Satellite Imaging	Large-scale monitoring and wide coverage	Lower field-level precision
Deep Learning	High prediction accuracy and automation	Requires large labeled datasets and high computational power



Graph 1: Dataset 1: Accuracy Comparison (%)



Graph 2: Dataset 2: Cost vs Field Coverage

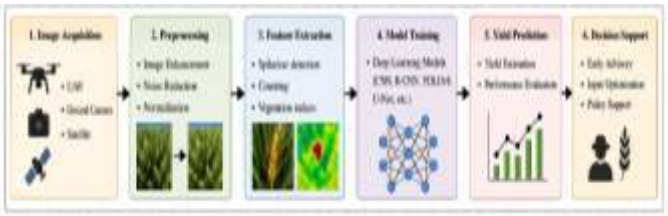


Fig. 1. Workflow of computer vision-based wheat yield prediction system

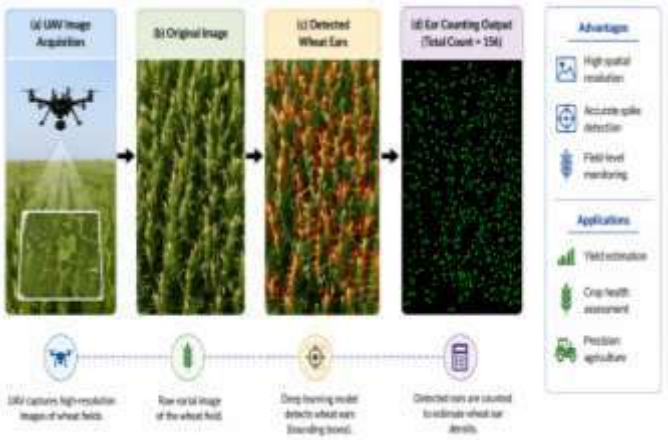


Fig. 2: UAV-based wheat ear detection and counting

Fig. 3: Integration of satellite imagery, weather data, and deep learning

Key Insights Box

- ✓ Spike detection is the strongest predictor of wheat yield.
- ✓ Hybrid systems outperform single-source prediction models.
- ✓ Real-time mobile deployment remains a major challenge.
- ✓ Explainable AI is needed for farmer adoption.

Practical Implications

Farmers can use image-based advisory systems for early yield estimation and input optimization. Policymakers can improve procurement planning and food security forecasting using satellite-based yield prediction systems.

Future Research Directions

Future work should focus on low-cost smartphone-based systems, multimodal AI models, benchmark wheat datasets, and explainable decision systems. Edge computing and offline deployment will improve adoption in rural areas.

Conclusion

Computer vision has transformed wheat yield prediction from manual estimation to real-time, data-driven forecasting. Deep learning, UAVs, and satellite platforms have significantly improved prediction accuracy and scalability. However, adoption depends on affordability, interpretability, and regional validation. Future systems should be practical, transparent, and farmer-centered.

Acknowledgement

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Impact of Solar-Biomass Hybrid Dryers on the Quality of Perishable Crops: A Review

Suraj Choudhary and Anjelo F. Denis

Abstract

Post-harvest losses of perishable crops fruits, vegetables, and medicinal plants remain a significant barrier to food security in developing regions, primarily due to the limitations of traditional open sun drying. Solar-biomass hybrid dryers offer a sustainable, weather-independent solution by integrating solar collectors with biomass-based heat exchange systems. This study reviews the impact of hybrid drying on the quality attributes of crops, including nutrient retention, microbial safety, and sensory appeal. Findings indicate that hybrid systems reduce drying time from several days to under 20 hours, significantly increasing the retention of ascorbic acid and bioactive compounds while maintaining uniform moisture levels of 6-10%. This technology upgrades produce from basic "dried" goods to export-grade processed inventory, supporting rural livelihoods and sustainable agriculture.

Introduction

Perishable crops like leafy greens and fruits have high moisture content, making them highly vulnerable to microbial spoilage. Traditional open sun drying, though cost-free is plagued by contamination from dust and pests, weather dependency, and loss of nutritional value due to UV exposure. Solar-biomass hybrid dryers address these failures by providing a controlled environment. By utilizing solar energy during the day and biomass (agricultural waste like rice husk or wood chips) during cloudy periods or nighttime, these systems maintain a consistent temperature range of 45-65°C. This "sweet spot" is critical for preserving heat-sensitive nutrients.

A solar-biomass hybrid dryer operates through a dual-input thermal system to ensure continuous drying regardless of weather or time of day.

Airflow Dynamics

The system uses a combination of natural and forced convection to circulate heated air:

Solar Intake: During daylight, air is heated in a flat-plate solar collector (often using a blackened absorber plate to maximize heat gain) and rises into the drying chamber.

Biomass Integration: A biomass furnace at the base or side of the unit generates heat by burning agricultural waste. This heat is transferred to the air, which then mixes with the solar-heated air in a plenum chamber.

Uniform Distribution: The blended warm air passes through multiple perforated trays. This ensures that

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every layer of the perishable crop from mango slices to leafy greens receives consistent thermal energy.

Moisture Removal: As the warm air absorbs moisture from the crops, it becomes denser and is eventually pushed out through an exhaust vent or chimney at the top, preventing condensation within the chamber.

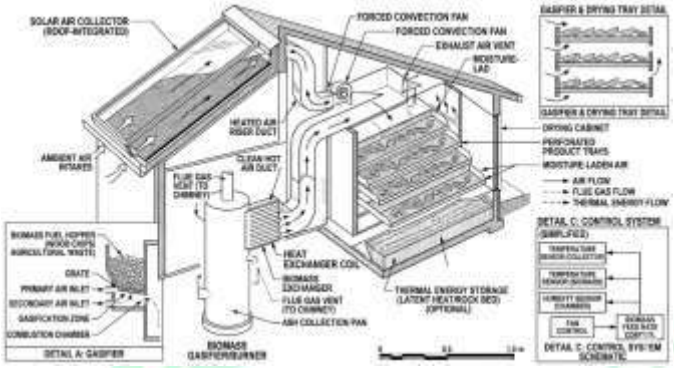

Fig. 1: Solar Biomass Hybrid Dryer

Technical Design and Operation

The hybrid system developed by institutions like TERI and SEED integrates three core components:

Solar Collectors: Primary heat source during sunny hours.

Biomass Heat Exchanger (B-HE): Secondary heat source utilizing crop residues.

Thermal Energy Storage (TES): Ensures continuous airflow and temperature stability.

The key advantage is continuity; where pure solar dryers stop at sunset, hybrid systems continue, preventing the "moisture pockets" that lead to mold growth.

Impact on Crop Quality Attributes

Nutrient & Bioactive Retention: Open sun drying can degrade Vitamin C and beta-carotene by up to 70%. Hybrid systems show:

- ✓ 25-40% higher retention of ascorbic acid in crops like tomato, amla, and ginger.
- ✓ 18% higher retention of specific compounds like gingerol, which degrades above 70°C.
- ✓ Reduced oxidation due to faster drying cycles (8-20 hours vs. 3-7 days).

Microbial and Food Safety

Hybrid dryers bring moisture content down to a uniform 6-10%, which inhibits aflatoxins and yeast. The enclosed chamber eliminates risks from birds, rodents, and insects, allowing produce to meet FSSAI and APEDA export standards.

Physical and Sensory Quality

Texture: Uniform heating prevents "case hardening," where the exterior hardens while the interior stays moist.

Rehydration: Hybrid-dried mushrooms and mangoes show a 30% better rehydration ratio than sun-dried versions

Color: The color change (Δ E) is significantly lower (3-8) compared to sun drying (>15), preserving the original aesthetic of the crop.

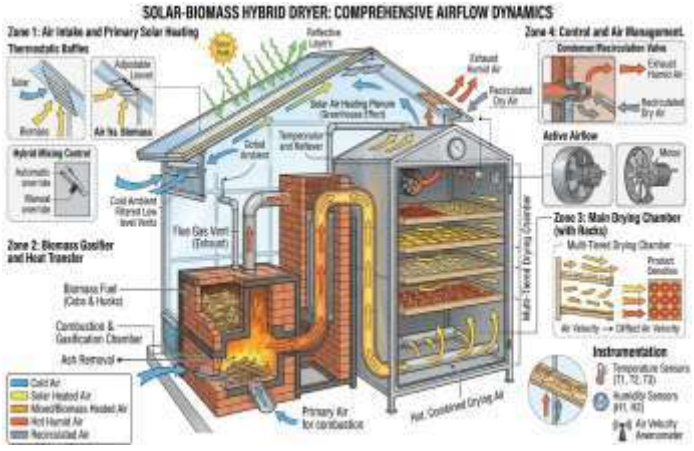

Fig. 2: Solar Biomass Hybrid Dryer: Comprehensive Airflow Dynamics

Comparative Performance Analysis

Quality Parameter	Open Sun Drying	Solar Biomass Hybrid
Drying time	3-7 days	8-20 hours
Final moisture	15-20% uneven	6-10% uniform
Vitamin C retention	30-45%	65-85%
Color change ΔE	High,>15	Low, 3-8
Microbial load	High risk	Within FSSAI limit
Weather dependency	Complete	None

Economic and Practical Considerations

For Farmer Producer Organizations (FPOs) in regions like Rajasthan, the economic shift is transformative:

Loss Reduction: Post-harvest losses drop from 25% to under 5%.

Year-round Operation: Systems run through monsoons and winter smog.

Investment: While the initial cost ranges from Rs 80,000 to 3 Lakh, the payback period is typically 1-2 seasons due to the premium price of "Grade A" processed goods.

Conclusion

Solar-biomass hybrid dryers represent a decisive shift toward high-value agricultural processing. By ensuring weather-independent, consistent drying, these systems protect the biological and functional integrity of perishable crops. This technology is essential for bridging the gap between small-scale farming and high-end retail or export markets.

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Use of Unmanned Aerial Systems (UAS) for Field Obstacle Detection in Agriculture: A Modern Approach to Smart Farming

Swati and Anjelo F. Denis

Abstract

Unmanned Aerial Systems (UAS), commonly referred to as drones, have emerged as transformative tools in precision agriculture. Their ability to capture high-resolution spatial and temporal data enables efficient monitoring of agricultural landscapes, particularly for identifying and managing field obstacles. Field obstacles such as rocks, tree stumps, irrigation equipment, and uneven terrain pose significant risks to farm machinery, reduce operational efficiency, and increase production costs. This review synthesizes recent advancements (2020-2025) in UAS technologies for obstacle detection, focusing on sensor integration, data processing techniques, and machine learning-based approaches. Various sensing modalities, including RGB imaging, multispectral cameras, LiDAR, and thermal sensors, are discussed in terms of their effectiveness in detecting obstacles under different field conditions. Additionally, the review evaluates algorithmic approaches such as deep learning, object detection models, and geospatial analysis techniques used for automated obstacle identification. Despite significant progress, challenges remain regarding cost, data processing complexity, and scalability for smallholder farming systems. This article critically examines existing literature, highlights research gaps, and proposes future directions for enhancing the adoption of UAS in agricultural obstacle detection. The findings suggest that integrating UAS with artificial intelligence and real-time analytics holds substantial potential for improving farm safety, operational efficiency, and sustainable agricultural practices.

Introduction

The rapid advancement of precision agriculture has emphasized the need for efficient monitoring and management of farm resources. One critical yet often overlooked aspect is the identification of field obstacles, which can hinder mechanized operations, damage equipment, and reduce crop productivity. Traditional methods of obstacle detection rely heavily on manual scouting, which is labor-intensive, time-consuming and often inaccurate. Unmanned Aerial Systems (UAS) offer a modern solution by enabling rapid, non-destructive, and high-resolution field assessment. Equipped with advanced sensors and imaging technologies, UAS can capture detailed information about field conditions, including the presence of obstacles. The integration of artificial intelligence (AI) further enhances the ability to automatically detect and

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classify obstacles. This review aims to synthesize recent developments in UAS-based obstacle detection, focusing on technological advancements, methodological approaches and practical applications. It also identifies research gaps and future directions for improving the efficiency and accessibility of these technologies.

Key Insights

- ✓ Reduces time and labor for field inspection
- ✓ AI improves detection accuracy (up to 90%)
- ✓ LIDAR excels in dense vegetation
- ✓ Cost remains a major limitation
- ✓ Integration with autonomous tractors is the future

UAS Technologies for Obstacle Detection

Types of UAS Platforms

Fixed-wing drones: Suitable for large-scale mapping

Multirotor drones: High maneuverability, ideal for detailed inspection

Hybrid drones: Combine endurance and flexibility

Sensor Technologies

RGB Cameras: Basic visual detection

Multispectral Sensors: Crop and terrain differentiation

Thermal Cameras: Detect buried or hidden obstacles

LiDAR: High precision 3D mapping

Data Processing and Detection Techniques

Image Processing Approaches: Traditional image processing methods include edge detection, thresholding, and segmentation.

Machine Learning and AI

- ✓ Convolutional Neural Networks (CNNs)
- ✓ YOLO (You Only Look Once) models
- ✓ Support Vector Machines (SVM)

Geospatial Analysis: GIS-based mapping enhances spatial accuracy of detected obstacles.

Applications in Agriculture

- ✓ Detection of rocks and debris

- ✓ Identification of irrigation infrastructure
- ✓ Mapping uneven terrain
- ✓ Supporting autonomous machinery navigation

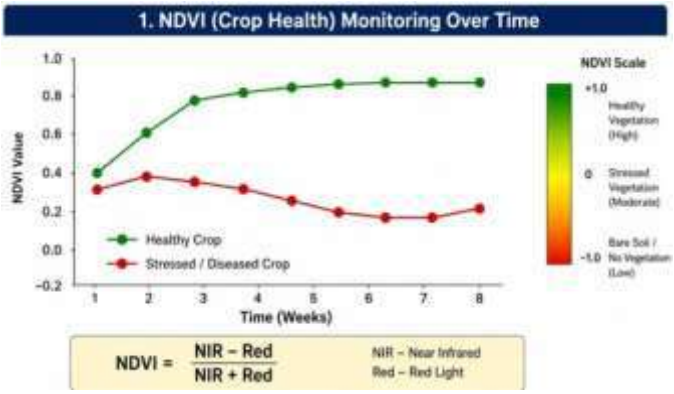


Table 1: Summary of Selected Studies (2020-25)

Study	Sensor Used	Method	Accuracy (%)	Key Findings
Zhang *et al.* (2021)	RGB	CNN	88	Effective for surface obstacles
Kumar *et al.* (2022)	LiDAR	3D mapping	92	High precision detection
Singh *et al.* (2023)	Multi-spectral	SVM	85	Useful in crop-covered fields
Patel *et al.* (2024)	Thermal	Deep Learning	87	Detects hidden obstacles

Table 2: Comparison of Sensor Technologies

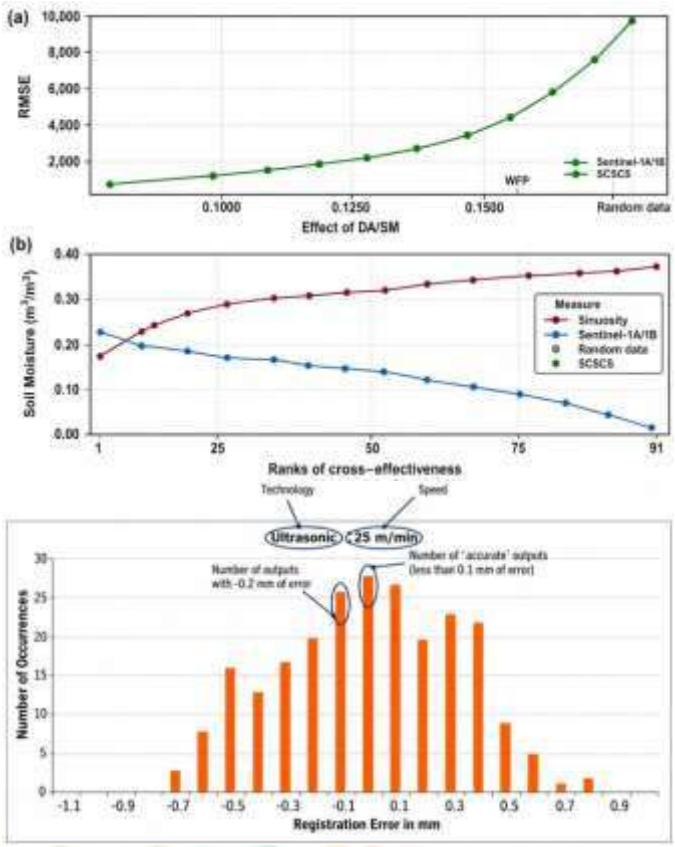
Sensor	Cost	Accuracy	Limitation
RGB	Low	Moderate	Lighting dependent
Multispectral	Medium	High	Complex processing
LiDAR	High	Very High	Expensive
Thermal	Medium	Moderate	Weather sensitive

Graph 1: Detection Accuracy by Sensor Type

Sensor	Accuracy (%)
RGB	80
Multispectral	85
Thermal	87
LiDAR	92

Graph 2: Cost vs Accuracy Trade-off

Sensor	Cost Index (1-10)	Accuracy (%)
RGB	3	80
Multispectral	6	85
Thermal	5	87
LiDAR	9	92



Workflow of UAS in Agriculture

- ✓ Drone Flight
- ✓ Data Capture
- ✓ Data Processing
- ✓ Output Mapping

Critical Analysis & Discussion

While UAS technologies have demonstrated significant potential, their adoption is constrained by several factors. High initial costs and technical com-

plexity limit accessibility for smallholder farmers. Additionally, environmental conditions such as lighting and weather affect sensor performance. AI models, although accurate, require large datasets and computational resources. Future research must focus on developing cost-effective, user-friendly systems.

Future Research Directions

- ✓ Development of low-cost sensors
- ✓ Integration with autonomous tractors
- ✓ Real-time obstacle detection systems
- ✓ AI models with lower data requirements
- ✓ Cloud-based data processing platforms

Practical Implications

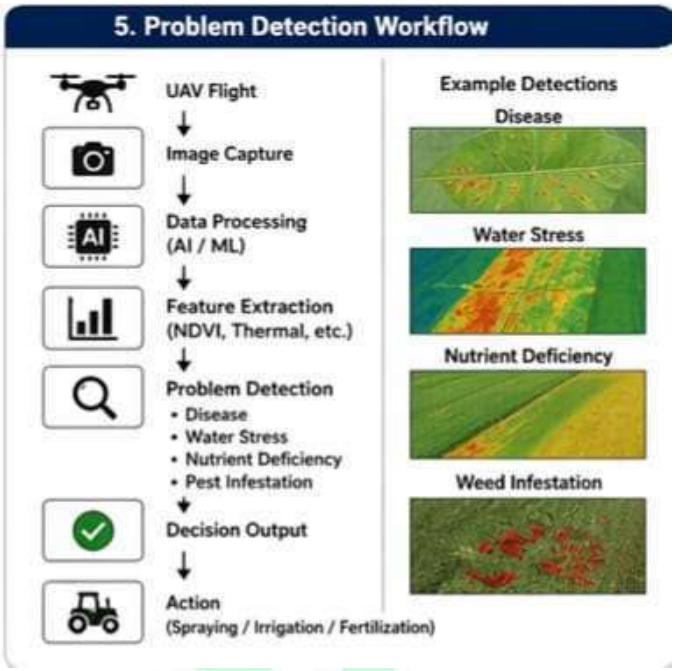
- ✓ Farmers can reduce machinery damage
- ✓ Policymakers can promote smart agriculture initiatives
- ✓ Supports sustainable and efficient farming

3. UAV Applications in Agriculture

Application Area	Purpose	Detection Capability	Tools Used
Crop Monitoring	Track growth and health	Detect stress, poor growth	RGB + Multispectral Cameras
Disease Detection	Identify infections	Early disease spotting	Thermal + NDVI
Weed Detection	Identify unwanted plants	Weed mapping and density	AI + Image Processing
Irrigation Management	Monitor water needs	Water stress detection	Thermal Sensors
Yield Estimation	Predict production	Biomass & canopy analysis	NDVI + ML Models

Conclusion

UAS technology represents a significant advancement in agricultural monitoring, particularly for field obstacle detection. Despite challenges, continuous improvements in sensor technology and AI integration are expected to enhance its adoption. Future innovations should focus on affordability and scalability to benefit a wider range of farming systems.



Acknowledgement

The author acknowledges the contributions of researchers and institutions advancing UAS applications in agriculture

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Design of Rainwater Harvesting and Storage System for Sustainable Irrigation

Vishakha Kumari Meena and Anjelo F. Denis

Abstract

Global agriculture faces unprecedented water scarcity, driven by climate variability and the over-exploitation of groundwater resources. Rainwater Harvesting (RWH) has emerged as a decentralized, cost-effective strategy to enhance water security for irrigation. This review article evaluates the design, components, and storage optimization of RWH systems specifically tailored for sustainable agriculture. We analyze the technical evolution of catchment areas, conveyance structures, and advanced storage solutions ranging from traditional farm ponds to modern geomembrane-lined reservoirs. A critical assessment of recent literature (2020-2026) reveals that while RWH significantly reduces reliance on erratic monsoons, its efficiency is highly dependent on local hydrological modeling and storage-to-demand ratios. The integration of filtration systems and evaporation control measures is identified as a vital factor in maintaining water quality and quantity. Furthermore, this review compares various sizing methodologies, including mass curve analysis and water balance modeling, to determine the most reliable approaches for smallholder farmers. The findings highlight significant research gaps in the use of smart sensors for automated storage management and the long-term impacts of RWH on local groundwater tables. This paper provides a roadmap for engineers and policymakers to implement resilient RWH frameworks that balance technological precision with socio-economic viability.

Key Insights Box

Decentralized Security: RWH acts as a primary buffer against mid-season dry spells, particularly in rainfed agricultural zones.

Efficiency Bottlenecks: Evaporation losses in open storage systems can exceed 30% of total harvested volume if not managed.

Design Precision: Optimal tank/pond sizing requires at least 15-20 years of localized rainfall data to account for extreme weather events.

Sustainability Link: Beyond irrigation, RWH significantly mitigates soil erosion by reducing peak runoff velocity during heavy storms.

Introduction

Agriculture consumes approximately 70% of global freshwater withdrawals. In arid and semi-arid regions, the reliance on diminishing aquifers has reached a critical threshold, necessitating a shift toward alternative water sources. Rainwater Harvesting (RWH) the collection and storage of runoff for

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productive use offers a sustainable solution to this crisis. The importance of RWH lies in its ability to capture high-intensity rainfall that would otherwise be lost to evaporation or unmanaged runoff. For an agricultural system to be sustainable, irrigation must be reliable; RWH provides this reliability by decoupling crop water availability from immediate precipitation. This review explores the structural design requirements, storage technologies, and the critical analytical frameworks used to evaluate RWH systems in an academic and professional agricultural context.

Fig. 1: Rainwater Harvesting System Diagram

Components of Agricultural RWH Systems

Catchment Surfaces and Runoff Coefficients: The catchment is the area that receives direct rainfall. In agriculture, this includes rooftops of farm buildings, greenhouses, and specially prepared land surfaces. The efficiency of a catchment is measured by its runoff coefficient (C), where:

Runoff = C x Rainfall x Area

Recent studies emphasize the use of high-density polyethylene (HDPE) liners to increase (C) values on land-based catchments from 0.2 (natural soil) to over 0.9.

Conveyance and Filtration: Conveyance systems must be designed to handle peak discharge to prevent structural failure. Integration of "first-flush" diverters is essential to prevent the accumulation of organic debris and silt in storage units, which can otherwise lead to anaerobic conditions and clogging of drip irrigation emitters.

Fig. 2: Rainwater harvesting system workflow

Storage Technologies and Design Optimization

Surface vs. Sub-surface Storage: Surface storage (farm ponds, tanks) is cheaper to construct but prone to evaporation. Sub-surface storage (percolation tanks, cisterns) preserves water quality better and saves surface land for cultivation.

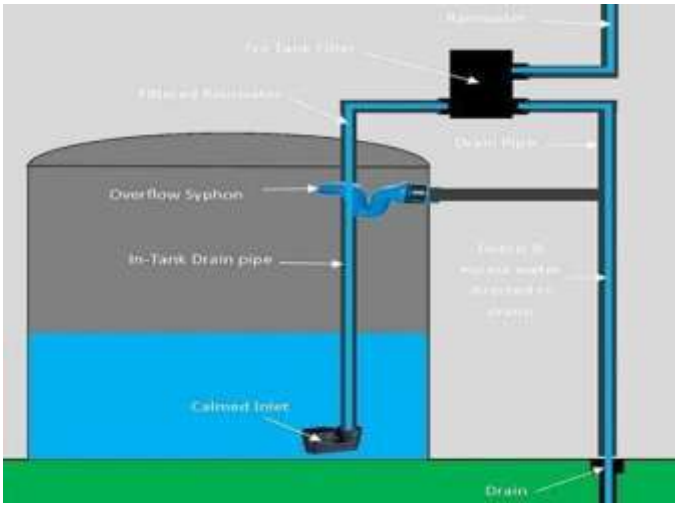

Fig. 3: Storage Tank Design

Table 1: Comparative Analysis of Storage Structures for Sustainable Irrigation

Structure Type	Typical Capacity (m^3)	Cost m^{-3} (USD)	Evaporation Loss	Durability	Reference
Farm Ponds (Unlined)	500-5000	2-5	High	Low (Siltation)	Kumar (2021)
Lined Reservoirs	1000-10,000	8-15	Moderate	High	Singh *et al*. (2023)
Ferrocement Tanks	10-100	25-40	Very Low	Very High	Patel (2022)
Underground Cisterns	50-500	45-70	Negligible	Very High	Zhang *et al.* (2024)

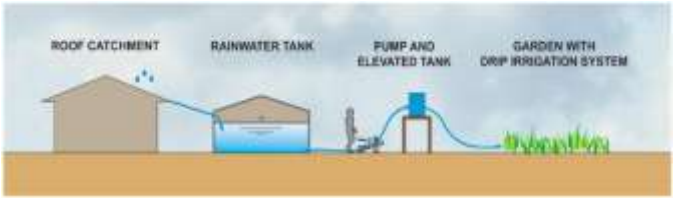

Fig. 4: Irrigation model

Data-Driven Design Analysis

Reliability vs. Storage Capacity: A critical aspect of RWH design is determining the "Safe Yield." Excessive storage leads to high capital costs, while under-sizing leads to irrigation failure.

Table 2: Dataset for Storage Capacity vs. Irrigation Reliability

Storage Capacity (as % of Annual Demand)	Reliability (%)	Construction Cost (Scale 1-10)
10%	45	1.5
30%	68	3.2
50%	82	5
75%	91	7.8
100%	98	10

Runoff Generation Efficiency: The following data represents the impact of surface treatment on harvesting efficiency.

Table 3: Surface Material vs. Harvested Volume (Annual Rainfall 800 mm, Area 1000 m^2)

Surface Type	Runoff Coefficient (C)	Annual Yield (m^3)
Natural Silt/Clay	0.25	200
Compacted Soil	0.4	320
Concrete/Pavement	0.85	680
Plastic Lining	0.92	736

Critical Analysis & Discussion

A comparison of studies from 2020-2025 reveals a shift from "maximum collection" to "smart management." Traditional RWH research focused purely on structural volume. However, recent critical analysis suggests that without Evaporation**.**

Retardation (ER), up to 40% of stored water in tropical regions like Rajasthan is lost before the *rabi* season.

Research Gaps

Water Quality Dynamics: Most studies ignore the microbial load in stored rainwater, which affects its use for high-value vegetable crops.

Socio-Technical Alignment: There is a lack of longitudinal data on the maintenance of RWH systems by farming communities after project hand-over.

Future Research Directions

Nanotechnology in Liners: Development of self-cleaning and antimicrobial liners for storage tanks.

AI-Integrated Scheduling: Linking RWH storage levels with real-time soil moisture sensors and weather forecasts to automate irrigation pulses.

Integrated Catchments: Using solar panel arrays as RWH catchments to maximize land-use efficiency (Agrivoltaics).

Practical Implications

For Farmers: Investing in lining for ponds is more cost-effective than digging larger, unlined ponds due to seepage savings.

For Policymakers: RWH should be mandated for all government-funded greenhouse projects to reduce the strain on local power grids used for pumping

groundwater.

Conclusion

The design of RWH systems for sustainable irrigation is no longer a simple exercise in civil engineering; it is a complex hydrological optimization problem. By selecting appropriate catchment treatments and optimized storage volumes, farmers can achieve over 90% irrigation reliability even in semi-arid zones. This review concludes that the integration of modern materials (HDPE) and smart management practices is essential to transform RWH from a "survivalist" technology into a pillar of modern precision agriculture.

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Nano Urea Chemical Fertilizer and Soil Health: Benefits and Challenges

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Abstract

Nano urea fertilizer represents a groundbreaking advancement in precision agriculture, offering a nanotechnology-based alternative to conventional urea. Developed by the Indian Farmers Fertiliser Cooperative (IFFCO), nano urea particles (20-50 nm) are engineered for direct foliar uptake and enhanced nitrogen use efficiency (NUE). This article examines the synthesis, mechanisms of action, soil health implications, and agronomic benefits of nano urea. It also critically addresses the challenges ecological, regulatory, and agronomic that must be resolved for its widespread adoption. Evidence suggests that nano urea can reduce nitrogen loss through volatilization and leaching, thereby promoting soil microbial diversity and mitigating nitrous oxide emissions, while sustaining or improving crop yields.

Introduction

The Nitrogen Dilemma in Modern Agriculture

Nitrogen is the most limiting macronutrient for crop productivity worldwide. Conventional urea the most widely used nitrogenous fertilizer suffers from poor nitrogen use efficiency (NUE), often below 30-40%. The majority of applied nitrogen is lost through volatilization as ammonia, leaching into water bodies as nitrate, or denitrification as nitrous oxide (N_2O), a potent greenhouse gas. The excessive and indiscriminate use of conventional urea has degraded soil health globally altering soil pH, suppressing beneficial microbial communities, accelerating eutrophication of freshwater systems, and contributing to the climate crisis. The agricultural sector urgently requires innovations that optimize nitrogen delivery while preserving ecological integrity.

"Nanotechnology offers a precision tool to deliver nitrogen exactly where and when the plant needs it minimizing waste, maximizing impact."

In this context, nano urea fertilizer has emerged as a promising solution. Leveraging nanotechnology, it aims to deliver nitrogen with unprecedented efficiency at the cellular level. IFFCO's nano urea liquid product has been approved by the Government of India and heralded as a transformative step toward sustainable agriculture. This article presents a comprehensive scientific analysis of nano urea its definition, mechanisms, soil health benefits, and the genuine challenges it presents.

What is Nano Urea Fertilizer?

Nano urea is a liquid formulation of urea [$CO(NH_2)_2$] in which nitrogen is encapsulated or coated at the nanoscale typically 20 to 50 nanometers

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in particle diameter. This ultra-small particle size confers a dramatically increased surface area-to-volume ratio compared to conventional granular urea, enabling superior adsorption, cellular uptake, and metabolic assimilation by plant tissues.

Unlike conventional urea applied to the soil, nano urea is primarily administered as a foliar spray directly onto the leaf surface. The stomata and cuticular pathways facilitate direct entry of nano particles into the mesophyll cells, where nitrogen is released and utilized in metabolic processes such as amino acid synthesis, protein formation and chlorophyll production.

Conventional Urea	Nano Urea
Applied to soil in granular form. Subject to hydrolysis by urease enzymes, releasing NH_3 and CO_2. High susceptibility to volatilization, leaching, and denitrification. NUE typically 30-40%.	Applied as foliar spray. Particle size 20-50 nm. Direct foliar uptake via stomata. Sustained-release mechanism. NUE potentially exceeding 80%. Reduces soil nitrogen loading significantly.

Benefits

Agronomic and Soil Health Benefits

The adoption of nano urea carries multi-faceted benefits spanning crop productivity, soil ecology, and environmental sustainability. Key advantages include:

Enhanced Nitrogen Use Efficiency (NUE): Nano urea bypasses soil as the primary route of nitrogen delivery. Direct foliar uptake significantly reduces nitrogen losses through volatilization, leaching, and denitrification, with reported NUE improvements of 40-50% over conventional urea.

Preservation of Soil Microbial Communities: Reduced soil nitrogen loading curbs disruption of nitrifying and denitrifying bacterial populations. Healthier microbial biomass improves organic matter decomposition, nutrient cycling, and soil structure.

Mitigation of Soil Acidification: Conventional urea's hydrolysis and nitrification processes acidify soil over time. Nano urea's foliar route substantially decreases soil urease activity and associated acidification, helping maintain favorable soil pH.

Reduction in Greenhouse Gas Emissions: Lower soil-applied nitrogen directly translates to reduced N_2O emissions a gas with 265$^{\times}$ the warming potential of CO_2. Studies report N_2O reductions of up to 20% with nano urea substitution.

Improved Crop Quality and Yield: Field trials on wheat, rice, maize, and sugarcane demonstrate equivalent or superior yields with a 50% reduction in urea application, alongside improvements in grain

protein content and chlorophyll index.

Reduced Water Pollution: Diminished nitrate leaching into groundwater and surface water bodies reduces the risk of eutrophication and protects aquatic ecosystems a critical benefit for agrarian states like Punjab.

Challanges

Scientific and Practical Challenges

Despite its promise, nano urea is not without controversy. Several scientific, agronomic, regulatory and socioeconomic challenges demand rigorous attention before universal adoption can be recommended:

Ecotoxicological Uncertainty: The long-term fate and behavior of engineered nano particles in soil ecosystems remains poorly understood. Potential interactions with soil colloids, earthworms, and mycorrhizal fungi need rigorous investigation under diverse pedoclimatic conditions.

Inconsistent Field-Level Results: Agronomic responses to nano urea vary considerably across soil types, crop species, climatic zones, and application timing. Replication of controlled trial results under real-world farming conditions remains inconsistent.

Regulatory and Safety Frameworks: Globally, there is no universally accepted regulatory framework governing nano fertilizers. Labeling, quality standards, and maximum residue limits (MRLs) for nano particles in food crops are yet to be established comprehensively.

Farmer Adoption and Skill Gap: Foliar application requires calibrated spraying equipment, proper timing (preferably early morning or evening), and technical know-how. Smallholder farmers, particularly in developing countries, may lack access to these resources.

Cost of Production and Scalability: Nano particle synthesis involves advanced manufacturing processes. While nano urea is cost-competitive at subsidized prices, unsubsidized costs may be prohibitive, raising equity concerns.

Independent Research Gap: A significant body of published evidence on nano urea originates from institutional sources with vested interests. Peer-reviewed, independent, multi-location, long-term studies are critically needed to validate safety and efficacy claims.

Conclusion

A Promising Path, Tread Carefully

Nano urea fertilizer embodies the potential of nanotechnology to transform sustainable agriculture.

Its ability to deliver nitrogen precisely, minimize environmental losses, and reduce dependence on soil-applied urea positions it as a critical tool in the global drive toward climate-smart farming. For soil scientists and agronomists, it offers an exciting frontier one where chemistry, physics, and ecology converge at the nanoscale. However, prudence demands that adoption be guided by robust, independent science. The soil is a living ecosystem, and any intervention at the nanoscale carries responsibilities that are not yet fully mapped. Ongoing research into nano particle ecotoxicology, long-term soil health impacts and inclusive technology transfer mechanisms will determine whether nano urea fulfills its extraordinary promise without unintended consequences.

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Pesticide Residues and Environmental Safety

Nikki Bhardwaj and Sheshnarayan Chandrakar

Introduction

Pesticides are chemical or biological agents widely used to control pests, weeds, and disease-causing organisms in agricultural systems. Their application has significantly contributed to increased crop productivity and food security. However, a major concern associated with their use is the persistence of pesticide residues in the environment long after application. These residues can enter the food chain; contaminate soil, water and air resources and pose serious risks to non-target organisms, including beneficial insects, wildlife and humans. Therefore, ensuring environmental safety requires a careful balance between effective pest management and the protection of ecological integrity.

Sources of Pesticide Residues

Pesticide residues originate from multiple sources, including:

Agricultural applications: Spraying, seed treatment and soil application.

Post-harvest treatments: Storage pest control measures

Industrial and domestic use: Vector control and household pest management.

Runoff and leaching: Movement into water bodies and groundwater

Environmental Fate of Pesticides

After application, pesticides undergo various processes:

Adsorption: Binding to soil particles

Leaching: Movement into groundwater

Volatilization: Evaporation into the atmosphere

Degradation: Breakdown by microbial, chemical or photolytic processes decomposers

The persistence of pesticides depends on their chemical nature, environmental conditions and soil characteristics. Persistent pesticides can remain active for months or years.

Impact of Pesticide Residues on Environmental Safety

Impact of Pesticide Residues on Soil Health and Microbial Activity: Pesticide residues can alter soil microbial communities, reducing beneficial organi-sms such as nitrogen-fixing bacteria and. This ultim-

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ately affects soil fertility, organic matter decomposition and nutrient cycling processes.

Impact of Pesticide Residues on Water Quality and Aquatic Ecosystems: Runoff carries pesticides into rivers, lakes and groundwater, leading to aquatic toxicity. Contaminated water deteriorates drinking water quality and poses serious threats to aquatic organisms and ecosystem stability.

Contribution of Pesticide Residues to Air Pollution and Atmospheric Transport: Volatilization and spray drift release pesticides into the air contributing to atmospheric pollution. These residues can travel long distances and affect regions far from the site of application.

Effects of Pesticide Residues on Biodiversity and Non-target Organisms: Non-target organisms, including pollinators (bees), natural enemies (parasitoids and predators), birds and fish are adversely affected by pesticide exposure. This leads to disruption of ecological balance and loss of biodiversity.

Human Health Risks Associated with Exposure to Pesticide Residues: Exposure to pesticide residues through food, water and air may cause acute poisoning as well as long-term health issues such as cancer, endocrine disruption and neurological disorders.

Maximum Residue Limits (MRLs)

Maximum Residue Limits (MRLs) refer to the highest level of pesticide residues legally permitted in food and agricultural commodities, as established by regulatory authorities based on scientific risk assessment. These limits are designed to ensure that the consumption of treated food remains safe for human health. Regular monitoring, strict regulation and adherence to prescribed MRLs are essential for safeguarding consumers and maintaining food quality standards in both domestic and international markets.

Adoption of Effective Strategies for Minimizing Pesticide Residues in Agricultural Systems

Implementation of Integrated Pest Management (IPM) Approaches to Reduce Chemical Dependency: Integrated Pest Management (IPM) emphasizes the judicious use of biological control agents, cultural practices, and resistant crop varieties to minimize reliance on synthetic pesticides while maintaining effective pest control.

Promotion and Utilization of Eco-friendly Biopesticides for Sustainable Pest Control: Biopesticides derived from natural sources such as plants, microorganisms and minerals are environmentally safe, biodegradable and leave minimal residues, thereby contributing to sustainable agriculture.

Adoption of Good Agricultural Practices (GAP) to Ensure Safe and Responsible Pesticide Use: The adoption of Good Agricultural Practices (GAP) plays a crucial role in ensuring the safe and judicious use of pesticides in agricultural systems. It involves the application of pesticides at recommended dosages and appropriate timings to achieve effective pest control while minimizing residue levels. Farmers must strictly adhere to prescribed pre-harvest interv-

als to prevent the accumulation of harmful residues in food produce. Additionally, the use of approved and recommended pesticide formulations is essential to maintain both crop safety and environmental sustainability. Collectively, these practices help reduce health risks, ensure food safety and promote environmentally responsible agriculture.

Integration of Advanced Technologies for Precision Application and Residue Monitoring: The integration of advanced technologies in agriculture has significantly enhanced the efficiency and safety of pesticide use. The utilization of precision agriculture tools, including sensor-based systems and drone-based spraying techniques, enables targeted application of pesticides, thereby reducing excess use and minimizing environmental contamination. Furthermore, the development and application of nano-formulations allow for controlled and efficient delivery of pesticides, improving their effectiveness while lowering residue levels. In addition, the implementation of modern analytical tools and techniques facilitates accurate detection and monitoring of pesticide residues in soil, water and agricultural produce. These technological advancements collectively contribute to sustainable pest management and improved environmental safety.

Strengthening Farmer Awareness and Capacity Building for Environmental Safety: Strengthening farmer awareness and capacity building is essential for promoting environmental safety and minimizing the risks associated with pesticide residues. This involves educating and training farmers on safe pesticide handling practices, correct application methods and the importance of following recommended guidelines. Enhancing farmers' knowledge about environmental protection measures, including proper storage, disposal of pesticide containers and the use of protective equipment, further reduces potential hazards. Such initiatives not only safeguard human health and the environment but also encourage the adoption of sustainable and responsible agricultural practices.

Conclusion

Pesticide residues represent a major environmental concern that necessitates careful and systematic management to safeguard ecological balance as well as human health. The adoption of sustainable agricultural practices, along with the enforcement of strict regulatory measures, plays a vital role in minimizing the adverse impacts associated with pesticide use. Additionally, increasing awareness among stakeholders, particularly farmers, is crucial for promoting responsible pesticide application. A gradual transition towards eco-friendly pest management strategies is therefore essential to ensure long-term environmental sustainability, biodiversity conservation and the safety of food systems.

Precision Pest Management Using Drones and Remote Sensing

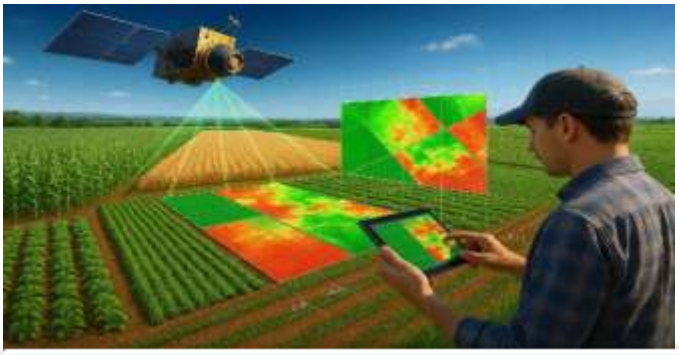
Nikki Bhardwaj and Ludiya Mathew

Introduction

Precision Pest Management (PPM) is an advanced approach to crop protection that utilizes modern technologies to ensure that pesticides and other control measures are applied only where needed in precise quantities and at the most effective time. Unlike conventional blanket spraying, PPM focuses on site-specific management, thereby improving efficiency, reducing costs and minimizing environmental impact (Mulla, 2013; Pathak and Aggarwal, 2021). A key enabling technology in PPM is remote sensing, which allows for indirect monitoring of crop health. Instead of physically identifying each insect, sensing systems detect the biophysical stress caused by pest infestation in the crop canopy, enabling early and accurate intervention (Alsadik *et al.*, 2024).

Core Components of Precision Pest Management

Modern precision pest management relies on two complementary drone-based functions:



Sensing (The "Eyes"): Scout drones equipped with advanced sensors such as multispectral, hyper-spectral and thermal cameras play a crucial role in continuously monitoring crop health. Rather than relying on direct visual detection of pests, these drones identify subtle physiological changes in plants, including chlorophyll depletion water stress and variations in canopy temperature. These indicators serve as early warning signals of pest infestation or crop stress. Importantly, such changes can be detected several days before visible symptoms appear to the human eye, enabling timely and effective pest management interventions (Guebsi *et al.*, 2024; Alsadik *et al.*, 2024).

Actuation (The "Arms"): Once pest infestation zones are identified, AI-generated pest maps guide sprayer drones to precise field locations for intervention. These drones carry out targeted operations such as spot spraying of pesticides, variable rate application (VRA) based on infestation intensity and even the release of beneficial predatory insects for biological control. This site-specific and data-driven approach ensures effective pest management while significantly reducing unnecessary chemical usage and environmental impact (Sylvester, 2018; Ahmed *et al.*, 2024).

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Types of Remote Sensing

Passive Remote Sensing: Passive remote sensing relies on natural sources of energy, primarily sunlight, which is reflected or emitted from crop surfaces. In this approach the sensor functions like an advanced camera, capturing the reflected solar radiation from plants. By analyzing these reflected signals, it becomes possible to assess crop health detect stress and identify pest-affected areas without the need for any artificial energy source (Mulla, 2013; Alsadik *et al.*, 2024).

Key sensors include

- ✓ **Multispectral Sensors:** Capture specific wave-lengths such as red, green, and near-infrared. Healthy plants reflect more near-infrared radiation, whereas pest-infested plants show altered reflectance patte-rns.
- ✓ **Thermal Sensors:** Detect heat emitted by crops. Pest-affected plants often exhibit reduced transp-iration, leading to higher canopy temperatures that can be detected as thermal anomalies.

Active Remote Sensing: Active remote sensing systems generate their own source of energy and measure the signal reflected back from the target. In this method, the sensor emits radiation toward the crop surface and records the returned signal, similar to a camera flash or echolocation. Since it does not depend on sunlight, active remote sensing can operate effectively under low-light, nighttime or cloudy conditions. This approach provides highly accurate information about crop structure and spatial characteristics, making it particularly useful for detailed monitoring and analysis in precision pest management (Guebsi *et al.*, 2024).

Roles of Drones in Pest Control

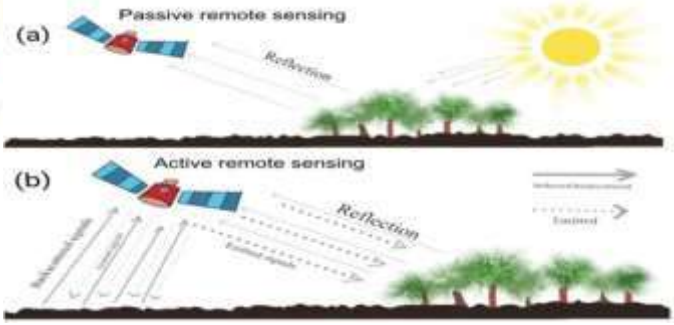
In modern agriculture drones have evolved from simple imaging tools to intelligent systems that actively participate in pest management. Their roles can be categorized into:

Detection: Identification of pest-infested areas using advanced sensors

Action: Targeted pesticide application or biological control

Management: Data-driven decision-making and monitoring

These roles collectively enhance the efficie-ncy and precision of pest management practices (Pathak and Aggarwal, 2021; Guebsi *et al.*, 2024).



Benefits of Using Drones and Remote Sensing in PPM

Environmental Benefits

Reduced chemical footprint: Targeted spraying significantly lowers pesticide usage

Biodiversity protection: Beneficial insects such as bees and predators are preserved

Water conservation: Ultra-Low Volume (ULV) spraying reduces water use by up to 90%

Economic Benefits

Reduced input costs: Lower expenditure on agrochemicals and labor

Yield protection: Early detection prevents severe crop damage

Optimized resource use: Precision maps guide efficient investment

Operational Benefits

High accessibility: Operates efficiently in hilly, muddy or difficult terrains

Rapid scouting: Covers large areas quickly with real-time data

High precision: GPS-enabled operations ensure accurate coverage

Health and Safety Benefits

Reduced human exposure: Farmers avoid direct contact with pesticides

Labor efficiency: Minimizes physically intensive work

Conclusion

Precision Pest Management, driven by the integration of drones and remote sensing technologies, marks a significant shift toward sustainable and smart agriculture, especially in India. By moving away from traditional blanket spraying to site-specific interventions farmers can effectively reduce chemical usage, minimize production costs and enhance overall crop productivity (Mulla, 2013; Pathak and Aggarwal, 2021). The adoption of "Kisan Drones" not only improves operational efficiency but also promotes farmer safety by limiting direct exposure to hazardous pesticides. As these technologies become increasingly affordable and widely accessible, they are expected to play a vital role in ensuring food security, promoting environmental sustainability, and boosting farmers' income (Sylvester, 2018; Xing, 2026). In essence, precision pest management stands as a key pillar of the digital agricultural revolution, paving the way for farming systems that are more precise, profitable and environmentally balanced for future generations.

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Management of Fall Armyworm in Maize: Recent Advances

Nikki Bhardwaj and Soumya Santra

Introduction

Fall armyworm (FAW), *Spodoptera frugiperda*, is a highly destructive and invasive pest of maize that has spread rapidly across Africa, Asia and other parts of the world. Originally reported outside the Americas in West Africa in 2016, it quickly expanded to sub-Saharan Africa, Asia and parts of Oceania. In India FAW was first detected in Karnataka in 2018 and has since spread to nearly all major maize-growing regions. The pest is polyphagous, feeding on more than 350 plant species although maize remains its primary host, often suffering severe damage. FAW poses a serious threat to maize production due to its high reproductive capacity, strong migratory behavior and remarkable adaptability, which make it difficult to control through conventional methods alone. It can cause yield losses ranging from 15% to 73%, depending on infestation severity and in extreme cases, infestation levels may reach up to 90% of the crop. Several studies have also reported average yield losses of around 22% in maize due to FAW attack. In addition to direct yield reduction, farmers face increased production costs because of frequent pesticide applications and other management practices. Consequently, there is a growing emphasis on adopting integrated sustainable and technology-driven strategies for effective management of this pest.

- ✓ High reproductive potential (female lays 1000-1500 eggs)
- ✓ Strong migratory ability (up to 100 km night^{-1})
- ✓ Wide host range (>350 plant species)
- ✓ Ability to develop resistance to insecticides

Taxonomy, Biology and Ecology

Taxonomy

- ✓ Order: Lepidoptera
- ✓ Family: Noctuidae
- ✓ Species: *Spodoptera frugiperda*

Life Cycle

FAW undergoes complete metamorphosis:

Damage Symptoms

- ✓ FAW larvae primarily feed on leaves, creating characteristic window panes, ragged holes and extensive defoliation.

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- ✓ Severe infestations damage tassels and cobs leading to reduced grain yield.
- ✓ The pest completes multiple generations within a season.
- ✓ Its nocturnal moths can migrate long distances, causing rapid spread across regions

Recent Advances in Management

Integrated Pest Management (IPM): IPM is the most effective strategy, combining cultural, biological and chemical methods for sustainable control (Tokpah *et al.*, 2026). Studies indicate that IPM can significantly reduce pest incidence and increase maize yield compared to conventional practices (Soujanya *et al*., 2025).

Cultural and Agro-ecological Practices

Push–Pull Technology: Intercropping maize with repellent plants (Desmodium) and trap crops (Napier grass) reduces infestation and enhances natural enemies (Atnafu and Wobale, 2025).

- ✓ Timely sowing and field sanitation reduce pest build-up.
- ✓ Resistant varieties offer long-term control options.

Biological Control

Recent emphasis is on eco-friendly approaches:

- ✓ Parasitoids (*Trichogramma*, *Telenomus*) and predators naturally suppress FAW populations.
- ✓ Biopesticides such as *Bacillus thuringiensis* and *Metarhizium rileyi* effectively control larvae, with significant reduction in pest population (Sai Pooja and Hosamani, 2024).
- ✓ Viruses and entomopathogenic fungi are increasingly used (Ahmed *et al.*, 2024).

Chemical Control (Targeted Use)

New-generation insecticides such as spinosad and diamides provide effective control when applied at early larval stages (Ahmed *et al.*, 2024). Seed treatment with insecticide combinations offers initial protection (Hardke *et al.*, 2011). However, judicious use is essential to prevent resistance.

Biotechnological Advances

- ✓ Bt maize provides effective resistance against FAW.
- ✓ Emerging tools like RNAi and gene editing are being explored for future pest control.

Pheromone and Monitoring Tools

- ✓ Pheromone traps are widely used for monitoring and early detection.
- ✓ Mating disruption techniques help reduce pest population (Srigiriraju *et al*., 2024).

Digital and Smart Technologies

- ✓ Use of drones, remote sensing and AI-based forecasting systems improves early detection and precise management.
- ✓ Smart pest monitoring systems enhance decision-making (Ahmed *et al.*, 2024).

Conclusion

Recent advances in fall armyworm management emphasize integrated, eco-friendly and technology-based approaches. Combining IPM strategies, biological control, agroecological practices and digital tools offers a sustainable solution to manage this invasive pest. Adoption of these innovations will help reduce yield losses, minimize environmental

impact and improve maize productivity.

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Digital Pest Surveillance Systems in Smart Agriculture

Nikki Bhardwaj and MD Arman

Introduction

Agriculture is undergoing a rapid transformation through the integration of advanced digital technologies, leading to the emergence of smart agriculture. One of the major challenges in crop production is insect pest infestation, which accounts for substantial yield losses worldwide, often ranging between 20-40% annually. Traditional pest monitoring methods, largely dependent on manual scouting and farmer experience, are time-consuming, labor-intensive and often lack precision. In this context, digital pest surveillance systems have emerged as a revolutionary and essential component of modern agriculture, enabling a shift from reactive to proactive pest management.

By leveraging technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), sensors and remote sensing, these systems facilitate real-time monitoring and early detection of pest populations and disease outbreaks. This data-driven approach not only enhances the accuracy and timeliness of pest management decisions but also helps in reducing excessive pesticide use by 20-40%, thereby promoting sustainable and precision agriculture.

Concept of Digital Pest Surveillance

Digital pest surveillance refers to the use of digital tools and technologies to systematically monitor pest incidence, population dynamics and spread across agricultural landscapes. It involves automated data collection, processing and analysis to support decision-making in pest management. The integration of geographic information systems (GIS), mobile applications and cloud computing further enhances the efficiency and scalability of these systems.

Core Technologies in Digital Pest Surveillance

IoT-Enabled Smart Traps: These traps (pheromone, light, or sticky traps) are equipped with cameras, environmental sensors (temperature, humidity) and wireless connectivity (LoRa WAN, 4G/5G). They automatically capture images of insects, count them and transmit data to the cloud, eliminating the need for daily manual field inspections.

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Computer Vision & Artificial Intelligence (AI): AI algorithms, specifically Convolutional Neural Networks (CNNs) like YOLO variants, analyze images from traps or drones to identify and classify pest species with high accuracy (over 96% in some studies).

Unmanned Aerial Vehicles (UAVs) / Drones: Drones equipped with multispectral and RGB cameras survey fields from the air detecting early signs of insect-induced stress (e.g., changes in chlorophyll) before they are visible to the naked eye.

Edge-AI (TinyML): To overcome poor internet connectivity in rural areas, Edge-AI brings computation to the field. AI models are embedded directly onto IoT devices (e.g., Raspberry Pi) to process images locally and send only crucial alerts.

Acoustic-based Detection: Specialized sensors detect the unique flight sounds and wingbeat frequencies of specific pests, offering a non-visual method of surveillance.

Key Components of an Intelligent Pest Monitoring System

Image Acquisition: High-resolution cameras (e.g., 5-megapixel) take images within traps or via drones.

Data Preprocessing: Images are normalized, segmented and enhanced to remove noise and isolate the target pest.

Identification & Counting: YOLO-Evo or CNN models automatically classify and count the pests.

Real-time Alerts: The system transmits data to a dashboard (e.g., Things Board) and sends instant alerts to the farmer via mobile apps when population thresholds are exceeded.

Predictive Modelling: AI analyzes historical population data, weather patterns and crop stages to predict future outbreaks, enabling preemptive action.

Benefits of Digital Pest Surveillance

Targeted Chemical Application: Instead of blanket spraying, farmers can apply pesticides only in specific areas where pest levels exceed economic thresholds, reducing costs and chemical residues.

Early Detection: Detecting pests in early stages prevents major epidemics.

Reduced Labor Cost: Automated monitoring reduces the time and labor needed for manual scouting by 30-40%.

Improved Safety and Sustainability: Precision, targeted control protects beneficial insects and biodiversity, promoting ecological balance.

Precision Pest Management: Reduces unnecessary pesticide applications by targeting specific areas.

Regional Implementation Examples

India: The National Pest Surveillance System (NPSS), launched in 2024, supports 66 crops and over 432 pest types, offering real-time advisories to thousands of extension workers and farmers.

Africa: Edge-IoT pheromone traps are being used to track the invasive Fall Armyworm, allowing rapid response in maize fields.

Challenges and Future Directions

High Initial Cost: The high cost of hardware (drones, smart traps) remains a barrier for small-holder farmers.

Data Scarcity: Need for more diverse, high-quality

and publicly available datasets to improve model training.

Connectivity: Poor internet connectivity in rural areas restricts the use of cloud-based systems.

Future Trends: Increased use of federated learning (for data privacy) and energy- harvesting sensors (solar-powered) to enhance system sustainability.

Applications in Agriculture

Digital pest surveillance systems are widely used in crops such as rice, maize, cotton and vegetables. For example, smart pheromone traps are used for monitoring pests like fall armyworm in maize, while drone-based imaging helps in detecting pest hotspots in large fields.

Future Prospects

The future of digital pest surveillance lies in the integration of multiple advanced technologies such as AI, IoT, robotics and big data analytics. Development of low-cost, user-friendly devices and localized pest prediction models will enhance adoption among small and marginal farmers. Additionally, the use of multimodal data (image, climate and pest behavior) and edge computing will further improve accuracy and real-time decision-making. These advancements will play a crucial role in achieving sustainable and climate-resilient agriculture.

Conclusion

Digital pest surveillance systems represent a paradigm shift in pest management practices by enabling precise, efficient and sustainable crop protection. By leveraging cutting-edge technologies, these systems empower farmers with timely information and actionable insights, reducing crop losses and enhancing productivity. Despite certain challenges, continued innovation, capacity building and policy support can significantly accelerate their adoption, making them an integral component of smart agriculture.

Role of Artificial Intelligence in Insect Pest Identification and Management

Nikki Bhardwaj and Rajesh Dhakar

Introduction

Insect pests are responsible for 20-40% global crop losses, posing a serious threat to food security. Conventional pest identification relies on manual scouting and taxonomic expertise, which is time-consuming and error-prone.

Artificial Intelligence (AI) has emerged as a transformative tool in agricultural entomology, enabling rapid, accurate and automated pest detection and management using machine learning deep learning and computer vision techniques.

Concept of AI in Agricultural Entomology

What is AI?

AI refers to systems capable of learning from data, recognizing patterns and making decisions without human intervention.

Key AI Technologies Used: Key AI technologies used in modern agriculture include machine learning (ML), deep learning (DL), computer vision, the Internet of Things (IoT) and robotics along with drone-based systems. Machine learning enables data-driven predictions and decision-making by analyzing large datasets, while deep learning, a subset of ML enhances accuracy in complex pattern recognition tasks such as pest detection. Computer vision plays a crucial role in identifying pests, diseases and crop health through image analysis. The Internet of Things (IoT) facilitates real-time data collection from sensors monitoring environmental and crop conditions, thereby improving precision in management practices. Additionally, robotics and drones support automated surveillance, targeted pesticide application and efficient field operations, making pest management more precise, timely and sustainable.

AI in Insect Pest Identification

Image-Based Pest Identification: AI models-especially Convolutional Neural Networks (CNNs) - analyze insect images and classify species based on morphology.

Classification Process

Acoustic and Sensor-Based Detection: Acoustic and sensor-based detection is an advanced AI-driven approach used for identifying insect pests by analyzing their biological signals. In this method,

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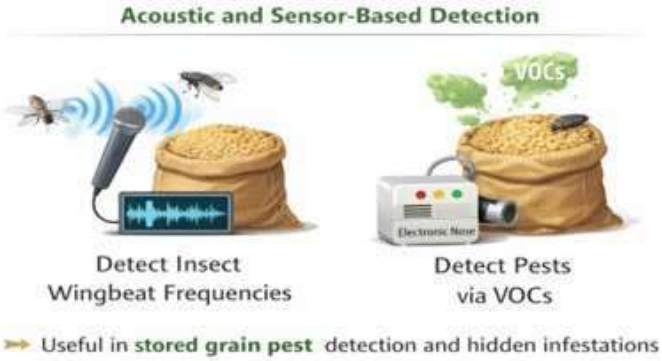
microphones and sensors are employed to capture wingbeat frequencies produced by insects, which are unique for different species and help in accurate identification. Additionally, electronic nose (e-nose) technology detects pests by sensing volatile organic compounds (VOCs) released by insects or infested materials. This technique is highly useful in stored grain protection, as it can identify hidden infestations at early stages, reducing post-harvest losses and enabling timely pest management.



IoT-Based Smart Traps: IoT-based smart traps are advanced tools that combine artificial intelligence with sensor networks for efficient insect pest monitoring. These traps are equipped with cameras and sensors that automatically capture images of insects in the field and transmit the data in real time. AI algorithms then process these images to identify pest species and estimate their population without manual intervention. This technology not only reduces labor but also improves accuracy and timely decision-making in pest management. Depending on the design and environmental conditions, these systems can achieve detection accuracy ranging from 70% to 98%, making them highly effective for precision agriculture and integrated pest management (IPM).

AI in Pest Monitoring and Surveillance

Artificial Intelligence has significantly enhanced pest monitoring and surveillance by enabling real-time, accurate and large-scale observation of agricultural fields. By integrating advanced tools such as drones, satellites and mobile applications, AI helps in early detection of pest infestations and supports timely decision-making, thereby reducing crop losses and improving pest management efficiency.

Drone-Based Monitoring: Drone-based monitoring uses Unmanned Aerial Vehicles (UAVs) equipped with high-resolution cameras to capture real-time images of crop fields. These images are analyzed using AI algorithms to detect pest hotspots and identify infestation patterns across large areas. AI-driven drones can generate detailed heat maps showing the intensity and distribution of pest attacks, which helps farmers adopt precision agriculture practices and apply control measures only where needed.

Satellite and Remote Sensing: Satellite imagery and remote sensing technologies play a crucial role in large-scale pest surveillance. AI analyzes spectral data obtained from satellites to detect subtle changes

in crop health, often before visible symptoms appear. This allows early identification of pest-induced stress in plants, enabling preventive action and minimizing damage.

Mobile-Based Pest Identification Apps: Mobile-based pest identification applications provide a simple and accessible tool for farmers. By uploading images of insects or damaged crops, farmers can receive instant identification of pests along with recommended control measures. These AI-powered apps bridge the gap between advanced technology and field-level application, making pest management more efficient and farmer-friendly.

AI in Pest Management Decision Support

Artificial Intelligence plays a crucial role in improving pest management by providing accurate, timely and data-driven decisions. Through advanced analytics and real-time data processing, AI helps farmers and researchers optimize pest control strategies, reduce input costs and enhance crop productivity.

Decision Support Systems (DSS): AI-based Decision Support Systems integrate multiple sources of information such as pest population data, weather conditions and crop growth stages to analyze field situations comprehensively. These systems process large datasets and provide real-time recommendations for pest control measures, enabling farmers to take timely and appropriate actions, thereby improving the efficiency of pest management practices.

Precision Pest Management: AI enables precision pest management by facilitating site-specific pesticide application based on the actual level of infestation in different parts of the field. This targeted approach helps in reducing excessive chemical use, minimizing environmental pollution and lowering production costs. By avoiding blanket spraying, AI contributes to more sustainable and eco-friendly agriculture.

Predictive Pest Forecasting: AI models use historical and real-time data to predict pest outbreaks and seasonal population dynamics. These predictive tools help in developing early warning systems, allowing farmers to take preventive measures before severe infestations occur. As a result, AI supports proactive pest management and reduces the risk of significant crop losses.

Case Studies / Applications

Recent advancements in agricultural entomology highlight the practical use of AI in pest management through innovative technologies. AI-based pest detection devices, equipped with field cameras and intelligent models, can automatically identify pest species and recommend suitable control measures, providing farmers with real-time diagnosis and advisory services. Similarly, AI-powered robots and smart farming systems, including flying drones, capture crop images and use GPS-based localization to detect pest-infested areas accurately. These technologies enable targeted pest control, reduce unnecessary pesticide use and ultimately help in minimizing crop losses while improving farm efficiency.

Advantages of AI in Entomology: Artificial Intelligence offers several advantages in agricultural entomology by improving the efficiency and sustainability of pest management practices. It ensures high accuracy and rapid pest identification, enabling early detection of infestations and timely intervention. AI also reduces dependence on manual labor, making pest monitoring more efficient and cost-effective. Additionally, it promotes eco-friendly pest management by minimizing unnecessary pesticide use and strongly supports the implementation of Integrated Pest Management (IPM) strategies.

Limitations and Challenges

Despite its significant potential, the application of AI in entomology faces several limitations and challenges. Technically, there is a lack of high-quality labeled datasets, difficulty in distinguishing closely related insect species, and reduced accuracy under complex field conditions. Practically, the high cost of AI technologies, limited awareness and adoption among small-scale farmers, and dependence on reliable internet and infrastructure restrict its widespread use. Additionally, biological challenges such as the detection of immature stages and natural variability in insect morphology further complicate accurate identification. These constraints collectively limit the large-scale adoption of AI, despite its promising benefits in pest management.

Future Prospects: The future of AI in agricultural entomology is highly promising, with advancements focusing on the integration of AI, IoT and robotics (AIoT) for smarter and automated pest management systems. The development of explainable AI models will improve transparency and trust among users, while the use of multimodal data-including images, sound and climatic factors-will enhance detection accuracy. Additionally, edge AI devices designed for rural areas will enable offline and cost-effective solutions for farmers. The emergence of smart pest forecasting systems will further support timely decision-making. Overall, future technologies are expected to be more accurate, affordable, and farmer-friendly, promoting sustainable agriculture.

Conclusion: Artificial Intelligence is revolutionizing agricultural entomology by enabling automated pest identification, real-time monitoring, and precision pest management. Despite current limitations, AI has immense potential to support sustainable agriculture by reducing pesticide use, improving crop productivity, and ensuring food security.

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Impact of Global Warming on Pest Outbreak

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Introduction

Global warming has emerged as one of the most serious environmental challenges affecting agriculture worldwide. Rising temperatures, irregular rainfall, increased carbon dioxide (CO_2) concentration, droughts, floods and extreme weather events are directly influencing crop production and indirectly affecting pest populations. Agricultural pests such as insects, mites, pathogens, nematodes and weeds are highly sensitive to climatic conditions. Even slight changes in temperature and humidity can significantly alter their survival, reproduction, migration and infestation patterns. According to the Food and Agriculture Organization (FAO), plant pests destroy up to 40% of global crop production annually, causing huge economic losses and threatening food security worldwide. Climate change is further intensifying this challenge by creating favorable conditions for frequent pest outbreaks.

Impacts of Global Warming on Pest Outbreaks

Increase in Temperature Accelerates Pest Development: Most insect pests are cold-blooded organisms, meaning their body temperature depends on the surrounding environment. When temperatures rise their metabolism, feeding rate, growth and reproduction increase rapidly. This results in shorter life cycles, faster population buildup, and more generations within a single cropping season. For example, pests such as aphids, whiteflies, stem borers and leaf miners reproduce much faster under warm conditions. This increases crop damage and makes pest management more difficult for farmers.

Expansion of Geographical Distribution: Global warming allows pests to survive in areas that were previously too cold for them. As a result, many pests are expanding their geographical range toward higher altitudes and higher latitudes. This creates new pest problems in regions where they were not previously found. For example, fall armyworm has spread rapidly across Africa and Asia, causing severe damage to maize crops. Similarly, fruit flies are invading new fruit-growing regions, while desert locust migration routes are changing due to unusual climatic conditions. This makes pest outbreaks more unpredictable and difficult to control.

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Increased Overwintering Survival: In colder climates, winter temperatures naturally kill a large number of pests and help maintain ecological balance. However, due to global warming, winters are becoming milder, allowing more pests to survive and reproduce in the following season. This leads to severe early-season infestations and stronger pest populations. Examples include brown plant-hopper in rice, mustard aphid, cotton bollworm and rice stem borer. Their survival during winter increases the risk of major outbreaks and heavy crop losses during the next cropping cycle.

Altered Phenology: Changes in rainfall patterns and humidity levels also play a major role in pest outbreaks. Excess rainfall and high humidity create favorable conditions for fungal diseases and moisture-loving pests, while drought conditions weaken crop resistance and increase the attack of sucking pests such as mites, thrips and whiteflies. For instance, high humidity encourages rice blast disease and brown planthopper infestation in paddy fields. On the other hand, drought stress makes crops weaker and more vulnerable to pest attack, especially in vegetables and cotton crops.

Disruption of Natural Enemies: Natural enemies such as predators, parasitoids and beneficial insects help maintain pest populations under control. However, climate change often affects these beneficial organisms differently than pests. In many cases, pests adapt faster than their natural enemies, resulting in pest resurgence. For example, ladybird beetles and parasitoid wasps that naturally control aphids may decline due to unfavorable weather conditions, while aphid populations continue to increase rapidly. This weakens biological control and increases dependence on chemical pesticides.

Increase in Invasive Pest Incidence: Global warming, combined with international trade and movement of plant materials, increases the spread of invasive pest species. These pests establish quickly in new environments and are often difficult and expensive to control. Examples include fall armyworm, in tomato, desert locust and rugose spiraling whitefly. These invasive pests cause severe economic losses and threaten food security in many countries. Once established, they can remain a permanent agricultural problem.

Case Studies

- ✓ The spread of fall armyworm (*Spodoptera frugiperda*) in Asia and Africa is strongly linked to climatic adaptability.
- ✓ Increased incidence of aphids and whiteflies has been reported in many crops due to warmer temperatures.
- ✓ Outbreaks of locusts have intensified due to unusual rainfall patterns associated with climate change.

Implications for Agriculture: The rise in pest outbreaks leads to significant yield losses, increased pesticide use, higher production costs, and environmental concerns. Farmers face difficulties in predicting pest incidence, making traditional pest management approaches less effective.

Conclusion

Global warming is reshaping pest dynamics in agricultural ecosystems, leading to more frequent and severe pest outbreaks. Addressing these challenges requires a multidisciplinary approach involving climate science, entomology and sustainable agricultural practices. Future pest management strategies must be adaptive, eco-friendly, and resilient to climate variability.

Next-Generation IPM Strategies for Sustainable Agriculture

Rashi Gehlot and Nikki Bhardwaj

Introduction

Sustainable agriculture has become a global priority in response to escalating challenges such as food insecurity, climate change, environmental degradation and biodiversity loss. Agricultural productivity is significantly constrained by insect pests, plant pathogens and weeds, which continue to cause substantial yield losses worldwide. Traditionally, pest management has relied heavily on chemical pesticides; while effective in the short term, their indiscriminate use has resulted in serious consequences including pesticide resistance, pest resurgence, ecological imbalance, environmental contamination and risks to human health.

To address these concerns, Integrated Pest Management (IPM) has emerged as an ecologically sound and economically viable approach. IPM integrates multiple control strategies-biological, cultural, mechanical and chemical-based on pest population dynamics and economic threshold levels. This holistic approach reduces dependence on chemical inputs while promoting sustainable crop protection. However, conventional IPM practices often face limitations such as delayed pest detection, inadequate real-time decision-making and challenges in large-scale implementation, particularly under changing climatic conditions. In recent years the emergence of advanced technologies has revolutionized agricultural practices, paving the way for next-generation IPM strategies. Innovations such as artificial intelligence (AI), the Internet of Things (IoT), remote sensing, big data analytics, predictive modelling and genetic tools are transforming pest management into a more precise, data-driven, and proactive system. These technologies enable real-time pest surveillance, early warning systems and targeted interventions, significantly enhancing the efficiency and accuracy of pest control measures.

Next-generation IPM represents a paradigm shift from reactive to predictive pest management. By integrating digital farming platforms with ecological principles; it minimizes reliance on synthetic pesticides while promoting environmental conservation, biodiversity protection and climate-

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resilient agriculture. Thus, it offers a sustainable and future-ready solution to meet the growing food demands while safeguarding ecosystem health.

Important Role of Next-Generation IPM in Sustainable Agriculture

Next-generation Integrated Pest Management (IPM) plays a central role in advancing sustainable agriculture by balancing productivity with environmental protection. Its importance lies in how it reshapes pest control into a smarter, more adaptive and eco-friendly system.

Reduces Environmental Impact: Modern IPM minimizes excessive pesticide use through targeted and need-based application. By integrating biological control agents and natural predators, it helps preserve soil health, water quality and biodiversity.

Enhances Crop Productivity: Early pest detection using technologies like sensors and data analytics allows farmers to act before infestations spread. This leads to healthier crops, reduced losses, and improved yield stability.

Supports Climate-Resilient Farming: Climate change has altered pest life cycles and distribution. Next-generation IPM uses predictive models and climate data to anticipate pest outbreaks, helping farmers adapt to changing conditions.

Protects Human and Animal Health: Lower chemical usage reduces exposure risks for farmers, consumers, and livestock, contributing to safer food systems and healthier communities.

Prevents Pest Resistance: Overuse of chemicals leads to resistant pest populations. IPM employs diverse control methods- biological, cultural and mechanical helping delay or prevent resistance development.

Encourages Biodiversity Conservation: IPM practices protect beneficial organisms such as pollinators and natural enemies of pests, maintaining ecological balance within agricultural systems.

Facilitates Sustainable Intensification: It enables higher productivity without degrading natural resources, which is key to feeding a growing population sustainably.

Key Components of Next-Generation IPM Strategies

Digital Pest Surveillance Systems: Advanced monitoring tools such as smart traps, drones and satellite imaging enable real-time pest detection and population tracking. AI-based image recognition systems can accurately identify pest species and assess infestation levels, reducing dependence on manual scouting.

Artificial Intelligence and Machine Learning: AI and machine learning models analyze large datasets to predict pest outbreaks, optimize control measures and provide early warning systems. These technologies enhance decision support systems (DSS) for farmers.

Internet of Things (IoT) in Agriculture: IoT-enabled sensors collect data on environmental parameters such as temperature, humidity and soil moisture, which influence pest development. This helps in forecasting pest incidence and improving intervention timing.

Biological Control Innovations: The use of bio agents such as parasitoids, predators, entomopathogenic fungi and bacteria is being enhanced through improved mass production and formulation technologies. Genetic tools are also being explored for pest suppression.

RNA Interference (RNAi) Technology: RNAi is an emerging, highly specific pest control method that targets gene expression in pests, offering an environmentally safe alternative to chemical pesticides.

Precision Pesticide Application: Technologies such as drone-based spraying and variable-rate applicators ensure precise pesticide application, reducing chemical usage and minimizing environmental impact.

Climate-Smart Pest Management: Next-generation IPM incorporates climate data to predict pest dynamics under changing climatic conditions, enabling adaptive and resilient pest management strategies.

Advantages of Next-Generation IPM

- ✓ Reduction in pesticide use and environmental pollution
- ✓ Improved pest control efficiency and crop productivity
- ✓ Enhanced farmer decision-making through real-time data
- ✓ Conservation of natural enemies and biodiversity
- ✓ Sustainable and climate-resilient agricultural practices

Challenges and Limitations of Next-Generation IPM

- ✓ Despite its potential, next -generation IPM faces several challenges
- ✓ High initial cost of advanced technologies
- ✓ Limited access and awareness among small-holder farmers
- ✓ Lack of technical expertise and training
- ✓ Data availability and standardization issues
- ✓ Infrastructure constraints in rural areas

Future Prospects: The future of IPM lies in the convergence of AI, IoT, robotics, and biotechnology often referred to as AIoT (Artificial Intelligence of Things). The development of user-friendly mobile applications, low-cost sensors, and region-specific decision support systems will further promote adoption. Integration of traditional knowledge with modern technologies will also play a crucial role in enhancing sustainability.

Conclusion

Next-generation IPM strategies represent a paradigm shift in agricultural pest management. By integrating modern technologies with ecological principles, these approaches address the limitations of traditional pest control methods. They offer a sustainable pathway to increase agricultural productivity while preserving environmental health and ensuring food security. Adoption of these strategies requires collaboration among researchers, policy-makers, and farmers, along with investment in education and infrastructure. As agriculture moves toward sustainability, next-generation IPM will play a pivotal role in shaping the future of food systems.

Role of Packaging in Post-Harvest Management of Perishable Foods

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Abstract

Post-harvest losses of perishable foods such as fruits, vegetables, dairy, and meat products remain a significant challenge in ensuring food security and economic sustainability. Packaging plays a vital role in maintaining quality, extending shelf life, and ensuring safety during storage and transportation. Modern packaging technologies such as modified atmosphere packaging, active packaging, and intelligent packaging have transformed traditional post-harvest practices. This article discusses the importance, functions, and recent advancements in food packaging and highlights its role in reducing losses and maintaining the quality of perishable foods.

Introduction

Perishable foods are highly susceptible to deterioration due to physiological, biochemical, and microbial activities that continue even after harvest. In India and other developing countries, post-harvest losses of fruits and vegetables are estimated to range between 20-30%, primarily due to inadequate handling, storage, and packaging systems (Kader, 2005). Packaging serves as a critical component of the post-harvest supply chain, acting as a protective interface between the food product and the external environment. Traditionally, packaging was limited to containment and transportation; however, it has now evolved into an advanced system that contributes significantly to food preservation, safety, and quality maintenance.

Functions of Packaging in Post-Harvest Management

Packaging performs multiple essential functions in preserving perishable foods. It provides physical protection against mechanical damage such as bruising, compression, and vibration that may occur during harvesting, handling, and transportation. The use of appropriate materials such as corrugated fiberboard boxes, plastic crates, and cushioning elements helps maintain the structural integrity of fruits and vegetables. Additionally, packaging acts as a barrier against environmental factors such as moisture, oxygen, light, and microbial contaminants. By regulating these external influences, packaging helps in slowing down deterioration processes and maintaining the freshness and nutritional quality of food products (Robertson, 2013). Furthermore, packaging facilitates convenient handling, storage, and marketing, thereby improving the overall efficiency of the supply chain.

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Modified Atmosphere Packaging (MAP): Modified Atmosphere Packaging (MAP) is one of the most widely used advanced packaging technologies for perishable foods. It involves altering the composition of gases surrounding the food product, typically by reducing oxygen levels and increasing carbon dioxide concentration. This modification slows down respiration and metabolic activities in fruits and vegetables, thereby delaying ripening and senescence. MAP has been successfully applied in the storage of fresh produce, meat, and dairy products, as it helps in maintaining quality and extending shelf life (Kader, 2002). The effectiveness of MAP depends on factors such as the type of product, packaging material, and storage conditions. By creating an optimal gaseous environment, MAP significantly reduces spoilage and enhances product stability.

Active Packaging Systems: Active packaging represents a significant advancement over conventional packaging systems by actively interacting with the food or its environment. This type of packaging incorporates functional components such as oxygen scavengers, moisture absorbers, ethylene absorbers, and antimicrobial agents. These components modify the internal atmosphere of the package to enhance preservation and extend shelf life. For instance, oxygen scavengers help in preventing oxidative spoilage, while ethylene absorbers are particularly useful in delaying ripening of climacteric fruits such as mango and banana. Antimicrobial packaging systems inhibit the growth of spoilage and pathogenic microorganisms, thereby improving food safety. Active packaging has gained considerable attention due to its effectiveness in maintaining product quality and reducing post-harvest losses (Vermeiren *et al.*, 1999).

Intelligent (Smart) Packaging Technologies: Intelligent packaging is an emerging technology that provides real-time information about the condition of food products during storage and transportation. It uses sensors and indicators to monitor parameters such as temperature, gas composition, and microbial activity. Time-temperature indicators and freshness indicators are commonly used to detect spoilage and ensure product safety. These systems enhance traceability and transparency in the food supply chain, enabling better decision-making and quality control. Intelligent packaging not only improves consumer confidence but also helps in reducing food waste by providing accurate information about product quality.

Sustainable and Biodegradable Packaging: With increasing concerns about environmental sustainability, there is a growing demand for eco-friendly packaging materials. Biodegradable and edible packaging materials derived from natural sources such as starch, cellulose, and proteins are gaining popularity. Edible coatings and films can be applied directly to fruits and vegetables to reduce moisture loss, delay ripening, and improve appearance. These materials not only enhance shelf life but also reduce dependence on synthetic plastics, thereby minimizing environmental impact. The development of

sustainable packaging solutions is essential for achieving a balance between food preservation and environmental conservation.

Role of Packaging in Different Perishable Foods

Packaging requirements vary depending on the type of perishable food. In fruits and vegetables, packaging helps in controlling respiration and moisture loss, thereby maintaining freshness. In dairy products, aseptic and vacuum packaging systems are used to prevent microbial contamination and extend shelf life. Similarly, in meat and fish products, vacuum packaging and MAP are widely used to inhibit microbial growth and maintain quality. The selection of appropriate packaging materials and technologies is crucial for ensuring product safety and quality throughout the supply chain.

Challenges in Food Packaging

Despite the significant advancements in packaging technologies, several challenges limit their widespread adoption. High cost of advanced packaging materials and equipment, lack of awareness among farmers and small-scale processors, and inadequate infrastructure are major constraints. Additionally, environmental concerns related to plastic waste pose a serious challenge to the sustainability of packaging systems. Addressing these challenges requires the development of cost-effective, eco-friendly packaging solutions and increased awareness among stakeholders.

Future Trends in Food Packaging

The future of food packaging lies in the integration of advanced technologies such as nano-technology, smart sensors, and biodegradable materials. Nano-packaging offers improved barrier properties and antimicrobial effects, while sensor-based systems enable real-time monitoring of food quality. The integration of packaging with cold chain systems and digital technologies will further enhance efficiency and reduce post-harvest losses. Continuous research and innovation in this field will play a crucial role in improving food preservation and ensuring food security.

Conclusion

Packaging plays a pivotal role in post-harvest management of perishable foods by providing protection, extending shelf life, and ensuring safety. Modern packaging technologies such as MAP, active packaging, and intelligent systems have significantly improved the efficiency of food preservation. The adoption of sustainable packaging solutions will further enhance environmental and economic benefits. Strengthening packaging systems is essential for reducing post-harvest losses, improving food quality, and ensuring the availability of safe and nutritious food.

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Cooperatives in Jharkhand: Transforming Lives and Local Economies

Avinash Kumar and B. K. Jha

Cooperative Structure in Jharkhand

In Jharkhand, multiple organizations focusing on agriculture, animal husbandry, and forest produce are at the core of the cooperative movement. Key organizations include: VEGFED, which focuses on vegetable processing and marketing. JHAS COLAMPF is responsible for Lac marketing. JHAMFCOFED manages minor forest produce (MFP - Minor Forest Produce). JHASCOFISH is involved in the promotion of fisheries. JMF (Medha) specializes in milk production. The Sidho Kanho Agri & Forest Produce Cooperative Federation (SKAFPCOFED) is primarily involved in the production of agricultural and forest products. In Jharkhand, there are 2028 LAMPS and 2374 PACS. Additionally, there are 9000 other cooperative societies operating in the region.

The Jharkhand Cooperative Department implements several schemes and programs to support farmers and strengthen the cooperative movement in the state. Some major schemes include, Jharkhand Rajya Fasal Rahat Yojana (JRFRY): Provides financial assistance to farmers facing crop damage due to natural calamities. Mukhya Mantri Kisan Credit Card Yojana: Offers interest subvention to farmers who repay loans on time. Paddy Procurement Scheme: Ensures Minimum Support Price (MSP) for paddy farmers through LAMPS/ PACS. Online and offline registration systems streamline the process. Infrastructure Development and Computerization: Aims to modernize LAMPS/PACS for efficient service delivery in rural areas. Skill Development and Training: Provides training programs on various trades like agriculture, allied activities, and handicrafts through cooperative societies and Krishi Chaupal. Working Capital Support: Allocates funds to LAMPS/PACS to ensure timely availability of agricultural inputs like fertilizers, seeds, and insecticides for farmers. These schemes play a crucial role in promoting farmer welfare, strengthening the agricultural sector, and fostering a robust cooperative movement in Jharkhand.

Activities and Achievements: Cooperatives, through the State Cooperative Bank, offer short and medium-term loans to LAMPS/PACS for agriculture and infrastructure development at lower interest rates, making them accessible to small farmers and rural communities. In 2021-22, ₹2033.76 crore was deposited, and ₹12.01 crore in Kisan Credit Card (KCC) loans was sanctioned. LAMPS/PACS act as Common Service Centres (CSCs), with 934 comput-

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erized and 573 functioning as Pragya Kendras. In 2021-22, 1,408,289 farmers were registered, with online registration now available. These cooperatives provide ₹21 crore in working capital for seed and fertilizer procurement and support 1,339 LAMPS/PACS with storage facilities of 1.46 lakh metric tons. As Custom Hiring Centres, they also offer agricultural equipment and inputs like seeds, fertilizers, and pesticides. To enhance storage and preservation, Jharkhand has established 19 cold storages (5000 MT), 139 cold rooms (30 MT), and 32 solar-powered cold rooms for perishables. In 2021-22, 681 LAMPS/PACS procured 7.5 lakh MT of paddy from 1.39 lakh farmers. The procurement of Minor Forest Produce (MFP) at Minimum Support Price (MSP) benefits thousands of tribal families. Twelve state-level Cooperative Federations support minor forest produce, vegetables, fisheries, lac production, and dairy sectors. The Jharkhand Milk Federation (JMF-Medha) operates six milk processing units and supports quality milk production in 18 districts. JHAMFCOFED directly aids over 25,000 tribal families and supports over 1 lakh MFP collectors, marketing products like tamarind, Chironji, and Biju mango through model outlets, with cold storage infrastructure boosting this trade.

Jharkhand State Minor Forest Produce Co-operative Development and Marketing Federation Limited (JHAMFCOFED) established in 2007 is a key organization in Jharkhand dedicated to promoting sustainable development and marketing of Minor Forest Produce (MFPs) throughout the state. As an apex federation, it plays a crucial role in empowering tribal communities and enhancing their livelihoods. The federation has 197+ primary co-operative societies /LAMPS/PACS/Special Societies and 50+ SHGs as its members and also support about 25,000 tribal families directly and Over 1 Lac MFP Collectors indirectly through its schemes. Except Lac and Tendu Leaves JHAMFCOFED is mandated to work on all MFPs in the state like Tamarind, Chironji, Mahua, Karanj, Kusum, Honey, Sal etc. JHAMFCOFED procures MFPs from affiliated cooperatives and Self-Help Groups (SHGs) across Jharkhand, adds value to products, implements the Minimum Support Price (MSP) scheme, supports tribal empowerment, and promotes sustainable development. The federation's efforts are instrumental in realizing the potential of Jharkhand's abundant non-timber forest resources, benefiting communities in all regions of the state.

Jharkhand Women Self Supporting Poultry Cooperative Federation Ltd. is a cooperative organization focused on empowering rural women in Jharkhand through poultry farming. Recognizing the limitations of traditional agriculture, the federation aims to provide alternative livelihood opportunities that are less land-dependent and can supplement agricultural income. The federation's mission is to develop rural enterprises that exploit the growing demand for new products, especially in urban centers. By promoting small-scale poultry farming, the organization seeks to provide a sustainable livelihood for rural women, who often belong to

resource-poor families. The federation's vision is to create a standardized model for small-holder poultry units that can be replicated across Jharkhand, benefiting a large number of poor rural women. Through initiatives like collective marketing, branding, and retailing, the federation aims to reduce production costs, ensure quality control, and establish a strong market presence for the products produced by its member cooperatives. By focusing on poultry farming, the federation is tapping into a sector with high growth potential and increasing demand. The organization's efforts align with the broader goal of enhancing rural livelihoods and promoting economic development in Jharkhand.

Jharkhand State Co-operative Lac Marketing & Procurement Federation Ltd. (JASCOLAMPF) is a cooperative organization dedicated to promoting the development of the lac industry in Jharkhand. Established in 1963, JASCOLAMPF is committed to social responsibility and focuses on services over profit. The federation was created to address the exploitation of lac growers and provide them with fair prices for their sticklac. By working with primary cooperative societies at the village level, JASCOLAMPF purchases sticklac at prices proportionate to the seedlac price offered by the State-trading Corporation of India. This ensures that lac growers receive a fair and supportive price for their product. JASCOLAMPF is one of the largest channels for lac-related products in Jharkhand and plays a crucial role in supporting the economic well-being of the tribal population engaged in lac cultivation.

Jharkhand State Adivasi Co-operative Vegetable Marketing Federation Ltd. (VEGFED) is an apex cooperative society established to address the challenges faced by vegetable producers in Jharkhand. The federation aims to create a more efficient and sustainable vegetable value chain by organizing producers into cooperative structures. VEGFED's mission is to ensure remunerative prices for vegetable growers and provide consumers with high-quality vegetables at reasonable prices. By establishing a brand called “VEGFRESH,” the federation seeks to build trust and promote the cooperative structure. The federation operates through a two-tier cooperative structure, comprising primary vegetable cooperative societies (PVCS) at the grassroots level and an apex federation at the state level. This structure facilitates efficient marketing and distribution of vegetables produced in Jharkhand.

Jharkhand State Fisheries Co-operative Federation Ltd. (JHASCOFISH) is a state-level organization that serves as a bridge between primary fisheries cooperative societies and the government in Jharkhand. Established to address the challenges faced by individual fisheries cooperatives, JHASCOFISH operates across the entire state and can open branches with prior approval. The federation acts as a Special Purpose Vehicle (SPV), providing services that may not be available through routine government channels. By promoting and facilitating the sustainable growth of the fisheries

sector, JHASCOFISH fulfills its mandated obligations as a registered cooperative body.

Sidho Kanho Krishi Evam Vanopaj Rajya Sahkari Sangh Ltd. is a state-level cooperative federation in Jharkhand aimed at improving the livelihoods of farmers and MFP collectors. By coordinating with district-level cooperative unions, the federation aims to eliminate the middleman's role in the agricultural and MFP sectors. This will ensure farmers receive fair prices for their produce, access storage facilities, and benefit from value addition initiatives. The federation will also conduct research, branding, and marketing to create a more efficient and transparent system for agricultural and MFP products in Jharkhand.

Role of Social Media in Disseminating Agricultural Information

Akanksha N. Xaxa, Avinash Kumar and Ravi Ranjan Kumar

Abstract

The rapid advancement of digital technologies and increasing penetration of smartphones and internet connectivity have transformed the way agricultural information is disseminated. Social media platforms have emerged as effective tools for real-time communication, knowledge sharing, and interaction among farmers, extension personnel, and other stakeholders. This article examines the role of social media in disseminating agricultural information, highlighting its applications in knowledge exchange, extension services, market access, and awareness generation. Evidence suggests that platforms such as WhatsApp, YouTube, and Facebook are widely used by farmers for accessing timely and relevant information, thereby improving decision-making and farm productivity. However, the effectiveness of social media is constrained by challenges such as digital illiteracy, poor connectivity, misinformation, and socio-economic disparities. The study also discusses the digital divide in India and its implications for equitable access to agricultural information. The findings emphasize that while social media has significant potential to complement traditional extension systems, addressing existing challenges through improved infrastructure, digital literacy, and localized content is essential for maximizing its impact.

Introduction

Social media refers to web and mobile-based platforms that enable individuals and organizations to create, share, and exchange information, ideas, and experiences within virtual communities. Since its emergence in the early 2000s, social media has evolved from simple networking platforms into powerful tools for communication, interaction, and real-time information exchange. Platforms such as Facebook, WhatsApp, YouTube, and Instagram are now widely used not only for social interaction but also for education, marketing, and knowledge dissemination.

In the agricultural sector, timely access to accurate information is essential for improving productivity, profitability, and decision-making. The agricultural information was traditionally disseminated through extension services, print media, radio, and television; however, these methods often faced limitations in terms of reach, speed, and personalization. With the rapid expansion of smartphones and internet connectivity, social media has emerged as an effective alternative, enabling farmers, extension workers, researchers and agribusiness stakeholders to exchange information on crop practices, pest management, market trends, and weather updates in real

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Social media	Date of Launch	Users (Approx. 2026)	Founder(s)
Facebook	4 Feb 2004	3.1-3.2 billion	Mark Zuckerberg (+ co-founders)
YouTube	14 Feb 2005	2.7-2.85 billion	Chad Hurley, Steve Chen, Jawed Karim
X (Twitter)	21 Mar 2006	550-660 million	Jack Dorsey, Biz Stone, Evan Williams, Noah Glass
WhatsApp	24 Feb 2009	3 billion+	Jan Koum, Brian Acton
Instagram	6 Oct 2010	2.2–3 billion	Kevin Systrom, Mike Krieger

time. Social media offers several advantages, including wide geographical coverage, rapid dissemination of information, enhanced networking among farmers, and opportunities for marketing agricultural produce. However, challenges such as misinformation, digital illiteracy, and unequal access to technology continue to limit its full potential. Against this background, the present article examines the role of social media in disseminating agricultural information, highlighting its significance, opportunities, and challenges in strengthening modern agricultural extension systems.

Network, Internet Usage and Digital Divide in India: Globally, smartphone adoption has expanded rapidly, with approximately 5.7–5.8 billion users in 2026, accounting for nearly 70% of the world's population. The total number of devices exceeds 7.5 billion, reflecting multiple device ownership. While growth has stabilized in developed countries, it continues to rise steadily in developing economies.

China remains the largest smartphone market with over 900 million users, followed by India with around 430-450 million users. Although smartphone penetration in India is relatively lower compared to developed nations, its large population and expanding digital infrastructure indicate substantial growth potential. Developed countries exhibit high smartphone penetration, with the United States exceeding 82%, and countries such as the United Kingdom, Germany, France, and Italy reporting levels above 75-80%. In contrast, developing countries are experiencing rapid expansion due to improved affordability and network infrastructure. The increasing adoption of 5G networks and rising digital engagement further enhance the potential of smartphones for real-time agricultural advisories.

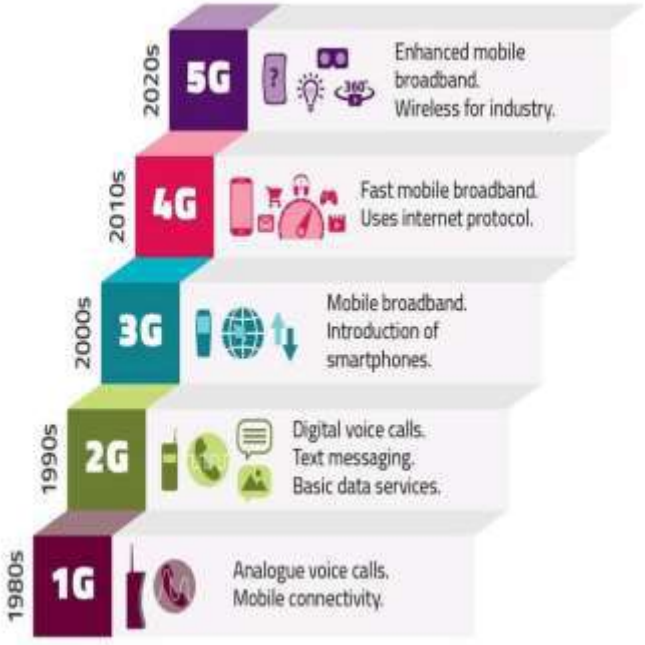

Fig. 1: Evolution of Mobile Network

India has witnessed significant growth in internet connectivity, with penetration reaching around 70-72% of the population. However, this growth remains uneven, with urban internet access significantly higher than in rural areas, indicating a persistent rural-urban digital divide. Although rural internet users are increasing, challenges such as poor connectivity, limited infrastructure, and low digital literacy continue to restrict effective utilization.

The term Digital Divide was first coined by Lloyd Morrisett. Digital Divide is used to describe the situations in which there is a market gap in access to, use of, and impact of digital technologies like the internet between different groups of people. The digital divide in India is further influenced by gender, socio-economic, and educational disparities. A large proportion of rural women lack independent access to mobile devices, often relying on shared usage, which limits their ability to access timely information. Similarly, access to digital technologies is significantly higher among economically better-off households compared to marginalized groups. Beyond access, the divide also extends to the quality of usage, as many users lack the skills required to effectively utilize digital platforms. In the context of agriculture, these disparities have important implications. While social media offers immense potential for disseminating agricultural information, its benefits are not equally accessible to all farmers. Addressing these challenges through improved infrastructure, digital literacy, gender inclusion, and localized content is essential for ensuring inclusive and effective agricultural communication.

Applications of Social Media in Agriculture:

Social media has emerged as a transformative tool in agricultural information dissemination by complementing traditional extension methods. It facilitates rapid, cost-effective, and interactive communication among farmers, extension personnel, researchers, and market actors. One of the most significant contributions of social media is the real-time dissemination of information. Farmers can access timely updates related to weather conditions, pest outbreaks, crop management practices, and government schemes, thereby enhancing decision-making and reducing dependence on delayed conventional sources. Social media also promotes knowledge sharing and peer learning by enabling farmers to exchange experiences, innovations, and indigenous knowledge across regions. This fosters collaborative learning and encourages the adoption of improved agricultural practices. In addition, it strengthens extension services by allowing experts to share advisories, training materials, and demonstrations through multimedia formats, thereby expanding outreach to remote areas. Furthermore, social media enhances access to market information by providing real-time updates on prices, demand trends, and buyer networks. It also facilitates direct marketing, reduces intermediaries, and improves farmers' income opportunities. Additionally, it plays a crucial role in awareness generation and mobilization by disseminating information about government schemes, training programs, and agricultural initiatives.

Table: Status of Agricultural Extension System in India (Based on Gulati *et al*., 2018 and FAO, 2012)

Aspect	Details
Total posts (Ag. Deptt)	1,43,863 sanctioned
Filled posts	91,288 filled (52,575 vacant)
Coverage	Extension services reach only about 6.8% of farmers
Current ratio	1 extension officer: 1162 operational holdings
Recommended ratio	1 extension officer: 750 holdings
Committee norms	Hilly: 1:400; Irrigated: 1:750; Rainfed: 1:1000
Central government posts	27,937 sanctioned; 13,672 filled; 14,265 vacant
If vacancies are filled	Ratio improves from 1:1162 to 1:1037

The agricultural extension system in India faces significant human resource constraints. According to Ashok Gulati *et al.* (2018), out of 1,43,863 sanctioned posts in the Department of Agriculture, only 91,288 were filled, leaving a substantial number of vacancies. This shortage results in limited outreach, with extension services reaching only about 6.8% of farmers (FAO, 2012). The extension worker-to-farmer ratio stands at approximately 1:1162, which is below the recommended level of 1:750. Even if all vacant positions are filled, the ratio would improve only marginally to 1:1037, indicating persistent gaps in service delivery. Despite these advantages, challenges such as digital illiteracy, connectivity issues, and misinformation continue to limit its effectiveness. Integrating social media with traditional extension approaches can significantly enhance agricultural communication systems.

Common Social Media Platforms used by Farmers: The table below presents the major social media platforms used by farmers along with their primary agricultural applications:

Platform	Major Use in Agriculture	Usage Level (%)
WhatsApp	Group communication, advisory exchange, peer interaction	~72.5% farmers use regularly
YouTube	Learning through videos, demonstrations, skill development	~66% farmers use for agri-information
Facebook	Networking, farmer groups, extension content	~59% farmers actively use
Instagram	Awareness, product promotion, youth engagement	Low–moderate
X (Twitter)	News, policies, expert opinions	Low
Telegram	Information sharing via channels	Very low (<50% usage)

Farmers predominantly prefer platforms that are simple, interactive, and capable of delivering multimedia content. Messaging and video-based platforms, particularly WhatsApp and YouTube, are the most widely used due to their effectiveness in facilitating real-time communication and visual learning.

Limitations and Challenges

The use of social media in agriculture, although promising, is constrained by several interrelated challenges. One of the primary limitations is the low level of digital literacy among farmers, particularly in rural areas, which restricts their ability to effectively access and utilize online information. In addition, poor internet connectivity, inadequate infrastructure, high data costs and unreliable electricity supply further limit accessibility, especially for small and marginal farmers. The spread of misinformation and lack of content authenticity is another major concern, as farmers may rely on unverified information, leading to inappropriate decision-making. Language barriers and the absence of localized, context-specific content further reduce the effectiveness of digital platforms. Moreover, factors such as age, lack of awareness, and limited technical skills influence the adoption and use of social media. Social media also cannot fully replace traditional extension systems, as face-to-face interaction and local validation remain essential for effective learning and technology adoption. Concerns related to data privacy, trust, and security further discourage active participation.

Addressing these challenges is crucial for ensuring the inclusive and effective use of social media in agriculture.

Fig. Innovative Initiatives in the field of social media

Conclusion

Social media has emerged as a powerful and dynamic tool for disseminating agricultural information, offering speed, accessibility, and interactivity. It complements traditional extension systems by enabling real-time knowledge sharing, peer learning, and improved market linkages. However, challenges related to digital access, literacy, and information reliability must be addressed to fully realize its potential. Strengthening digital infrastructure, promoting inclusive access, and integrating social media with conventional extension approaches can significantly enhance agricultural development and farmer empowerment.

Role of Sulphur Nutrition in Garlic Cultivation

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Introduction

Garlic (*Allium sativum* L.) is a high-value bulb crop widely cultivated for its culinary, medicinal and nutraceutical importance. It is particularly known for its characteristic aroma and therapeutic properties, which are primarily attributed to sulfur-containing compounds such as allicin, diallyl sulfide, and ajoene. Among the essential plant nutrients, sulphur (S) plays a critical role in garlic cultivation due to its direct involvement in the synthesis of these organosulfur compounds. Unlike many other crops, garlic has a relatively high sulphur requirement, making sulphur nutrition a key factor influencing yield, bulb quality, pungency, and storage life. Deficiency of sulphur can significantly reduce crop productivity and compromise the medicinal and commercial value of garlic. Therefore, understanding the role of sulphur in garlic physiology and implementing appropriate nutrient management strategies are essential for maximizing yield and quality.

Importance of Sulphur in Plant Nutrition: Sulphur is a secondary macronutrient requi-red by plants in moderate amounts but is essential for several physiological and biochemical processes. It is a constituent of amino acids such as cysteine and methionine, which are fundamental building blocks of proteins. Sulphur is also involved in the synthesis of vitamins, coenzymes, and secondary metabolites. In garlic, sulphur plays a particularly important role in the formation of volatile compounds responsible for flavor, aroma, and medicinal properties. Additionally, sulphur contributes to chlorophyll formation, photosynthesis, and enzyme activation, thereby supporting overall plant growth and development.

Sulphur Metabolism in Garlic: Sulphur uptake in garlic occurs primarily in the form of sulfate ions (SO_4^{2-}) from the soil. Once absorbed, sulphur is assimilated into organic compounds through a series of enzymatic reactions. It is incorporated into amino acids such as cysteine, which serves as a precursor for the synthesis of various sulfur-containing compounds. In garlic, these compounds are further converted into allicin and other organosulfur compounds that determine the crop's pungency and medicinal value. The efficient assimilation and metabolism of sulphur are crucial for enhancing both yield and quality.

Role of Sulphur in Growth and Development:

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Sulphur plays a vital role in vegetative growth and bulb development in garlic. It enhances cell division, promotes leaf expansion and improves photo-synthetic efficiency. Adequate sulphur supply ensures vigorous plant growth, which is essential for higher biomass accumulation and bulb formation. Sulphur also influences root development, enabling better nutrient and water uptake. Deficiency of sulphur results in stunted growth, reduced leaf area, and poor bulb development.

Effect on Bulb Yield and Size: Sulphur nutrition has a significant impact on bulb yield and size in garlic. Adequate sulphur application increases the number of cloves per bulb, bulb weight, and overall yield. It enhances carbohydrate metabolism and translocation, leading to better bulb filling and development. Studies have shown that sulphur application can significantly increase garlic yield compared to sulphur-deficient conditions. The improvement in yield is attributed to enhanced photosynthesis and efficient nutrient utilization.

Influence on Quality and Pungency: One of the most important roles of sulphur in garlic cultivation is its influence on bulb quality and pungency. Sulphur is directly involved in the synthesis of allicin and related compounds that impart the characteristic flavor and aroma of garlic. Higher sulphur levels lead to increased concentration of these compounds, enhancing the medicinal and culinary value of the crop. Sulphur also improves bulb firmness, reduces moisture content, and enhances storage life.

Sulphur Deficiency Symptoms in Garlic: Sulphur deficiency in garlic is characterized by yellowing of young leaves, reduced growth, and poor bulb development. Unlike nitrogen deficiency, which affects older leaves, sulphur deficiency primarily affects younger tissues due to its limited mobility within the plant. Deficient plants exhibit thin leaves, delayed maturity, and reduced yield. Early detection and correction of sulphur deficiency are essential to prevent significant yield losses.

Sources and Methods of Sulphur Application: Sulphur can be applied through various sources such as elemental sulphur, gypsum, ammonium sulphate, and single super phosphate. The choice of source depends on soil properties, crop requirement, and availability. Sulphur can be applied as a basal dose during land preparation or through fertigation in modern irrigation systems. Foliar application of sulphur-containing compounds can also be used for quick correction of deficiencies. Integrated nutrient management involving the combined use of organic and inorganic sources ensures efficient sulphur utilization.

Interaction with Other Nutrients: Sulphur inter-acts with other nutrients, particularly nitrogen, in influencing plant growth and yield. A balanced nitrogen-to-sulphur ratio is essential for optimal protein synthesis and crop performance. Excess nitrogen without adequate sulphur can lead to nutrient imbalance and reduced quality. Sulphur also enhances the availability and uptake of micro-nutrients, contributing to overall plant health.

Role in Stress Tolerance: Sulphur plays a role in

enhancing plant tolerance to abiotic and biotic stresses. It is involved in the synthesis of glutathione, a key antioxidant that protects plants from oxidative stress. Sulphur-containing compounds also contribute to plant defense mechanisms against pests and diseases. Adequate sulphur nutrition improves plant resilience and reduces yield losses under stress conditions.

Impact on Storage and Shelf Life: Sulphur nutrition influences the storage quality of garlic bulbs. Bulbs with adequate sulphur content have lower moisture content, higher dry matter, and better resistance to microbial infection. This results in improved shelf life and reduced post-harvest losses. Proper curing and storage practices further enhance the benefits of sulphur nutrition.

Constraints and Challenges: Despite its importance, sulphur nutrition is often neglected in garlic cultivation due to lack of awareness and soil testing. Continuous cropping and reduced use of organic manures have led to sulphur deficiencies in many soils. Overuse of nitrogen fertilizers without adequate sulphur supplementation further exacerbates the problem. Addressing these challenges requires improved nutrient management practices and farmer education.

Future Prospects

Future research should focus on optimizing sulphur application rates, developing sulphur-efficient garlic varieties, and improving nutrient management strategies. Advances in precision agriculture and nano-fertilizers offer new opportunities for enhancing sulphur use efficiency. Integration of sulphur management with sustainable farming practices will be crucial for improving garlic productivity and quality.

Conclusion

Sulphur is a critical nutrient in garlic cultivation, playing a key role in growth, yield, quality, and medicinal properties. Adequate sulphur nutrition enhances bulb development, increases yield, and improves pungency and storage life. Integrated nutrient management practices that ensure balanced sulphur supply are essential for achieving sustainable and profitable garlic production. Increasing awareness among farmers and promoting scientific nutrient management will be key to maximizing the benefits of sulphur nutrition in garlic cultivation.

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Nutritional and Medicinal Importance of Okra

V. Balamurugan, T. Anitha and M. Kabilan

Introduction

Okra (*Abelmoschus esculentus* L.), commonly known as bhendi or lady's finger, is an important vegetable crop belonging to the family Malvaceae. It is widely cultivated in tropical and subtropical regions and is valued for its tender pods, which are consumed as a vegetable. Okra is not only a dietary staple but also a rich source of essential nutrients and bioactive compounds with significant medicinal properties. The crop plays an important role in nutritional security due to its high content of vitamins, minerals, dietary fiber and antioxidants. In addition to its nutritional value, okra has been traditionally used in various medicinal systems for the treatment of ailments such as diabetes, gastrointestinal disorders and inflammation. Recent scientific studies have further validated its pharmacological properties, highlighting its potential as a functional food and nutraceutical.

Nutritional Composition of Okra

Okra is a nutrient-dense vegetable that provides a wide range of essential nutrients required for human health. It is rich in dietary fiber, which aids in digestion and helps regulate blood sugar levels. Okra contains significant amounts of vitamins such as vitamin C, vitamin A, vitamin K and folates, which are important for immune function, vision, blood clotting and cellular metabolism. It also provides essential minerals such as calcium, potassium, magnesium and iron. The low calorie content and high water content of okra make it suitable for weight management and healthy diets. Additionally, okra contains mucilage, a soluble fiber that contributes to its characteristic texture and offers various health benefits.

Bioactive Compounds in Okra: The medicinal properties of okra are attributed to its diverse bioactive compounds, including flavonoids, phenolic acids, polysaccharides and vitamins. Compounds such as quercetin and isoquercitrin exhibit strong antioxidant activity, protecting cells from oxidative stress. The presence of polysaccharides contributes to its immunomodulatory and anti-inflammatory effects. Okra seeds also contain bioactive compounds, including proteins and unsaturated fatty acids,

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which enhance its nutritional and therapeutic value.

Antioxidant Properties: Okra is a rich source of antioxidants that help neutralize free radicals and reduce oxidative stress in the body. Oxidative stress is associated with the development of chronic diseases such as cardiovascular diseases, cancer and diabetes. The antioxidants present in okra, including vitamin C and phenolic compounds, protect cells from damage and support overall health. Regular consumption of okra can enhance the body's antioxidant defense system and reduce the risk of chronic diseases.

Antidiabetic Effects: One of the most significant medicinal properties of okra is its antidiabetic potential. The soluble fiber and mucilage present in okra help slow down the absorption of glucose in the intestines, thereby regulating blood sugar levels. Okra extracts have been shown to improve insulin sensitivity and reduce blood glucose levels in experimental studies. This makes okra a valuable dietary component for the management of diabetes and prevention of related complications.

Cardioprotective Effects: Okra contributes to cardiovascular health by lowering cholesterol levels and improving lipid profiles. The soluble fiber in okra binds to cholesterol in the digestive tract, reducing its absorption and promoting its excretion. Additionally, the antioxidants in okra help reduce oxidative stress and inflammation, which are key factors in the development of cardiovascular diseases. Regular consumption of okra can help maintain healthy blood pressure and reduce the risk of heart disease.

Gastrointestinal Health: Okra is highly beneficial for digestive health due to its high fiber content and mucilage. The mucilage acts as a natural lubricant for the digestive tract, facilitating smooth bowel movements and preventing constipation. It also supports the growth of beneficial gut bacteria, improving gut health and digestion. Okra is often recommended for individuals with gastrointestinal disorders such as gastritis and irritable bowel syndrome.

Anti-Inflammatory and Immunomodulatory Effects: The bioactive compounds in okra exhibit anti-inflammatory properties by inhibiting inflammatory pathways and reducing the production of pro-inflammatory mediators. This helps in managing inflammatory conditions such as arthritis and other chronic diseases. Okra also enhances immune function by stimulating the activity of immune cells and improving the body's defense mechanisms against infections.

Anticancer Potential: Okra has shown potential anticancer properties due to its high antioxidant

content and presence of bioactive compounds. Flavonoids and phenolic compounds in okra can inhibit the growth of cancer cells and induce apoptosis. These compounds also enhance detoxification processes in the body, reducing the risk of carcinogenesis. Although more research is needed, preliminary studies suggest that okra may play a role in cancer prevention.

Role in Weight Management: Okra is a low-calorie, nutrient-rich vegetable that is beneficial for weight management. Its high fiber content promotes satiety and reduces appetite, helping in weight control. The low glycemic index of okra makes it suitable for individuals aiming to manage body weight and prevent obesity-related disorders.

Neuroprotective Effects: Emerging research suggests that okra may have neuroprotective properties due to its antioxidant and anti-inflammatory activities. These properties help protect brain cells from oxidative damage and may reduce the risk of neurodegenerative diseases such as Alzheimer's disease. The presence of vitamins and minerals further supports brain health and cognitive function.

Nutraceutical Applications of Okra: Okra is increasingly being used in the development of nutraceutical products such as powders, extracts and functional foods. Okra-based products are used for managing diabetes, improving digestion and enhancing overall health. The incorporation of okra into dietary supplements highlights its potential as a functional food with multiple health benefits.

Factors Affecting Nutritional Quality

The nutritional and medicinal quality of okra is influenced by factors such as variety, cultivation practices, maturity stage and post-harvest handling. Fresh and tender pods have higher nutrient content compared to over-mature pods. Organic cultivation practices can enhance the nutritional quality by reducing chemical residues and improving soil health.

Safety and Consumption

Okra is generally safe for consumption and is widely used in various cuisines. However, excessive consumption may cause gastrointestinal discomfort in some individuals due to its high fiber content. Proper cooking and preparation methods can enhance its palatability and nutritional benefits.

Future Prospects

Future research on okra should focus on identifying new bioactive compounds, improving nutritional quality through breeding and developing innovative nutraceutical products. Advances in biotechnology and food processing technologies can further enhance the utilization of okra in health-promoting applications.

Conclusion

Okra is a highly nutritious vegetable with significant medicinal and nutraceutical properties. Its rich composition of vitamins, minerals, fiber and bioactive compounds contributes to its antioxidant, antidiabetic, cardioprotective, anti-inflammatory and anticancer effects. The increasing demand for functional foods and natural health products highlights the importance of okra in promoting human health.

Adoption of improved cultivation and processing practices can further enhance its nutritional value and economic potential. Okra holds great promise as a sustainable and health-promoting crop in modern agriculture.

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Vertical Farming: A Comparative Analysis of Sustainability, Challenges, and Economic Cost in Modern Agriculture

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Abstract

Vertical farming is an advanced technology and intensive farming method that can increase production exponentially. Vertical farming faces many challenges, such as water scarcity, climate change, labour shortage and urbanisation, which lead to diminishing arable land. Vertical farming provides job opportunities that support local economies and healthy diets in areas where fresh produce is scarce. Vertical farming is beneficial for increasing food production, maintaining high-quality products, ensuring safety and also contributes to sustainable urban agriculture. The main advantages of vertical frames are environmental, social and economic benefits. Vertical farming can also provide solutions to improve food security around the world. This study is a critical review of articles published in relevant journals and online scientific databases. The crops are grown using a variety of vertical farming media such as perlite, cocopeat, and vermiculite to ensure rapid growth and higher yields. Vegetables are perfect for this type of vertical farming because they have a high net income in a short period of time.

Introduction

Vertical farming is the practice of growing produce in vertically stacked layers. The practice can use soil, hydroponic or aeroponic growing methods. Vertical farms attempt to produce food in challenging environments, like where arable land is rare or unavailable. The method helps mountainside towns, deserts and cities grow different types of fruits and vegetables by using skyscraper-like designs and precision agriculture methods. Most vertical farms use enclosed structures similar to greenhouses that stack vertically, either directly above each other or staggered for better natural light exposure. If saving space is of utmost importance, hydroponic methods as a growing medium instead of soil allow for reduced weight and lower water requirements by up to 70%. The use of aeroponics further reduces weight and water requirements. Most vertical farms are either hydroponic or aeroponic and do not have runoff, which would make the potted plants heavier. Vertical farming is the practice of growing crops in vertically stacked layers. It often incorporates controlled-environment agriculture, which aims to optimise plant growth, and soilless farming techniques such as hydroponics, aquaponics, and aeroponics. Some common choices of structures to house vertical farming systems include buildings, shipping containers, tunnels, and abandoned mine shafts. As of 2020, there is the equivalent of about 30 ha (74 acres) of operational vertical farmland in the

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world. Vertical farming is much more than just stacking plants and hoping for the best. The practice requires artificial temperature, light, water, and humidity control. If a delicate balance is not maintained, it's possible to lose an entire crop, the way a traditional farm might in the event of a drought or flood.

In a vertical farming system, multiple layers of growing trays are arranged in stacks. In each of these, plants are grown in nutrient-rich water instead of soil. Also called a vertical hydroponic system, this grow automation system is an excellent option to get fresh produce in large volumes even when space and other resources are limited, especially in urban cities. Vertical farming is the urban farming of fruits, vegetables, and grains, inside a building in a city or urban centre, in which floors are designed to accommodate certain crops. The objective of this dissertation was to investigate the feasibility and plausibility of the vertical farming concept in three specific and interrelated research domains.

- ✓ The first research question was to investigate whether enough energy can be generated onsite to meet the needs of the building.
- ✓ The second research question was to investigate the carbon footprint of produce grown vertically and compare that to produce grown conventionally (greenhouse and outdoors).
- ✓ The final research question was to investigate how relevant stakeholders perceive the concept of vertical farming and what they believe are current barriers and opportunities towards uptake of the technology. The purpose of this investigation was to determine ways to supply food to cities in an energy-efficient and sustainable manner from both a quantitative and qualitative perspective.

List of crops grown under vertical farming

Crop Category	Examples
Leafy Greens	Lettuce, Spinach, Kale, Arugula, Swiss Chard
Herbs	Basil, Mint, Cilantro, Parsley, Rosemary
Microgreens	Radish, Broccoli, Sunflower, Pea Shoots, Wheatgrass
Fruiting Crops	Tomatoes, Peppers, Cucumber, Strawberry, Eggplant
Roots Crops	Carrots, Radishes, Beets, Turnips, Potatoes

Comparison of vertical farming and traditional agriculture

Characteristic	Traditional Agriculture	Vertical Farming
Land Use	Extensive	Intensive
Water Consumption	High	Low
Pesticide Use	Common	Minimal
Crop Yield	Moderate	High
Labor Requirement	High	Moderate
Energy Efficiency	Low	High
Weather Dependency	High	Low
Transportation costs	High	Low
Carbon Footprint	High	Low
Urban Accessibility	Low	High

The cost of vertical farming is generally estimated according to Times of Agriculture magazine, 2023:

Infrastructure Costs: These are the structural requirements for the buildings, racks, climate control

List of different vertical farm in India

S. No.	Name	Location	Year	Products
1.	Growing Greens	Bangalore, Karnataka	2012	Mint, Spinach and Coriander
2.	Home crop	Hyderabad, Telangana	2017	Coco peat and composting kits
3.	Pin fresh	Nayagaon, Punjab	2016	Clay balls, grow bags and net pots
4.	Urban Kisan	Vishakhapatnam, A. P	2017	Lettuce and hydroponic system
5	Sure Grow	Coimbatore, T. N	2017	Lettuce and strawberry
6.	The Living Greens	Jaipur, Rajasthan	2013	Organic input kits and fruit bags
7.	City Greens	Bangalore, Karnataka	2017	Growing media and seed starters
8.	Ikheti	Mumbai, Maharashtra	2011	Seeds and gardening tools

systems, and irrigation setups. Generally, it varies from ₹10,00,000 to ₹1 crore.

Costs of Technology and Equipment: Advanced technologies include hydroponics, aeroponics, cooling systems, fertigation equipment, and automation systems in vertical farming. It depends on the scale of operations, ranging from ₹5 lakhs to ₹50 lakhs.

Operating Cost: The term used to describe the running cost for operating a facility, that is, labour, electricity, water, nutrient solutions, and seeds or seedlings. These costs lie around ₹2 lakhs to ₹5 lakhs every year.

Vertical farming is an innovative agricultural practice in which space is optimised to make food production in the urban setting possible through advanced technologies. As the population increases worldwide and the traditional constraints of urbanisation farming accelerate, with land, water shortage and high transportation costs. This problem is answered by vertical farming, as crops are grown in layers or in structures that can be controlled in their environments to efficiently use resources and space. The key enabling technologies

LED lighting: Advanced LED lighting systems mimic natural sunlight by offering specific light spectrums that are necessary for photosynthesis. These lights are energy-efficient and can be adjusted to fit the specific growth stages of crops, ensuring optimal plant development.

Climate Control Systems: These climate control technologies manage temperature, humidity, airflow, and carbon dioxide concentration. By creating a stable environment, these systems allow year-round cultivation regardless of external weather conditions, enhancing productivity and crop quality.

Automation and IoT: Automation and Internet of Things (IoT) are an integral part of vertical farming in modern times. Parameters like nutrient levels, light intensity, and environmental conditions can be monitored in real-time through sensors and actuators. Automation will help ensure consistency and bring down labour costs while ensuring efficient operations.

Challenges

Despite their advantages, these systems face several challenges:

High Initial Costs: Vertical farming systems require a lot of investment in infrastructure, equipment, and technology. The costs involved include LED lighting systems, climate controls, sensors, and automation technologies that can be a barrier to small-scale or resource-constrained farmers.

Energy Dependence: These systems depend on artificial lighting, climate control systems, and automated processes, which tend to incur a high operational energy cost. This dependence on energy sources is challenging in regions with unreliable power supply or high electricity costs.

Technical Skills: Skilled operators are necessary in managing and maintaining the operation of vertical farming systems. Technical competencies will be in aspects like plant science, nutrient management, and troubleshooting.

Scalability: Expansion in terms of volume for massive demand necessitates considerable invest-ment and logistics. Scaling these systems requires transcending spatial challenges, optimising resource use, and ensuring the sustainability of performance within large configurations.

With these challenges tackled through continued innovation and collaboration, vertical farming is going to transform global agriculture with sustainable solutions for the ever-growing demand for food.

Challenges and Limitations of Vertical Farming

Challenges	Description
High Initial Costs	Significant upfront investment in infrastructure and technology
Energy Requirements	High energy consumption for lighting, climate control, and automation
Skilled Labor	Need for specialised knowledge and technical expertise
Limited Crop Variety	Not all crops are suitable for vertical farming systems
Public Perception	Scepticism and resistance towards unconventional farming methods
Regulatory Framework	Lack of clear regulations and standards for vertical farming
Scalability Concerns	Challenges in expanding and replicating vertical farms on a large scale

Conclusion: Vertical farming represents highly transformational agricultural approaches in order to address important issues related to land shortages, water deficiencies, and the requirements of sustainable food. As a result, such systems show potential promise for their utilization in the context of urban-isation and scarce resource utilisation for year-round cultivation with zero pesticides. However, the journey to widespread use will need concerted efforts to overcome current limitations. The high initial costs, energy demands, and technical expertise barriers will need to be overcome through technolo-gical innovation, policy support, and collaborative initiatives. Advances in automation, renewable energy integration, and cost-effective designs will continue to push these systems toward broader accessibility and scalability. The role of supporting government policies coupled with public and private investment to create the enabling environment to facilitate growth cannot be down-played. As such systems develop, they hold promises of transformation in food production and, therefore, contribute to food security in the world, as well as sustainable urbanisation.

Nagami Mithun: Morphological Features and Socio-Economic Importance

Jagdish Choudhary, V. K. Vidyarthi, Harshit Kumar and Girish Patil S.

Introduction

Mithun (*Bos frontalis*), also known as the "cattle of the hills," is an indigenous bovine species exclusively found in the hilly forests of Northeastern states of India at an altitude of 300-3000 m and plays an important role in socio- economic and ecological importance for the tribal communities of North-East India. Besides Northeast India, it inhabits China, Bangladesh, Thailand, Bhutan, Myanmar and Malaysia (Khan *et al.*, 2019). Unlike conventional cattle, Mithun is primarily reared under forest-based, free-range systems and is closely linked with traditional customs, social status and livelihood security.

Despite its significance, Mithun remained scientifically under-represented for decades, with no officially registered breed at the national or global level. The recent registration of Nagami Mithun, native to Nagaland, marks a historic milestone in livestock biodiversity conservation. This recognition has established Nagami Mithun as the world's first officially registered Mithun breed, giving global visibility to an indigenous genetic resource that has long been preserved by tribal communities.

Mithun in North-East India: North-East India is the primary habitat of Mithun, with populations distributed across Arunachal Pradesh, Nagaland, Manipur and Mizoram. Mithun rearing is deeply rooted in indigenous knowledge systems, where animals are maintained in forest ecosystems with minimal external inputs (Khan *et al.*, 2019). Traditionally, Mithun management emphasizes natural grazing, community ownership, and sustainable use of forest resources. However, the lack of scientific characterization and formal breed recognition has limited structured conservation and genetic improvement programs, highlighting the urgent need for systematic documentation and breed registration.

Origin and Native Tract of Nagami Mithun: Nagami Mithun originates from the hilly and forested regions of Nagaland, characterized by high rainfall, humid climate and rugged terrain. The breed is distributed across Kohima, Peren, Chümoukedima, Zunheboto, Phek, Tuensang, Kiphire, Noklak, Shamator, Mon, Wokha, Tseminyiu and Longleng districts. The breed is traditionally reared by various Naga tribes, including Angami, Ao, Sumi, Lotha, Chakhesang and others. The natural habitat consists of dense forests, steep slopes and rich biodiversity, where animals thrive under extensive systems. Over generations, natural selection and indigenous management practices have shaped Nagami Mithun into a well-adapted and genetically

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distinct population.

Fig. 1: Map showing native tract and distribution of Nagami Mithun in Nagaland

Breed History and Development: Mithun has been an integral part of Naga society for centuries, symbolizing wealth, prestige and social identity. Although no formal breeding program existed historically, selective retention of superior animals by tribal farmers gradually contributed to the development of distinct phenotypic traits. In recent years, systematic field surveys, phenotypic characterization, and population studies conducted by research institutions and state agencies led to the scientific identification of Nagami Mithun as a distinct breed. This process culminated in its official registration, acknowledging the long-standing conservation efforts of indigenous communities.

Distinct Morphological Characteristics

Fig. 2: Nagami Mithun showing characteristic morphological features in its natural forest habitat of Nagaland

Nagami Mithun is characterized by a strong, compact and well-built muscular body, reflecting its robustness and suitability for forest-based production systems. Animals with a black body coat and characteristic white stockings on the lower legs are most common, although white-patched and piebald coat patterns are also observed. The face is inverted triangular with a straight forehead and the line joining the base of the horns is completely straight. A prominent dorsal ridge is evident in both males and females. The horns are massive and corrugated at the base, emerging outward and subsequently curving upward with pointed tips, giving the breed a distinctive and powerful appearance. These physical traits reflect the breed's excellent adaptation to forest ecosystems and extensive rearing conditions.

Production and Performance Traits

Nagami Mithun is primarily valued for meat production and social utility rather than milk yield. Adult males attain a body weight ranging from 470 to 500 kg, indicating good growth performance under low-input systems.

Cows produce approximately 184-193 kg of milk over a lactation period of about 300 days, mainly for household consumption. The breed exhibits:

- ✓ Good growth rate under extensive systems
- ✓ High-quality meat preferred in local markets
- ✓ Efficient utilization of forest vegetation
- ✓ Satisfactory reproductive performance under natural conditions

These traits make Nagami Mithun economically viable for tribal farmers while maintaining ecological sustainability.

Adaptive and Functional Traits

One of the most notable strengths of Nagami

Mithun is its exceptional adaptability. The breed is highly resilient to:

- ✓ High humidity and heavy rainfall
- ✓ Parasitic and infectious diseases common in forest environments
- ✓ Nutritional fluctuations due to seasonal forage availability

Its ability to survive and perform under minimal management highlights its importance in climate-resilient livestock production systems.

Breed Registration and Global Significance: Breed registration is a critical step in recognizing, conserving, and sustainably utilizing indigenous livestock genetic resources. The official registration of Nagami Mithun represents a landmark achievement, as it is the first Mithun breed in the world to receive formal recognition.This status safeguards the genetic identity of Nagami Mithun and places India at the forefront of Mithun research and conservation. The recognition contributes significantly to global databases on animal genetic resources and promotes awareness of indigenous breeds.

Socio-Economic and Cultural Importance: In Nagaland, Mithun is deeply embedded in social and cultural traditions. It plays a central role in festivals, customary ceremonies, conflict resolution and bride price systems. Ownership of Mithun is often associated with social prestige and economic security. Beyond cultural value, Nagami Mithun supports rural livelihoods by providing income, food security, and employment opportunities, particularly in remote and tribal areas. The estimated population of Nagami Mithun is around 23,000 animals.

Conservation Status and Challenges

Despite its recognition, Nagami Mithun faces several challenges, including:

- ✓ Habitat degradation and shrinking forest areas
- ✓ Genetic dilution due to unplanned breeding
- ✓ Changing socio-economic conditions and declining traditional practices

These factors underline the need for targeted conservation strategies.

Conservation Strategies and Future Prospects

Sustainable conservation of Nagami Mithun requires a multi-pronged approach, including:

- ✓ In-situ conservation, community participation
- ✓ Development of selective breeding and recording systems
- ✓ Policy support and institutional involvement
- ✓ Promotion of value addition and market linkages

Future research focusing on genetics, nutrition and health management will further enhance the breed's productivity and conservation.

Conclusion

Nagami Mithun represents a valuable indigenous livestock genetic resource with unique morphological, adaptive and socio-economic traits. Its recognition as the world's first registered Mithun breed is a major step toward conserving forest-adapted bovines and strengthening tribal livelihoods. Community-based conservation, scientific support and policy interventions are essential to ensure the sustainable future of this culturally and economically important breed.

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Farmer Participation in Plant Breeding for Crop Variety Development

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Abstract

Participatory plant breeding is an innovative approach that involves farmers directly in the process of crop variety development. This method combines the scientific knowledge of breeders with the practical experience of farmers to develop varieties that are better adapted to local environments and farming conditions. Farmer participation in selection and evaluation helps in identifying high-yielding, stress tolerant and farmer preferred varieties. This approach improves the adoption of new varieties and contributes to sustainable agricultural development.

Agriculture plays a vital role in ensuring food security and improving the livelihoods of rural communities. Over the years, scientists have developed improved crop varieties to increase productivity, enhance quality and provide resistance to pests and diseases. Traditionally, most crop varieties have been developed by scientists in research stations and later released to farmers for cultivation. However, sometimes these varieties may not fully meet the specific needs and preferences of farmers under local field conditions. To address this gap, a new approach known as Participatory Plant Breeding (PPB) has gained importance in modern agriculture. Participatory Plant Breeding involves the active participation of farmers in the process of developing new crop varieties. In this approach, farmers work together with scientists and researchers during different stages of variety development, including selection, evaluation, and testing. Participatory Plant Breeding is an important innovation in the field of Plant Breeding and Genetics, as it combines scientific knowledge with farmers' traditional experience. This collaboration helps develop crop varieties that are better suited to local environments and farmers' needs.

Concept of Participatory Plant Breeding

Participatory Plant Breeding is a collaborative approach where farmers, plant breeders, and agricultural scientists jointly participate in the process of crop improvement. Instead of conducting all research activities only in laboratories or research stations, plant breeders work directly with farmers in their fields. Farmers are involved in several stages of breeding programs such as:

- ✓ Selection of suitable crop varieties
- ✓ Evaluation of breeding lines under local conditions
- ✓ Identification of desirable plant traits

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- ✓ Field testing and final selection of improved varieties

This approach ensures that the developed varieties are practical, adaptable, and acceptable to farmers. Participatory Plant Breeding is especially useful in regions where environmental conditions are diverse and complex. Farmers have deep knowledge about their fields, soil conditions, climate patterns and crop performance, which can greatly help breeders in developing suitable varieties.

Importance of Participatory Plant Breeding

Better Adaptation to Local Conditions: One of the major advantages of participatory breeding is that crop varieties are tested directly under farmers' field conditions. This helps identify varieties that perform well in real farming environments rather than only under controlled experimental conditions.

Utilization of Farmers' Knowledge: Farmers possess valuable traditional knowledge about crop cultivation, soil management, and climate patterns. By involving farmers in breeding programs, scientists can benefit from this knowledge to develop better varieties.

Increased Adoption of Improved Varieties: When farmers participate in the development of crop varieties, they develop greater trust and confidence in the new varieties. As a result, the adoption rate of improved varieties becomes higher.

Conservation of Genetic Diversity: Participatory breeding encourages the use and conservation of local crop varieties and traditional germplasm. These genetic resources often possess valuable traits such as stress tolerance and disease resistance.

Development of Farmer-Friendly Varieties: Farmers often prefer varieties with specific characteristics such as early maturity, high yield, good taste and resistance to pests and diseases. Participatory breeding ensures that these traits are considered during variety development.

Steps in Participatory Plant Breeding

Participatory Plant Breeding involves several stages where farmers and scientists collaborate closely.

Identification of Farmers' Needs: The first step in participatory breeding is understanding the needs and preferences of farmers. Farmers may require varieties with traits such as drought tolerance, early maturity or resistance to specific diseases.

Selection of Breeding Materials: Scientists select appropriate genetic materials or germplasm lines that possess desirable traits. These materials are used in breeding programs to develop improved varieties.

Field Testing in Farmers' Fields: Experimental lines and varieties are grown in farmers' fields under normal cultivation practices. Farmers observe the crop performance and provide feedback on important traits.

Evaluation and Selection: Farmers and scientists jointly evaluate the performance of different crop lines. Farmers may select plants based on yield, grain quality, maturity period and adaptability.

Release and Dissemination of Varieties: After successful evaluation and testing, the best-performing varieties are recommended for cultivation and

distributed among farmers.

Role of Farmers in Participatory Plant Breeding

Farmers play a central role in participatory breeding programs. Their involvement ensures that the developed crop varieties are practical and beneficial for real farming conditions.

Farmers contribute in the following ways:

- ✓ Identifying important crop traits needed in their region
- ✓ Participating in field trials and demonstrations
- ✓ Selecting superior plants and varieties
- ✓ Providing feedback about crop performance

This collaboration strengthens the relationship between farmers and researchers and helps improve agricultural technologies.

Advantages of Participatory Plant Breeding

Participatory breeding offers several benefits to both farmers and researchers.

Improved Crop Adaptation: Varieties developed through participatory breeding are better adapted to local environmental conditions and farming practices.

Faster Development of Suitable Varieties: Because farmers are involved in the evaluation process, unsuitable varieties can be quickly rejected and promising lines can be identified faster.

Increased Farmer Empowerment: Participatory breeding empowers farmers by involving them directly in scientific research and decision-making processes.

Sustainable Agriculture: By promoting the use of diverse genetic resources and farmer knowledge, participatory breeding supports sustainable and resilient agricultural systems.

Challenges in Participatory Plant Breeding

Despite its many advantages, participatory breeding also faces some challenges.

Limited Awareness: Many farmers are not aware of participatory breeding programs or their potential benefits.

Need for Training: Farmers may require training to understand breeding methods and evaluation techniques.

Coordination Between Scientists and Farmers: Effective communication and coordination between researchers and farmers are essential for the success of participatory breeding programs.

Resource and Time Requirements: Participatory breeding requires additional resources and time compared to traditional breeding methods.

Conclusion

Participatory Plant Breeding represents a collaborative and farmer-centered approach to crop improvement. By involving farmers directly in the process of variety development, scientists can develop crop varieties that are better adapted to local conditions and farmer preferences. This approach not only improves crop productivity but also empowers farmers and strengthens sustainable agricultural systems. With continued support from researchers, agricultural institutions, and extension services, participatory plant breeding can play a vital role in shaping the future of agriculture and ensuring food security for growing populations.

Herbal Teas from Fruit Leaves

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Introduction

Herbal teas are often mistaken for traditional teas because they resemble tea in appearance and are prepared similarly. However, in reality, they are not considered true teas because they do not originate from the Camellia sinensis plant, the source of all conventional teas. Instead, herbal teas are more accurately called *tisanes*. Tisanes are blends of dried botanical ingredients such as leaves, seeds, grasses, nuts, bark, fruits, flowers, and other plant parts. These components contribute not only to the flavour of herbal teas but also to their therapeutic properties (Lindsay Goodwin). Unlike conventional teas, herbal teas are naturally caffeine-free, making them easy to consume and suitable for people of all age groups. They may consist of a single herbal ingredient or a combination of several herbs, carefully selected to achieve specific effects such as relaxation, rejuvenation, or relief from particular health conditions (Aoshima *et al.*, 2007)

A wide range of herbal teas is available on the market, each formulated to provide specific medicinal or therapeutic benefits. Despite this diversity, many herbal teas share common health-promoting properties. Regular consumption of herbal teas may help promote relaxation and mental calmness, support heart health, aid digestion, cleanse the body, enhance overall energy and wellness, nourish the nervous system, strengthen immunity, and provide antioxidant protection. Additionally, herbal teas may help relieve stress, prevent colds, stimulate internal organs, improve sleep quality, and boost vitality all while being caffeine-free and enjoyable to drink.

Tea is the world's most popular beverage, valued for its flavour, aroma, and cultural significance. Traditionally made from Camellia leaves, modern trends now favour herbal teas from other plants. Herbal teas are caffeine-free and soothing, made from herbs that promote relaxation and relieve ailments. Diabetes mellitus is a major global health issue. While medications can help manage it, no cure currently exists for complete recovery. In 2000, diabetes affected 2.8% of the global population, and this is projected to rise to 5.4% by 2025. Although treatments like insulin and oral antidiabetic drugs exist, they are expensive and less accessible in developing countries. Due to the side effects of synthetic drugs, herbal remedies are increasingly preferred for managing diabetes.5 Plant-based medicines are gaining importance as natural hypoglycemic agents. Over a thousand plant species are traditionally used to treat diabetes, rich in compounds such as phenolics, flavonoids, and terpenoids that help lower blood sugar. Herbal remedies are favoured for their effectiveness, afford-

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ability, and fewer side effects

Importance of Herbal Tea

- ✓ Achieving a calmer and more relaxed state of mind
- ✓ Supporting heart health
- ✓ Aiding with stomach and digestive problems
- ✓ Providing cleansing properties for the body
- ✓ Promoting energy and wellness
- ✓ Nourishing the nervous system
- ✓ Strengthening the immune system
- ✓ Providing antioxidants to the body
- ✓ Boosting energy levels and invigorating the body
- ✓ Relieving stress and helping to avoid colds
- ✓ Stimulating the internal organs
- ✓ Promoting a good night's sleep
- ✓ Caffeine-free and tastes great

Fruit-based herbal tea

Bael: The development of herbal tea granules incorporating Bael fruit extract along with complementary medicinal herbs offers a promising natural approach for managing diabetes. The phytochemical screening of Bael fruit confirmed the presence of key bioactive constituents, including alkaloids, flavonoids, tannins, and terpenoids, which are well-documented for their hypoglycemic and antioxidant properties. These compounds are believed to stimulate pancreatic activity and improve insulin secretion, aligning with traditional uses of Bael in Ayurvedic medicine. The bael fruit pulp was dried and grinded and the powder was made, then the extract was formed. The combination of other herbs like cinnamon, fenugreek, turmeric, ginger, and orange peel adds to the therapeutic potential, as each has demonstrated antidiabetic, anti-inflammatory, and antioxidant effects. The pH measurement of the herbal tea granules (pH 5.2) suggests that the formulation is mildly acidic, aligning well with the typical pH range suitable for consumption without causing gastrointestinal discomfort. Organoleptic properties, such as yellowish-brown color, aromatic smell, and sweet-spicy taste enhance patient acceptability, which is crucial for adherence in herbal therapies. Bael fruit extract and other medicinal herbs appear promising as a natural, cost-effective, and accessible approach for managing blood glucose levels in diabetic patients.

Fig: Fig fruits have traditionally been appreciated for their taste and nutritional value, while the leaves have other potential uses. Fig leaves are a sustainable and valuable source of bioactive compounds, including antioxidants such as tocopherols, poly-phenols, and flavonoids, with strong antioxidant and antimicrobial properties. In particular, it has been demonstrated that the amount of phenolic compou-nds in figs is higher than in red wine and tea. Moreover, a range of health-promoting effects, such as anti-tumour, hypolipidemic, antioxidant, anti-bacterial, and hypoglycemic properties. Fig fruits have traditionally been appreciated for their taste and nutritional value, while the leaves have other potential uses. Fig leaves are a sustainable and valuable source of bioactive compounds, including antioxidants such as tocopherols, polyphenols, and flavonoids, with strong antioxidant and antimicrobial

properties. In particular, it has been demonstrated that the amount of phenolic compounds in figs is higher than in red wine and tea (Li *et al., 2021*). Moreover, a range of health-promoting effects, such as anti-tumour, hypolipidemic, antioxidant, anti-bacterial, and hypoglycemic properties.

Guava: Guava have the potential pharmacologic activities of the extract from the fruit, leaf, bark or roots; these activities include antioxidant, hepatoprotective, anti-allergy, anti-microbial, anti-genotoxic, anti-plasmodial, cytotoxic, anti-spasmodic, cardioactive, anti-cough, anti-diabetic.

Mango: Herbal teas contain bioactive compounds that have been reported to have beneficial effects in the prevention of various metabolic diseases. Hence, the current study was conducted to assess the qualitative and quantitative phytochemical composition, functional properties and sensorial attributes of different formulations of mango leaf teas supplemented with Moringa oleifera and ginger powder as supporting and activating herbs. The qualitative phytochemical analysis indicated the presence of tannins, flavonoids, terpenoids and cardiac glycosides. While quantitative analysis revealed that flavonoids ranged from (0.17-0.52 mg g^{-1}), tannins (0.07-0.11 mg g^{-1}), cardiac glycosides (1.08-1.89 mg g^{-1}) and terpenoids (50%-70%). Mango leaf tea supplemented with moringa and ginger is a reservoir of phytochemicals. It can be consumed and commercially distributed to household and community as herbal tea.

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Slow-Release Fertilizers: A Sustainable Approach to Enhancing Nitrogen and Phosphate Availability in Soil

K. Pooja, M. Saravana Kumar and Chandru B.

Abstract

The limitations of conventional fertilizers, which usually show low efficiency with nearly 40–70% of nitrogen and a significant portion of phosphorus lost through leaching, volatilization, and soil fixation, have been addressed by slow-release fertilizers, which have emerged as an advanced strategy to enhance nutrient use efficiency and support sustainable agriculture. The use of slow-release nitrogen fertilizers, such as neem-coated urea, sulphur-coated urea, and nano-urea developed by IFFCO, has become increasingly important in India, where annual fertilizer consumption exceeds 60 million tonnes and nitrogenous fertilizers dominate usage with relatively low recovery efficiency. By adding nitrogen and phosphate to polymeric, coated, or nanostructured matrices, these sophisticated formulations control nutrient availability and allow for controlled and prolonged release. Diffusion and matrix degradation control nutrient release in these systems, guaranteeing a steady supply of nutrients in the root zone. Additionally, eco-friendly starch-based hydrogels and gel-based fertilizers improve soil moisture retention and control nutrient release, boosting crop drought resistance and nutrient efficiency. All things considered, slow-release fertilizers offer substantial agronomic, financial, and environmental advantages. These advantages include fewer applications, lower labour costs, fewer nutrient losses, less pollution in the environment, increased phosphate availability through less soil fixation, and improved nitrogen use efficiency by limiting volatilization losses.

Introduction

The efficiency of conventional fertilizers is still a major concern because a significant amount of nutrients, including nitrogen and phosphorus, are lost through leaching, volatilization, and soil fixation. Agriculture is essential to ensuring food security for the world's rapidly expanding population. These losses greatly contribute to environmental pollution in addition to decreasing crop productivity. Slow-release fertilizers have become a viable solution to these problems because they release nutrients gradually in accordance with plant demand, increasing nutrient use efficiency and reducing losses. By increasing soil moisture retention and guaranteeing sustained nutrient availability, recent developments such as gel-based fertilizers, nanocomposite fertilizers, and environmentally friendly hydrogels have further improved their performance, making them a promising strategy for sustainable agriculture.

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Approximately 70-71 million tonnes of fertilizer are used annually in India, one of the biggest fertilizer consumers in the world, with nitrogenous fertilizers dominating the consumption pattern. Nearly 38-39 million tonnes are made up of urea alone, demonstrating how heavily Indian agriculture depends on nitrogen inputs. A considerable imbalance in the use of nutrients is evident from the average fertilizer application of approximately 160 kg NPK per hectare, which is made up of roughly 101 kg nitrogen (N), 44 kg phosphorus (P), and 16 kg potassium (K). The need for effective nutrient management techniques, like slow-release fertilizers, to increase productivity while preserving environmental sustainability is further highlighted by this distorted pattern of fertilizer consumption.

Types of Slow-Release Fertilizers

Hydrogel-Based Fertilizers: Hydrogels, especially starch-based eco-friendly hydrogels, absorb and retain water while gradually releasing nutrients, enhancing soil moisture and fertility.

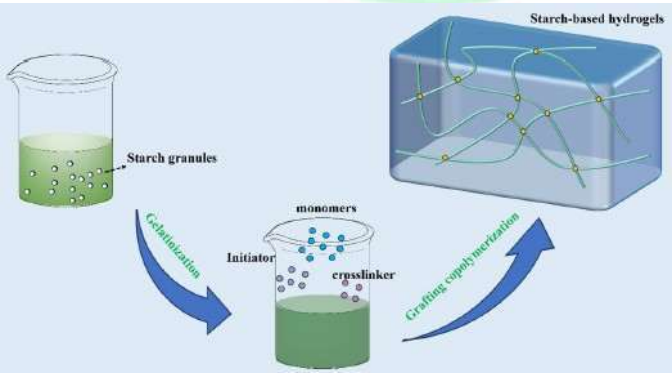

Fig. 1: Schematic diagram of process of preparing hydrogel by starch graft polymerization in aqueous solution

Nanocomposite Fertilizers: Nanocomposite fertilizers incorporate nutrients into nanoscale materials such as polymers and clay composites. These materials regulate nutrient release and improve nitrogen and phosphate availability.

Gel-Based Fertilizers: Gel-based fertilizers use a structured matrix to encapsulate nutrients and release them slowly over time, ensuring a steady nutrient supply.

Mechanism of Nutrient Release

Controlled release processes like diffusion, swelling, and biodegradation are how slow-release fertilizers work. While nanocomposite materials permit slow nutrient diffusion, hydrogels swell and release nutrients gradually when exposed to soil moisture. This minimizes losses and guarantees extended nutrient availability in the root zone.

Role in Nitrogen Availability

Nitrogen is essential for plant growth but is highly susceptible to losses. Slow-release fertilizers minimize nitrogen loss by providing a steady supply over time. This improves nitrogen use efficiency, reduces environmental pollution, and enhances crop yield.

Role in Phosphate Availability

Phosphorus often becomes fixed in soil, making it unavailable to plants. Slow-release nanocomposite fertilizers help maintain phosphate in a soluble form, increasing its bioavailability and supporting plant growth and development.

Eco-Friendly Innovations

Hydrogels: Hydrogels improve soil water retention and nutrient delivery, especially in dry regions.

Gel-Based Systems: These systems provide stable

nutrient storage and reduce nutrient loss, contributing to sustainable agriculture.

Benefits

In addition to increasing nutrient use efficiency and lowering losses from leaching and volatilization, slow-release fertilizers progressively supply vital nutrients like phosphate and nitrogen. They promote ongoing plant growth, improve root development, and raise total crop yields. Particularly in regions that are vulnerable to drought, sophisticated formulations like hydrogels, gel-based systems, and nanocomposites enhance soil water retention. Farmers save money on labour and operating expenses when they apply less frequently. These fertilizers support the long-term fertility and health of the soil. They also promote sustainable agriculture by reducing greenhouse gas emissions and environmental pollution.

Obstacles and Prospects for the Future

A number of obstacles prevent slow-release fertilizers from being widely used. For small-scale farmers, the high initial cost of sophisticated formulations like hydrogels and nanocomposites may be an obstacle. Their use is also decreased by a lack of awareness and understanding of appropriate application techniques. Complexity is increased by large-scale production limitations and regulatory approvals. Additionally, the type of soil, moisture content, and environmental factors can affect their performance, necessitating careful management. Future studies will concentrate on creating affordable, environmentally friendly materials to increase their use in agriculture.

Conclusion

A sustainable way to increase the availability of phosphate and nitrogen in soil is through slow-release fertilizers. They increase overall nutrient use efficiency by lowering nutrient losses through leaching, volatilization, and fixation. Plant growth is supported even in difficult circumstances by nanocomposite, gel-based, and hydrogel systems that provide better water retention and controlled nutrient release. By reducing pollution and greenhouse gas emissions, these fertilizers help to protect the environment. The long-term economic and ecological advantages outweigh the initial costs, even though they might be higher. All things considered, slow-release fertilizers are a significant development for productive and sustainable agriculture.

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Role of Food Corporation of India (FCI) in Food and Nutrition Security

Nikita Kumari Meel and Shweta Srivastav

Introduction

Food and nutrition security exists when all people, at all times, have physical, social, and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 2008). It encompasses not only the availability and access to food but also its proper biological utilization, which is influenced by nutritional quality, health status, sanitation and care practices (HLPE, 2020). Despite achieving record levels of food grain production, India continues to face persistent challenges of malnutrition and unequal food distribution, leaving a substantial proportion of its population undernourished. Thus, ensuring food and nutrition security remains a major concern in a developing country like India. In this context, the Food Corporation of India (FCI), established in 1965, plays a crucial role in strengthening national food security through the procurement, storage, distribution and price stabilization of food grains. Acting as the backbone of India's food security framework, FCI ensures the availability and equitable distribution of food grains across the country, particularly through various welfare schemes aimed at supporting vulnerable sections of society.

Functions of FCI in Food Security

Procurement of Food Grains: FCI procures food grains, mainly wheat and rice, at Minimum Support Price (MSP) to ensure remunerative prices to farmers and maintain production incentives. This procurement mechanism stabilizes agricultural markets and prevents distress sales. Recent studies highlight that MSP-based procurement enhances farmer income security and supports sustainable agricultural production systems (Kumar *et al*., 2023).

Maintenance of Buffer Stocks: FCI maintains buffer stocks to ensure food availability during emergencies such as droughts, pandemics or supply shocks. India's central pool storage capacity exceeded 900 lakh metric tonnes in 2025, strengthening national food resilience (GoI, Press Information Bureau). Buffer stocking helps stabilize supply and ensures continuity in food distribution systems.

Public Distribution System (PDS) Support: FCI supplies food grains to states for distribution under the Public Distribution System (PDS) and the National Food Security Act (NFSA). The PDS covers around 800 million beneficiaries, ensuring access to subsidized food grains (Source: NFSA). This system plays a crucial role in reducing hunger and improving calorie intake among vulnerable populations.

Price Stabilization: FCI intervenes in the market

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through procurement and release of food grains to stabilize prices and prevent inflation. Open Market Sale Scheme (OMSS) is one such mechanism used to control price fluctuations.

Role of FCI in Nutrition Security

While FCI traditionally focused on food grain availability, its role has expanded toward nutrition security, including:

Distribution of Fortified Food Grains: FCI supports the distribution of fortified rice enriched with micronutrients such as iron, folic acid and vitamin B_{12} to combat malnutrition. This initiative is crucial in addressing hidden hunger and micronutrient deficiencies.

Supporting Welfare Schemes: FCI supplies grains for major nutrition-oriented schemes such as:

- ✓ Mid-Day Meal Scheme
- ✓ Integrated Child Development Services (ICDS)
- ✓ Pradhan Mantri Garib Kalyan Anna Yojana (PMGKAY)

These programs contribute significantly to improving nutritional outcomes among children and low-income groups.

Ensuring Food Accessibility: By providing subsidized food grains, FCI improves economic access to food, which is a key pillar of nutrition security.

Recent Developments and Reforms

Digitalization and Supply Chain Efficiency: FCI has adopted end-to-end computerization and depot management systems to improve transparency and reduce leakages in grain distribution (Source: FCI).

Infrastructure Modernization: Recent initiatives include modernization of storage systems, construction of silos and expansion of decentralized storage through Primary Agricultural Credit Societies (PACS) (GoI, Press Information Bureau).

Logistics and Transport Improvements: Development of modern cargo terminals and rail connectivity has enhanced the efficiency of food grain movement, reducing transit losses and improving supply chain resilience (Times of India, 2026).

Conclusion

The Food Corporation of India plays a central role in ensuring food and nutrition security in India through procurement, storage and distribution of food grains. While it has significantly contributed to reducing hunger and stabilizing food supplies, reforms are needed to address inefficiencies and align its operations with nutrition-sensitive goals. Strengthening FCI will be crucial for achieving sustainable food and nutrition security in the future.

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Smt. Usha: Doubling Income through Crop Diversification under Farmer FIRST Programme

Mukul Kirar

Name of Farmer: Smt. Usha

Village: Hadmasi

Block: Joura

District: Morena, Madhya Pradesh

Landholding: 1.5 acres

Programme Support: Farmer FIRST Programme (ICAR-RVSKVV, ZARS Morena)

Background

Smt. Usha, a smallholder farmer from Hadmasi village of Morena district, belongs to a modest farming family dependent primarily on agriculture for their livelihood. With only 1.5 acres of land, she traditionally practiced monocropping of pearl millet during *Kharif* and mustard during *Rabi* season. Despite her hard work, productivity remained low due to:

- ✓ Use of local seed varieties
- ✓ Heavy weed infestation
- ✓ Imbalanced fertilizer application
- ✓ Limited pest and disease management
- ✓ Lack of crop diversification

Her total annual net income from farming was only ₹44,750, which was insufficient to meet household needs, education expenses, and health requirements.

Intervention under Farmer FIRST Programme:

Under the Farmer FIRST Programme implemented by ICAR through RVSKVV-ZARS Morena, scientists regularly visited her village and conducted participatory discussions to understand farmers' constraints. After diagnosis of field problems, the following interventions were introduced on her farm:

- ✓ Introduction of high-yielding improved varieties
- ✓ Scientific nutrient management (balanced fertilizer use)
- ✓ Integrated weed and pest management
- ✓ Timely sowing and proper spacing
- ✓ Crop diversification with green gram (moong) in addition to pearl millet and mustard
- ✓ Continuous technical guidance and field monitoring

The interventions were simple, cost-effective, and suitable for her small landholding.

Impact on Production and Income

Before Intervention (2016-17)

Crop	Area (Acre)	Production	Gross Income (₹)	Net Income (₹)
Pearl Millet	1.5	14.30 q	36,300	21,800
Mustard	1.5	11.90 q	41,700	22,950
Total			78,000	44,750

After Intervention (2022-23)

Crop	Area (Acre)	Production	Gross Income (₹)	Net Income (₹)
Pearl Millet	1.5	20.00 q	45,600	31,150
Mustard	1.5	17.60 q	44,800	33,400
Greengram	1.5	5.00 q	52,050	25,500
Total			1,42,450	90,050

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Overall Benefits Achieved

- ✓ Net annual income increased from ₹44,750 to ₹90,050.
- ✓ Additional annual cost saving of ₹19,150.
- ✓ Productivity of pearl millet increased from 14.30 q to 20.00 q.
- ✓ Mustard yield increased from 11.90 q to 17.60 q.
- ✓ Improved soil fertility through better nutrient management.
- ✓ Enhanced food and nutritional security due to crop diversification.
- ✓ Reduced production risk and increased livelihood stability

Her income nearly doubled within a few years, significantly improving her family's standard of living.

Social and Livelihood Impact

- ✓ Improved ability to invest in children's education
- ✓ Better household nutrition through pulse production
- ✓ Increased confidence in adopting scientific practices
- ✓ Became a role model for other women farmers in the village

Smt. Usha now actively participates in extension meetings and motivates fellow farmers to adopt improved technologies.

Conclusion

The case of Smt. Usha clearly demonstrates that even small and marginal farmers can substantially enhance their income and livelihood security through scientific crop management and diversification under participatory extension programmes.

The Farmer FIRST Programme played a catalytic role by bridging the gap between research and farmers' fields. Her journey reflects how knowledge-based interventions, when combined with farmer participation, can transform rural livelihoods in semi-arid regions like Morena district.

Developing Future Heat-Resilient Vegetable Crops

S. Nisha, A. Ravanachandar and Prakash K.

Introduction

Edible plant components are collectively referred to as veggies. The components of plants include leaves, stems, tubers, roots, bulbs, and fruits (Radovich, 2018). Vegetables are a varied category of plants. Over 200 species of plants are classified as veggies globally. Approximately 30 to 40 vegetable crops are often utilized for cultivation (Chen *et al*., 2019). All vegetable crops cultivated outside their optimal temperature range, whether excessively cold or hot, experience stress. Global warming has resulted in a 41% reduction in vegetable production from 1965 to 2016 (Scheelbeek *et al*., 2018). Current climate changes induce environmental pressures that disrupt and alter the plant's physical structure. Heat stress (HS) adversely impacts potato productivity, with a documented 35% reduction in production under elevated temperatures (Rykaczewska, 2015). Similarly, yield reductions of 93%, 91%, and 98% were seen in sweet pepper, chili pepper, and tomatoes, respectively (Aleem *et al*., 2020). Elevated temperatures impact growth, result in inadequate fruit sets, and ultimately diminish output (Kawasaki and Yoneda, 2019). A temperature increase of 0.73 °C has been documented over a century (Ito *et al*., 2022). Vegetables are crucial for a consistent food supply and are influenced by temperature, both diurnally and nocturnally (Nie *et al*., 2022). High temperatures influence flowering in Chinese cabbage, resulting in premature flowering (Huang *et al*., 2020). In addition to affecting flowering duration, it also reduces seed output and the amount of flowers (Liu *et al*., 2012). Elevated temperatures also influence the quality and color of wild cabbage (Johansen *et al*., 2017). In tomatoes and potatoes, HS influences the fruit setting rate and yield, respect-ively (Kim and Lee, 2020; Cappetta *et al*., 2021). Numerous vegetable crops are, contingent upon their growth stage and crop type, vulnerable to various pressures. Abiotic stressors, including temperature extremes (both cold and heat), salinity, and drought, directly impact the yield and quality of plants (Bulgari *et al*. 2019; Raza *et al*., 2022). Conventional breeding, in conjunction with genome editing, can facilitate the introduction or modifica-tion of genes of interest in crops, resulting in transgene-free plants. The present review empha-sizes the impact of HS on the yield of principal vegetable crops. Their morpho-physiological and biochemical responses to stress are examined for vegetable resilience against extreme climate conditions in various ways.

In what kind of way does climate change induce

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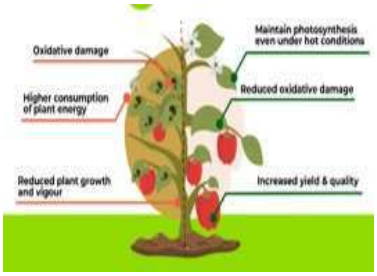
temperature stress?

The globally averaged surface temperature is rising annually owing to several factors. One of the primary contributors is modified anthropogenic activities that rapidly induce climatic changes (Junaid *et al*., 2021). The alteration in the mix of atmospheric gas emissions results in increased heat by disrupting energy flow (Karimi *et al*., 2021). Consequently, altered greenhouse gas emissions from modifications in agricultural land use precipitate global warming. Severe climatic conditions often exacerbate prolonged heat waves. It is anticipated to negatively impact the Earth's vegetation patterns, posing a risk to world food security. Climatic forecasts indicate a rise in temperature, particularly in Mediterranean nations, which will experience hotter and drier conditions, leading to significant yield losses (Morán-Ordóñez *et al*., 2020). Temperature is a critical element influencing global species distribution, and the overall biological activities of plants are also sensitive to climatic fluctuations. Climatic changes will result in significant temperature swings, hence altering the thermal environment of plants. The effects of temperature fluctuations, both cold and hot, induced by climate change are detailed below. These climate changes will undoubtedly affect agriculture and horticulture, encompassing vegetable crops in a comprehensive manner. The annual decline in water availability is critical for the healthy cultivation of vegetables. Insufficient water supply for plants induces drought stress. Under stress conditions, the closing of stomata is intricately associated with water consumption efficiency, a crucial metric of plant response to stress (Hatfield and Dold, 2019). Under HS, it is anticipated that plants can enhance water absorption for reproduction and growth (Grossiord *et al*., 2017). It is characterized by inadequate soil moisture or subnormal precipitation resulting from severe climatic conditions for an extended duration, leading to diminished growth, production, and quality of vegetables (Chaudhry *et al*., 2021). Furthermore, climate change is a contributing element that leads to diminished rainfall patterns and elevated temperatures. Consequently, drought exacerbates the adverse effects of heat stress (Giordano *et al*., 2021). Drought typically correlates with elevated air temperatures that increase evapotranspiration, leading to stomatal closure, reduced photosynthetic rates, and damage to photosynthetic pigments (Giordano *et al*., 2021). Numerous research projects have been published demonstrating the impact of combined stresses on the adaptation of vegetable crops to future climate changes, hence ensuring food security (Demirel *et al*., 2020; Mushtaq *et al*., 2022; Gökçe *et al*., 2022).

Heat Stress



Heat stress (HS) is characterized by a temperature elevation for a designated duration that inflicts irreversible damage to plants, typically occurring with a temperature increase of 10-15°C

above the threshold level (Raza *et al*., 2022; Zahra *et al*. 2021). HS modifies the effects of other abiotic stressors. Elevated air temperatures enhance the transpiration rate, necessitating increased water absorption by plants (Asim *et al*., 2021). It also elevates soil temperature, so enhancing evaporation and leading to a deficiency of accessible water for plants, which may occur over a brief duration or result in extended drought stress (Hassan *et al*., 2021). Furthermore, an elevated evaporation rate promotes the accumulation of salts, which induces salinity stress in plants (Liu *et al*., 2021). It may also lead to an unbalanced nutrition supply, causing nutrient stress (Safdar *et al*., 2019). Plants exhibit various alterations at the biochemical, physiological, and molecular levels when subjected to heat stress. Consequently, it is imperative to assess the severity of HS for a specific vegetable crop during the key growth phase. Recently, recurrent extreme heat episodes have induced several phenological disruptions across various plant species worldwide (Lamichaney *et al*., 2021). Climatic models estimate that yield losses in crop plants due to heat stress may rise by 40% in the next fifty years (Shahzad *et al*., 2021). Heat stress amplifies a plant's susceptibility based on the plant's sensitivity, the intensity and duration of exposure, and the prevalence of extreme heat episodes (Jagadish *et al*., 2021). HS is projected to cause a 32% reduction in potato yields by 2050 (Hijmans, 2003). The HS during the initial development phase inhibits seed germination and seedling emergence. As the plant progresses into the vegetative development phase, it has deficiencies in photosynthetic pigments and light sensitivity. Metabolism of carbon and translocation of organic solutes lead to diminished growth (Hassan *et al*., 2021; Karkute *et al*., 2021; Roeber *et al*., 2021). The physiological impact of temperature fluctuations on vegetables. HS can also impede the morphological development of vegetables. It impedes cellular proliferation, hence restricting the development of leaves, stems, and branches in plants (Zahra *et al*., 2021). Optimal potato tuber yield can be attained at a temperature range of 14-22°C. Optimal tuber growth commences at 25°C, but vegetative growth diminishes when air temperature exceeds 39°C. Moreover, soil temperatures exceeding 18 °C, in conjunction with elevated air temperatures, substantially diminish tuber output. HS also diminishes tuber output by inducing the sprouting of seed tubers (Aksoy *et al*., 2015, 2021; Demirel *et al*., 2020). Leafy vegetables such as cauliflower, cabbage, and broccoli are classified as cool-season crops; hence, high temperatures during their growing period result in significant growth losses. In contrast, tomato and pepper exhibit heightened sensitivity to heat stress, particularly during the reproductive phase.

Heat Stress-Related Physiological Changes in Major Vegetables

Vegetables employ many ways to endure high salinity conditions. The primary mechanism is the preservation of normal physiological function (Bisbis *et al*., 2018). HS initially impairs gaseous

exchange characteristics and affects photosynthetic pigments, machinery, membrane integrity, photo-phosphorylation of proteins, and photoassimilate translocation, subsequently inducing secondary oxidative stress (Asim *et al*., 2021). The internal water content of plants is the most crucial factor in reactions to temperature fluctuations. Plants often regulate their tissue water content to ensure optimal growth. However, HS elevates the transpiration rate, thereby reducing water content, which directly disrupts plant physiology (Demirel *et al*., 2020). In tomatoes, HS disrupted the leaf water content and the hydraulic conductivity of the roots. During daylight hours, the transpiration rate elevates water shortage in plants, resulting in a decrease in water potential (Raja *et al*., 2020). Photosynthesis is a crucial physiological activity for carbon cycling. As it predominantly influences the growth and productivity of veggies. Nonetheless, at high salinity, leaves absorb greater light energy, which harms the photosynthetic apparatus and diminishes the photosynthetic rate (Abdalla *et al*., 2020). It is regarded as the primary sensor of environmental stress that triggers unbalanced cellular energy, as seen by the modified redox chemistry associated with the thylakoid membrane. It is acutely responsive to HS, as it promptly inhibits gaseous exchange in contrast to the disruption of other cellular functions (Yalçin and Öztürk Gökçe, 2021). Stomatal closure primarily accounts for the reduction in photosynthetic rate by limiting gas exchange following exposure to heat stress. Moderate heat stress limits both stomatal conductance and photosynthetic rate in numerous vegetables, attributed to decreased activation of Rubisco (Asim *et al*., 2021; Haque *et al*., 2021). Temperature fluctuations influence vapor pressure and can alter plant hydraulic conductance, leading to a reduced water supply to the leaf (Grossiord *et al*., 2020). Consequently, it also impedes the transpiration rate. Heat tolerance closely links the plant's ability to facilitate gas exchange in leaves and its CO_2 absorption rate. HS influences leaf water status, stomatal conductance, and intracellular CO_2 concentration. The photosynthetic rate in cabbage significantly declined due to the deactivation of Rubisco, which is linked to the detrimental impact of heat on the electron transport system (Lee *et al*., 2021). Numerous research studies have indicated that HS resulted in a decrease in chlorophyll content via disrupting chlorophyll production. This is ascribed to the degradation of several enzymes essential for chlorophyll production. The initial enzyme, 5-aminolevulinate dehydratase, implicated in the pyrrole biosynthesis pathway, was documented to diminish in reaction to HS (Fahad *et al*., 2017). The synthesis of protochlorophyllide (Pchlide) and the activity of Pchlide oxidoreductase are both diminishing in plants. This may account for the diminished production of chlorophyll in the plants. Cauliflower subjected to heat stress exhibited reduced fluorescence, chlorophyll concentrations, and photosystem efficacy as a result of impairment to the photosynthetic apparatus (Rurek *et al*., 2018). Tomato plants acclimated to 32°C exhibited dimin-

ished net CO_2 uptake alongside a decline in stomatal conductance, indicating their vulnerability to temperatures beyond 30°C. Furthermore, it impacted the quality and coloring of tomatoes (Rodriguez-Ortega *et al*., 2017). The diminished rate of photosynthesis in tomatoes is attributed to reduced chlorophyll levels under heat stress (Zhou *et al*., 2017). An elevated respiration rate resulting from increased nocturnal temperatures diminished the sugar content of the peas and adversely affected the product's marketability. Progressive exposure of potato to heat stress diminishes internal water content, impairs photosynthetic pigments, and reduces gas exchange characteristics (Şanlı and Öztürk Gökçe, 2021). Photosynthesis in plants is influenced by heat stress due to the thermal sensitivity of Rubisco and the Rubisco activase enzyme. In tomatoes, heat stress at 40°C diminishes the incorporation of Rubiscoenzyme isoforms.

Conclusion

The stress caused by temperature has significantly impacted the growth and development of vegetables. Heat stress (and also cold stress) directly alters the plant's biochemical, physiological, and molecular responses. Consequently, it will affect vegetation. Table production. There is a lack of studies concerning vegetarianism. Comparative evaluation of vegetable adaptability to heat stress relative to grains. The traditional breeding technique is employed to enhance vegetables. It is arduous and time-intensive to compile data against HS. It requires precision and an extended duration to generate a tolerant cultivar. Conversely, novel genetic technologies are emerging. Available resources will decrease the time required to develop tolerances. Ant HS cultivars in various vegetables. Genomics-assisted breeding, including QTLs and GWAS, remains underexplored for the development of temperature-resilient vegetable crops. The transgenic technology has enabled various crops to develop tolerance to heat stress; nevertheless, research has been confined to vegetable crops, specifically chili peppers & tomatoes. Modern genomic studies can aid in enhancing the resilience of other vegetables against temperature fluctuations. Temperature. Moreover, innovative plant breeding technologies can effectively yield veggies with our preferred characteristics. To ensure the success of these technologies, it is essential to comprehend and improve their use. Modern genomic techniques. It is essential to identify the primary genetic factors involved in signaling and regulating genes that have either beneficial or detrimental effects during stress management. The implementation of a genome editing system necessitates the availability of vegetable genome sequences and effective transformation systems. Consumer acceptability will likely increase for CRISPR-edited crops due to the potential for transgene-free crop production. Optimization of genome editing technologies in various vegetables is necessary to generate temperature-resilient crops. In conclusion, it is essential to integrate transgenic and genome-editing technologies with conventional methods.

National and genomics-assisted breeding to create temperate. Develop climate-resilient crops to sustain the expanding world population.

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Regenerative Agriculture: Restoring Soil Health and Biodiversity

Priyanka Kantwa, A. D. S. S. Ajay Nikhil and Vinod Kantwa

Abstract

Regenerative agriculture has emerged as a transformative approach for restoring soil health, enhancing biodiversity, and strengthening the resilience of farming systems. Unlike conventional agriculture, which often depletes natural resources, regenerative practices focus on rebuilding ecological processes through minimal soil disturbance, continuous soil cover, diversified cropping, integration of livestock, and organic nutrient recycling. These methods not only enhance soil organic matter and microbial activity but also improve water retention, carbon sequestration, and climate resilience. This article discusses the principles, key practices, benefits, and future potential of regenerative agriculture highlighting its significance for sustainable food production in India and globally.

Introduction

Agriculture is currently facing unprecedented challenges due to soil degradation, biodiversity loss, and climate change. More than one-third of global agricultural land is degraded, leading to declining productivity and ecological instability (FAO, 2021). The excessive use of chemical fertilizers, monocropping, intensive tillage, and unsustainable irrigation practices have accelerated the deterioration of soil organic matter and weakened natural ecological processes that support plant growth. As a result, modern agriculture is increasingly vulnerable to climate extremes such as droughts, floods, heat stress, and unpredictable weather patterns.

Regenerative agriculture offers an ecologically sound alternative by shifting the approach from extractive farming to a system that restores and regenerates natural resources. It emphasizes harmony with natural processes through soil restoration, biodiversity enhancement, and reduced dependency on synthetic inputs (Rhodes, 2017). This approach not only focuses on rebuilding soil structure and nutrient cycles but also aims to strengthen the entire agroecosystem by improving water retention, promoting natural pest regulation, and enhancing carbon sequestration. In India, where nutrient depletion, groundwater decline, and erratic monsoons are widespread challenges, regenerative agriculture provides a long-term pathway for resilient and sustainable farming.

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By integrating traditional knowledge with modern ecological principles, it supports improved productivity, environmental conservation, and livelihood stability for millions of farmers (Reganold and Wachter, 2016).

Core Principles and Key Practices of Regenerative Agriculture

Enhancing Soil Health through Biological Processes: Healthy soil is central to regenerative agriculture. Practices such as minimal tillage, cover cropping, and organic amendments help rebuild soil structure, fertility, and biological activity (Montgomery and Biklé, 2016). Reduced tillage preserves soil aggregates, protects microbial habitats, and prevents carbon loss. Cover crops such as legumes and grasses improve soil organic matter, reduce erosion, and enhance nitrogen fixation (Giller *et al.*, 2021). Organic manures, compost, and biofertilizers stimulate microbial diversity and nutrient cycling, making farming systems more resilient to drought and diseases (Reganold and Wachter, 2016).

Promoting Biodiversity and Ecological Balance: Regenerative agriculture views biodiversity as the backbone of a healthy farming ecosystem. Approaches like intercropping, multispecies cover cropping, crop rotation, agroforestry, and livestock integration create complex ecological interactions that support natural pest control and pollination (Rhodes, 2017). Agroforestry enhances carbon sequestration, moderates microclimate and diversifies farm income sources (Lal, 2020). Integrated livestock systems further accelerate nutrient recycling by returning organic matter to the soil (Giller *et al.*, 2021). Together, these practices rebuild ecological balance and reduce the need for chemical interventions.

Benefits and Future Potential of Regenerative Agriculture

Regenerative agriculture provides benefits across environmental, economic, and social domains. One major advantage is carbon sequestration, where plants capture atmospheric carbon and store it in soil, helping mitigate climate change (Lal, 2020). Improved organic matter enhances water infiltration and retention, increasing resilience to drought and erratic rainfall (FAO, 2021). Economically, farmers gain from lower input costs due to reduced reliance on fertilizers and pesticides (Rhodes, 2017). Socially, regenerative systems promote healthier ecosystems, diversified food production, and improved rural livelihoods (Reganold and Wachter, 2016). With growing global attention to sustainability, regenerative agriculture is being promoted through government initiatives, carbon credit markets, and corporate sustainability commitments (Giller *et al.*, 2021). India's policies on natural farming, organic agriculture and agroforestry align strongly with regenerative principles, indicating significant potential for wider adoption.

Conclusion

Regenerative agriculture marks a major shift from conventional, resource-intensive farming toward a restorative, nature-positive system.

By prioritizing soil health, biodiversity, and ecological integrity, it provides a sustainable pathway to improve agricultural resilience and environmental stability. As environmental challenges continue to rise, regenerative practices offer an essential strategy for ensuring long-term food security, soil restoration, and the well-being of farming communities. With proper implementation, training, and policy support, regenerative agriculture can reshape modern farming into a system that restores the land for future generations.

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Microplastics in Agriculture: A Silent Driver of Soil Degradation

Navjot Kaur, Chaitanya Thakur and Sudarshna Kumari

Introduction

Plastics are synthetic materials derived from a wide range of organic polymers and are valued for their durability, low cost and moldability. These same properties, however, render them highly persistent in the natural environment. When plastic debris enters the environment through insecure dumpsites, open-pit burning or direct disposal, it undergoes gradual physical, chemical and microbial degradation of soil, fragmenting into progressively smaller particles (Lozano *et al.*, 2021). Particles ranging from 1 µm to 5 mm in diameter are classified as microplastics, while those below 1 µm are termed nano plastics (Anand and Sheel, 2025).

Microplastics are categorized by their origin as primary or secondary. Primary microplastics are manufactured at small sizes for use in industrial processes, cosmetics and medicine. Secondary microplastics arise from the fragmentation of larger plastic objects such as agricultural mulch films, synthetic textiles, vehicle tyres and packaging materials. In terms of polymer composition, the most commonly detected types in agricultural soils include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET) and polyamide (PA), among others (Li *et al.*, 2023). Microplastics reach agricultural soils through multiple pathways: land application of sewage sludge and compost, irrigation with contaminated surface water or treated wastewater, atmospheric deposition, and the direct use of plastic-based agricultural materials such as mulch films and polymer-coated seeds (Chia *et al.*, 2021). Once in the soil, they are redistributed horizontally by runoff, wind, and tillage, and vertically through water infiltration, root channels, soil cracking and the bioturbation activities of earthworms and other soil fauna (Okeke *et al.*, 2023). The concentration of microplastics in agricultural soils globally ranges widely, from as low as 110 items kg^{-1} in some Indian agricultural fields to over 3,000 items kg^{-1} in desert soils of Central Asia and coastal soils of India. Greenhouse soils consistently accumulate higher concentrations than open-field soils due to enclosed plastic structures and intensive management. The dominant polymer types and shapes vary by soil system: fibers and films tend to predominate in agricultural and urban soils, while fragments are more common in coastal and roadside environments. The ecological significance of micro-plastic contamination in soil lies in the complex, multidimensional ways these particles interact with

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the soil matrix. Unlike many conventional pollutants, microplastics affect the soil system across physical, chemical and biological dimensions simultaneously (Bello *et al.*, 2025).

Fig. 1: Distribution of Coloured Microplastic Fragments in Soil Sample

Effects on Physical Properties of Soil

Bulk Density: Bulk density is the mass of dry soil per unit volume it is a fundamental indicator of soil compaction and structural integrity. The introduction of microplastics into the soil matrix can alter bulk density by filling inter-aggregate pore spaces or by interfering with the packing arrangement of soil particles. The magnitude and direction of this effect depend critically on the shape and polymer type of the microplastic. Linear microplastics such as polyester and polyacrylic fibers, by virtue of their elongated geometry, tend to create entangled networks within the soil, interrupting particle-to-particle contact and thereby reducing bulk density as concentration increases. Non-linear forms such as polyamide beads and polyethylene fragments, which are more compact in shape, integrate differently within the soil matrix and produce comparatively smaller reductions in bulk density. Research conducted on loamy sand soils confirmed that polyester fibers at concentrations up to 2% (w/w) produced the most pronounced decline in bulk density among common microplastic polymer types, while polyacrylic fibres and polyamide beads showed more modest effects. Similarly, fibrous (polyester) and granular (polypropylene) microplastics in silt loam agricultural soils reported that granular forms at 1.89% (v/v) significantly reduced bulk density relative to soil-only controls, while fibrous forms at equivalent concentrations did not produce the same effect.

Water Holding Capacity and Pore Structure: Soil water holding capacity (WHC) and pore size distribution govern the availability of water to plant roots and the movement of solutes through the profile. Microplastics modify these properties through their physical presence within the pore network and through their influence on aggregate stability. Polyester microfibers have been shown to increase the volume of large macropores (>30 µm) while simultaneously decreasing the volume of smaller micropores (<30 µm), as established in field experiments using clay loam soils subjected to multiple wetting-drying cycles over 75 days. The entanglement of fibrous microplastics within soil aggregates appears to preferentially create larger inter-aggregate voids while compressing smaller intra-aggregate pores. The net effect is a redistribution of pore size classes, which has important implications for preferential flow pathways, drainage efficiency, and the retention of plant-available water. Granular microplastics such as polypropylene show a different pattern: at higher concentrations and finer particle sizes (20 µm), they tend to reduce saturated

hydraulic conductivity (Ks) in sandy and clay soils by clogging existing pore networks. In loam soils, low concentrations of fine polypropylene particles initially increased Ks, but this effect reversed at higher application rates (≥2% by weight). These results suggest that below a threshold concentration, fine particles can increase connectivity between pore spaces, while above it, pore blockage becomes the dominant mechanism.

Aggregate Stability: Water-stable aggregates are critical to soil structural stability, erosion resistance and the protection of organic matter. Microplastics influence aggregate stability in polymer-specific ways. Polyester fibers, due to their physical binding action, have been reported to decrease water-stable aggregates at concentrations above 0.1%, with the most pronounced decline at 0.3-0.5%. Conversely, polyethylene fragments and polyamide beads at equivalent concentrations produced slight increases in aggregate stability, possibly because non-fibrous particles occupy inter-aggregate spaces and physically reinforce the aggregate structure.

Effects on Chemical Properties of Soil

Soil pH: Soil pH regulates nutrient availability, microbial activity and mineral weathering. The influence of microplastics on soil pH is variable and depends on the polymer type, shape and duration of exposure. Among different polymer shapes, foam-type and fragment-type microplastics particularly polyethylene foams and polycarbonate fragment they have been observed to significantly raise soil pH relative to controls, while fibrous and film-type microplastics exert comparatively little effect on pH.

Among polymer types, PET-based micro-plastics at low concentrations (1%) have been found to increase pH above control levels, but this effect reverses at higher concentrations (5-10%), where both PS and PET depress pH below controls. Nylon (polyamide) microplastics, it tends to maintain or slightly elevate pH across a range of concentrations. The mechanisms underlying pH shifts are believed to involve the slow leaching of additives (plasticizers, stabilizers and flame retardants) from the plastic surface, alterations in soil buffering capacity, and indirect effects on microbial communities that drive proton production or consumption. If polypropylene microplastics added to clay soils at 0.1% and 0.2% concentrations reported progressive increases in pH compared to unamended controls, suggesting that even at low concentrations certain polymers can induce measurable changes in soil reaction.

Organic Carbon and Dissolved Organic Carbon

Soil organic carbon (SOC) is central to soil fertility, water retention and the global carbon cycle. Microplastics can affect SOC dynamics through several mechanisms: they may physically protect organic matter from microbial degradation by occupying pore spaces, they may supply low-molecular-weight carbon compounds through the weathering of biodegradable polymers, or they may alter microbial community structure in ways that affect carbon mineralization rates. Non-biodeg-radable polymers such as polystyrene generally reduce SOC over time, consistent with their ability to

suppress microbial activity and alter aggregate structure in ways that expose previously protected organic matter to decomposition. Conversely, biodegradable microplastics such as polylactide (PLA) significantly increase SOC, functioning as a supplementary carbon substrate for microbial communities.

Nitrogen Availability and Cation exchange capacity

Available nitrogen and cation exchange capacity (CEC) are critical determinants of soil fertility. Microplastics interfere with nitrogen cycling through their effects on microbial communities and enzyme activities that mediate nitrification, denitrification and mineralization. At higher concentrations (5-10%), most polymer types including PS and PET - significantly reduced available nitrogen, while nylon (polyamide) showed less severe effects on N availability at lower concentrations. Nitrate nitrogen concentrations in soils amended with biodegradable PHA and PLA were significantly lower than in n soils amended with non-biodegradable PS, suggesting that microbial N immobilization in the presence of readily degradable plastic carbon substrates may temporarily reduce plant-available nitrate. CEC, total carbon and total nitrogen were consistently lower in greenhouse soils (containing microplastic residues from plastic infrastructure) than in adjacent open-field soils, with greenhouse-to-open-field ratios indicating reductions of 14-82% across different sites and soil types.

Effects on Biological Properties of Soil

Microbial Activity and Enzyme Activity: Soil microorganisms are the primary drivers of nutrient cycling, organic matter decomposition and disease suppression. Microplastic contamination alters microbial activity through direct toxicity of leached additives, physical modification of the soil habitat and changes in substrate availability. In greenhouse experiments on loamy sand soils, all four major polymer types tested polyester, polyacrylic, polyamide and polyethylene which reduced microbial activity (measured by fluorescein diacetate hydrolysis) at low concentrations relative to controls, suggesting a broad initial suppression of microbial metabolism. Enzyme activity particularly urease, which catalyzes the hydrolysis of urea to ammonium is a sensitive indicator of microbial-mediated nitrogen transformation. Studies on paddy sandy loam soils documented that all tested polymer types (PE, PAN, PET at 200 µm and PET at 10 µm) reduced urease activity below control levels at a 0.5% (w/w) application rate, with reductions ranging from 5% to over 12%. Finer particle sizes of PET produced greater suppression of urease activity than coarser forms, indicating that particle size it's not just polymer type governs enzymatic responses. Among polymer types tested in a 230-day incubation study, biodegradable PBS and PLA most strongly suppressed urease activity, while non-biodegradable LDPE, PA, and PS maintained urease activity closer to control levels.

Soil Fauna: Earthworms are keystone organisms in soil ecosystems, responsible for bioturbation, orga-

nic matter incorporation, and aggregate formation. Microplastic exposure has been consistently associated with negative outcomes for earthworm populations. In a 30-day mesocosm study using clay soils amended with polypropylene microplastics, earthworm (*Lumbricus terrestris*) population counts declined with increasing MP concentration: from 102 individuals at 0.1% PPMP to just 42 individuals at 0.2% PPMP, compared to 102 in controls. The mechanism of earthworm decline likely involves physical ingestion of microplastic particles, which can cause gut blockage and tissue inflammation, as well as indirect effects arising from changes in soil structure and food availability. Beyond earthworms, microplastics have been shown to alter the broader soil faunal community, with implications for predator-prey dynamics and nutrient cycling. The ingestion and egestion of microplastics by soil fauna also serves as an important vector for the horizontal redistribution of particles through bioturbation and cast deposition.

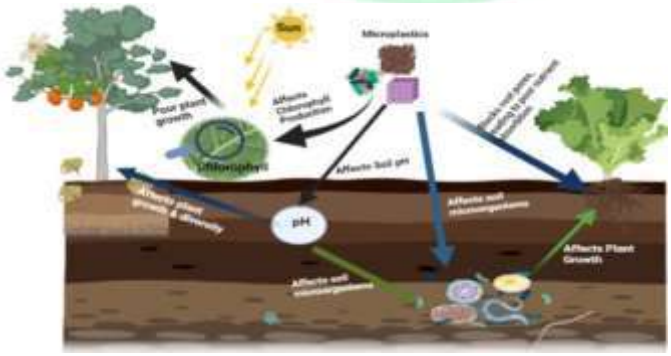

Fig. 2: MNPs affect plant diversity, soil biota and nutrient cycling in agroecosystems

Microbial Community Diversity: Shifts in microbial community composition under micro-plastic stress have significant consequences for soil function. Poly vinyl chloride at 14% (w/w) is the highest concentration tested produced the most dramatic disruption to soil bacterial community structure, nearly doubling the Simpson diversity index and substantially reducing the Shannon diversity index, indicating a pronounced loss of community evenness and the dominance of a few opportunistic taxa. Lower concentrations of PVC (7%), as well as polyethylene and polystyrene at both concentrations, produced comparatively minor shifts in diversity indices. At the taxonomic level, high-concentration PVC treatment reduced the relative abundance of Actinobacteria and Actinobacteria - groups associated with decomposition and stable soil carbon cycling while dramatically increasing the proportion of Firmicutes and Proteobacteria. Proteobacteria comprised 67.2% of the total bacterial community under PVC1 (14%) treatment, versus a much smaller fraction under control conditions. Such community-level shifts alter the functional capacity of the soil microbiome, potentially impairing nutrient cycling, organic matter decomposition and plant-pathogen suppression over the long term.

Conclusions

Microplastic contamination of agricultural soils is a complex, multidimensional problem whose consequences extend across physical, chemical, and biological soil properties. Fibrous microplastics particularly polyester and polyacrylic fibers are among the most disruptive to soil physical structure, reducing bulk density, altering pore size distribution, and diminishing aggregate stability.

Hydraulic conductivity is progressively impaired as polypropylene concentrations increase, with fine particles being most effective at clogging soil pores. Foam and fragment-type microplastics tend to raise soil pH, while film and fibre types have minimal pH effects. At the chemical level, non-biodegradable polymers such as polystyrene generally depress soil organic carbon and available nitrogen, while biodegradable plastics such as polylactide may transiently enrich SOC and DOC but simultaneously suppress urease activity through microbial N immobilization. The effects on CEC, total carbon and total nitrogen are consistently negative in greenhouse-cultivated soils with high plastic usage. Biologically, nearly all tested polymer types reduce microbial activity and enzyme function, with the severity of suppression scaling with concentration and decreasing particle size. Earthworm populations decline significantly with increasing MP concentrations and bacterial community diversity is most severely disrupted by PVC at high doses.

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Head Blight of Wheat and Its Management

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Abstract

Fusarium Head Blight (FHB) is a devastating disease of wheat crop which severely affects wheat, barley, oat, rye, corn and some forage crops. This disease is predominantly caused by the fungus *Fusarium graminearum* where as other *Fusarium* spp such as *Fusarium avenacearum*, *Fusarium culmorum*, *Fusarium p*oae, *Fusarium acuminatum* and *Fusarium reticulatum* are also reported to be associated with FHB. FHB is reported to cause significant yield loss ranges of 20-100%. In India this disease causes significant yield losses in foot hills of Punjab, Himachal Pradesh, Uttarakhand and hilly areas of Tamilnadu. First symptoms of Fusarium Head Blight (FHB) disease occurs soon after flowering. Under moist condition, pinkish to orangish mycelium is observed at the base of the florets. On the progress of disease, the pathogen causes shrinkage and of light brown discolouration of grains. *Fusarium graminearum* overwinters on infested crop residues such as corn stalks, wheat straw, sorghum straw and other host plants. Macroconidia (asexual spores) and ascospores (sexual spores) are dispersed by rain-splash or wind. The pathogen requires 25 to 28°C temperature and >90% humidity for rapid spore germination and infection. As the pathogen is soil borne in nature, crop rotation with non-host crop such as pulses is recommended for disease management. Among the chemicals, Triazole group of fungicides such as Propiconazole, Prothioconazole and Tebuconazole perform best. Several biocontrol agents such as *Bacillus species*, *Penicillium olsonii* etc also contributes to control FHB and the reduction of mycotoxin (Deoxynivalenol) contamination.

Introduction

Fusarium Head Blight (FHB) is also called scab is a devastating disease of Wheat crop. It can also affect barley, oat, rye, corn and some forage crops. This disease was first recognised in North America in 1900. Over the past several years, severe outbreaks of FHB have been reported from Canada, Europe, Asia, Australia and South America. Since 1990, wheat and barley farmers in the United States have lost over $3 billion dollars due to FHB epidemics. This disease is predominantly caused by the fungus *Fusarium graminearum* where as other *Fusarium* spp such as *Fusarium avenacearum*, *Fusarium culmorum*, *Fusarium poae*, *Fusarium acuminatum* and *Fusarium reticulatum* are also reported to be associated with FHB. A mycotoxin called Deoxynivalenol (DON) is considered as primary toxin associated with FHB pathogen.

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This mycotoxin is also called as vomitoxin as it causes harmful effects on digestive system of vertebrates. According to USDA recommendation, the DON levels in human being should not exceed 1ppm whereas DON levels in FHB infected wheat are more than 20 ppm. FHB is reported to cause significant yield loss ranges of 20-100%. In India this disease causes significant yield losses in foot hills of Punjab, Himachal Pradesh, Uttarakhand and hilly areas of Tamilnadu.

Symptomatology: First symptoms of Fusarium Head Blight (FHB) disease occurs soon after flowering. Under moist condition, pinkish to orangish mycelium is observed at the base of the florets. On the rachis, glumes and spikelets, light pinkish sporodochia may appear. Later, bluish to black spherical bodies (Perithecia) may appear on the surface of affected spikelet. On the progress of disease, the pathogen causes shrinkage of grains due to which, infected kernels impart rough, shrivelled, pink to light brown discolouration. Premature bleaching occurs in diseased spikelets which may progress throughout the entire head and formation of Fusarium damaged kernels are also known as "Tombstone Kernels" which can result in a poor yield.

Fig 1: A fusarium-infected wheat head displaying orange, spore-bearing structures at the crevices and at the base of the glumes

Etiology: The asexual stage of *Fusarium graminearum* produces macroconidia. The macroconidia are hyaline, canoe-shaped usually with five or more septa. Conidium-producing cells called phialides are clustered together in cushion-shaped structure known as sporodochia. The sexual stage of the fungus is *Gibberella zeae* which bears bright colored fruiting body known as perithecia. The perithecia of *G. zeae* are a dark blue in colour at maturity. Sexual spores or ascospores are formed within a saclike structure known as ascus. The ascospores are hyaline to light brown in colour, and slightly curved with rounded ends.

Disease cycle: *Fusarium* fungi can survive as saprophytes or act as pathogens on various crops. *Fusarium graminearum* overwinters on infested crop residues such as corn stalks, wheat straw, sorghum straw and other host plants where the fungus produces asexual spores (macroconidia) which are dispersed by rain-splash or wind. During favourable condition, the sexual stage of the fungus develops on the infested plant debris.

Fig. 2: Disease Cycle of FHB pathogen

Bluish-black perithecia form on the surface of these residues, and forcibly discharge sexual spor-

es (ascospores) into the air. The ascospores forcibly discharge from perithecia and blown away by turbulent wind or can be spread by rain-splashes.

Pre disposing factors: Precipitation or high humidity (>90%) for at least 12 hours and 25 to 28°C temperature favours spore germination and infection. FHB infection is most likely to occur during July when the florets are open during flowering, allowing spores to come into contact with the floret. The FHB fungus can also enter through wounds caused by hail, birds or insects. High levels of mycotoxins are produced if conditions remain warm and moist after seed set.

Management strategies

- ✓ As the pathogen is soil borne in nature, crop rotation with non-host crop such as pulses is recommended. Practice a rotation away from cereal crops for at least one year and preferably two years reduces disease intensity. Planting cereals adjacent to fields which had significant FHB infection in the previous year should be avoid.
- ✓ Removal of cereal crop residue, tillage of soil at regular interval will reduce the amount of overwintering inoculum that can infect a subsequent wheat crop avoid irrigation during flowering to reduce humidity and, therefore, to reduce the infection period.
- ✓ Spore-producing bacteria such as *Bacillus* species and yeasts such as *Cryptococcus flavescens* contributes for the control of FHB and the reduction of mycotoxin contamination.
- ✓ Endophytes such as *Sarocladium strictum*, *Anthracocystis floculossa* and *Penicillium olsonii* are identified as potential biocontrol agents of FHB in wheat.
- ✓ The best timing of application of fungicide is early flowering but application up to 7 days after initiation of flowering canal so reduce FHB and mycotoxin contamination. Triazole group of fungicides such as Propiconazole @ 41.8% Prothioconazole@ 41%, Tebuconazole@ 38.7% work best when applied at or within a week of early flowering whereas Strobilurin fungicides are not recommended against FHB as these can increase mycotoxins accumulation.
- ✓ Root application of Silicon @ 1.7 mM enhances host resistance hence reduces FHB incidence and severity.
- ✓ Wheat genotype Sumai-3 and Ning-7840 are very important resistant sources for FHB and have been used worldwide.
- ✓ FHB forecasting models that can assist (e.g., at www.wheatscab.psu.edu) to exacerbate the probability of infection.

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Government Schemes Promoting Tasar Host Plantation in India: An Odisha Perspective

Bibhuti Kumar Malik

Abstract

Tasar sericulture is a vital livelihood activity for tribal and rural communities in India, largely dependent on the availability and quality of host plants. In recent years, both central and state governments have introduced several schemes to promote tasar host plantation, enhance productivity, and ensure sustainable development. This study examines major initiatives such as Silk Samagra, Promotion of Sericulture Industries, and convergence with Mahatma Gandhi National Rural Employment Guarantee Act, with a special focus on Odisha. The findings indicate that these schemes have significantly expanded plantation areas, improved cocoon productivity, and strengthened tribal livelihoods. However, challenges such as low plantation survival rates and climate variability persist. The study suggests integrated approaches involving technological interventions, community participation, and policy convergence to ensure long-term sustainability.

Introduction

India holds a unique position as the only country producing all major types of silk, with tasar silk being eco-friendly and forest-based. The tasar silkworm, *Antheraea mylitta*, depends entirely on host plants for survival and cocoon production. However, declining forest cover, poor plantation practices, and climate variability have adversely affected host plant availability. In response, government interventions have focused on expanding plantation areas, improving plant quality, and integrating sericulture into rural development programs. Odisha is one of the leading states in tasar silk production, with sericulture deeply embedded in the livelihoods of tribal communities. The state provides an excellent model for understanding how government schemes have successfully promoted tasar host plantation and rural development. Tasar sericulture in Odisha is primarily practiced in districts like Mayurbhanj, Keonjhar, Sundargarh, and Koraput. It is a traditional activity of tribal communities and serves as a supplementary income source.

- ✓ Around 50,000 families are engaged in sericulture in the state
- ✓ Nearly 90% of beneficiaries belong to tribal communities
- ✓ Odisha ranks among the top tasar-producing states in India

The availability of host plants such as *Terminalia arjuna* and *Terminalia tomentosa* in forest and plantation areas has supported the growth

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of this sector.

Central Government Schemes

Silk Samagra Scheme: The Silk Samagra is an integrated scheme aimed at holistic development of the silk sector.

Key Components

- ✓ Financial support for host plantation
- ✓ Nursery development and supply of quality saplings
- ✓ Training and capacity building
- ✓ Technology transfer and extension services

Outcome: Enhanced plantation coverage and improved productivity of tasar cocoons.

Integrated Scheme for Development of Silk Industry: Implemented through the Central Silk Board, this umbrella scheme focuses on research, seed production, and capacity building. It emphasizes interventions in critical areas like feed (host plants), breed, and post-cocoon technologies to improve silk productivity and reduce import dependency.

MGNREGA Convergence: The Mahatma Gandhi National Rural Employment Guarantee Act supports plantation activities through wage employment.

Benefits

- ✓ Creation of large-scale community plantations
- ✓ Soil and water conservation
- ✓ Employment generation in rural areas

Odisha State Government Schemes Promoting Host Plantation

POSI-Promotion of Sericulture Industries

The Promotion of Sericulture Industries is a key state plan scheme aimed at strengthening sericulture in Odisha.

Key Features

- ✓ Financial assistance for tasar host plantation
- ✓ Distribution of quality saplings to farmers
- ✓ Support for maintenance and protection of plantations
- ✓ Promotion of cluster-based sericulture development

Significance: POSI focuses on expanding host plant areas and improving livelihood opportunities for rural and tribal communities. It recognizes sericulture as a means to reduce migration and enhance income generation.

OMBADC Supported Sericulture Programs

The Odisha Mineral Bearing Areas Development Corporation supports tasar host plantation in mining-affected districts.

Achievements

- ✓ Plantation in backward and tribal regions
- ✓ Infrastructure development for sericulture clusters
- ✓ Livelihood support for marginalized communities

Mukhyamantri Resham Vikas Yojana (MRVY)

A recent initiative by Odisha government aims to boost sericulture through infrastructure and plantation support.

- ✓ Focus on tasar, eri, muga, and mulberry
- ✓ Significant financial investment over five years
- ✓ Targeted support for farmers and rural entrepreneurs

Table 1: Recent Trends in Tasar Sericulture and Host Plantation in Odisha (2019-2024)

Year	Tasar Host Plantation (ha)	DFL Production (lakh nos.)	Cocoon Production (lakh nos.)	Raw Silk Production (MT)	Farmers Covered (nos.)
2019-20	1812	23.13	1303.34	130.33	16,531
2020-21	1231	20.31	1002.12	100.50	13,745
2021-22	660	20.12	1003.29	101.58	14,884
2022-23*	~800-1000 (est.)	~21	~1100	~105	~15,500
2023-24*	~1000-1200 (est.)	~22	~1200	~110	~16,000

Source: Official data for 2019-2022 is taken from Odisha Economic Survey reports

Impact of Schemes: Government schemes have substantially contributed to the expansion and improvement of tasar host plantations in India. Increased plantation area has ensured a steady supply of quality leaves, leading to better growth and productivity of the tasar silkworm. Employment generation through plantation activities has strengthened rural livelihoods, particularly among tribal populations. Environmental benefits such as afforestation, soil conservation, and biodiversity enhancement further highlight the significance of these initiatives. Overall, the schemes have transformed tasar sericulture into a sustainable and income-generating activity.

Challenges in Implementation: Despite notable progress, several challenges hinder the effectiveness of these programs. Low survival rates of plantations, especially in drought-prone regions, remain a major concern. Limited technical knowledge among farmers and inadequate extension services affect proper plantation management. Climate variability, including irregular rainfall and temperature fluctuations, further impacts host plant growth and leaf quality. Institutional constraints such as delayed fund allocation and weak coordination among agencies also affect implementation efficiency.

Way Forward: To ensure long-term sustainability, it is essential to adopt climate-resilient host plant varieties and improve plantation techniques. Strengthening extension services and providing regular training to farmers can enhance productivity. Greater convergence among schemes and effective coordination among implementing agencies are required for optimal resource utilization. The integration of modern technologies such as GIS and remote sensing can improve monitoring and planning. Encouraging community participation, particularly among tribal women, will further enhance the sustainability and success of tasar host plantation programs.

Conclusion

Government schemes both central and state-level, including POSI have significantly contributed to the promotion of tasar host plantation in India. These initiatives have not only enhanced silk production but also improved the socio-economic conditions of tribal communities. With continued policy support and scientific interventions, tasar sericulture can emerge as a sustainable livelihood model for rural India.

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Market Linkages and Farmer Producer Organizations (FPOs) in Rural Areas

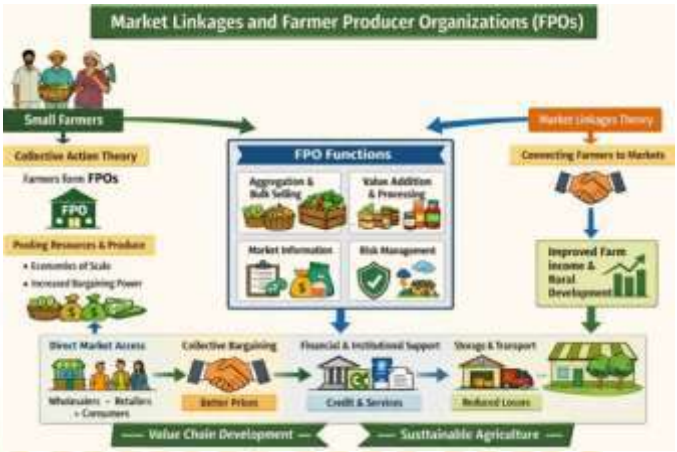
Dinesh Kumar Meena

Concept of Market Linkages

Market linkage theory explains the functional relationship between agricultural producers and various market agents involved in the agricultural value chain. It focuses on the flow of agricultural produce, market information, finance and support services from the farm level to the final consumer. Efficient market linkages reduce transaction costs, improve price discovery mechanisms and increase farmers' participation in organized and formal markets, thereby enhancing overall market efficiency.

Concept of Farmer Producer Organizations (FPOs): Farmer Producer Organizations are institutional arrangements based on the principles of collective action theory, wherein farmers unite to achieve common economic and marketing objectives. FPOs function on the principles of cooperation, mutual benefit and democratic decision-making. These organizations help small and marginal farmers overcome constraints related to small landholdings, limited resources and weak market access.

Theoretical Basis of Collective Action: According to collective action theory, individual farmers often face difficulties accessing markets due to small production volumes and low marketable surplus. By forming FPOs, farmers pool their resources and agricultural produce together. This collective approach leads to economies of scale, enhanced bargaining power and a reduction in per-unit marketing and transaction costs.



Role of FPOs in Strengthening Market Linkages: From a value chain perspective, FPOs act as intermediary institutional mechanisms that connect farmers directly with input suppliers, processors, wholesalers, retailers and consumers. This direct linkage reduces farmers' dependence on informal intermediaries and middlemen, thereby improving market transparency, efficiency and price realization.

Price Realization and Bargaining Power: Market linkage theory emphasizes the importance of organized and transparent markets for effective price discovery. FPOs enhance farmers negotiating capacity by aggregating their produce, ensuring uniform quality standards and enabling collective price negotiations. As a result, farmers receive better

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prices for their produce, leading to improved farm incomes.

Value Addition and Vertical Integration: The theory of vertical integration suggests that farmers' involvement in multiple stages of the value chain leads to higher economic returns for the farmers. FPOs facilitate value addition through activities such as grading, sorting, processing, packaging and branding agricultural produce. These activities increase the market value of the produce and contribute to income stability for farmers.

Risk Reduction and Market Stability: Institutional economics highlights the role of farmer organizations in reducing market-related risks. FPOs help farmers manage price volatility, post-harvest losses and market uncertainties by promoting collective storage facilities, contract farming arrangements and diversified market access. This collective risk management enhances the stability of the market.

Access to Institutional Support: From a development economics perspective, organized farmer groups have better access to institutional credit, crop insurance, government schemes and agricultural extension services than unorganized groups. FPOs reduce information asymmetry and improve farmers' integration into formal agricultural and financial systems, thereby supporting inclusive rural development.

Constraints and Institutional Challenges: Despite their theoretical advantages, FPOs face several challenges, including weak governance structures, limited managerial capacity, inadequate leadership and insufficient market orientation. Continuous institutional support, capacity building, professional management and appropriate policy interventions are essential for ensuring the long-term sustainability of FPOs.

Conclusion

Theoretically, market linkages and Farmer Producer Organizations provide an effective framework for integrating small and marginal farmers into modern agricultural markets. By promoting collective action, reducing transaction costs, strengthening agricultural value chains and improving market access, FPOs play a crucial role in enhancing farmers' income and achieving sustainable rural development goals.

Revolutionizing Textile Wastewater Management through Nanotechnology

Namrata Kushwah, Rupal Babel and Aarti Jangir

Abstract

The textile industry has been a major contributor to environmental pollution especially through the release of complex and toxic wastewater due to fast development of the industry. The effluent of textiles possesses a large variety of pollutants such as synthetic dyes, heavy metals, salts and organic compounds that cannot be easily broken down by traditional treatment techniques. Over the past few years, nanotechnology has become a superior and effective method to treat wastewater because of its peculiar characteristics of high-surface area, increased reactivity and functionality. This paper gives an in-depth discussion of the application of nanotechnology in affluent textile wastewater treatment, types of nanomaterials, treatment mechanisms, benefits, shortcomings and future perspectives. Nanotechnology application in the wastewater treatment systems presents a long-term solution to cleaner production and environment.

Introduction

One of the most water-intensive industries with a significant contribution to industrial wastewater pollution is the textile industry. Several wet processing processes like desizing, scouring, bleaching, dyeing, printing and finishing use a lot of water and chemicals which results into highly polluted effluents. The content of synthetic dyes, heavy metals, salts, surfactants and other organic, inorganic contaminants defines textile wastewater. It is also characterized by a high chemical oxygen demand (COD), biological oxygen demand (BOD), deep coloration and variable PH. The release of untreated or improperly treated wastewater into natural water bodies is extremely dangerous to the environment as well as to human health due to toxicity to aquatic organisms, ecosystem destruction, and possible occurrence of carcinogenesis in human beings. The traditional approaches to wastewater treatment, which include coagulation flocculation, adsorption, and biological technologies, are well-common and frequently cannot eliminate complex and non-biodegradable contaminants. These limit-ations highlight the need for advanced and efficient treatment technologies. Over the past years, nanotechnology has been developed as a promising solution to the management of textile wastewater. The nanoscale size, molecular surface area-volume ratio, and increased reactivity of nanomaterials make them the best in cleaning up contaminants.

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Different methods of nanotechnology such as adsorption with nano adsorbents, photocatalytic degradation with metal oxide nanoparticles, and nanofiltration with advanced membranes have proved very beneficial in the treatment of waste-water. Thus, a sustainable and innovative solution to managing cleaner textile wastewater is the deployment of nanotechnology.

Composition and Characteristics of Textile Wastewater: Textile wastewater is very complex and its composition differs with the nature of raw material, dyes and process methods employed in the textile industry. It usually has a broad scope of pollutants, such as synthetic dyes, heavy metals, salts, surfactants, and a variety of organic and inorganic substances. The highly coloured nature of textile effluent is one of the most noticeable properties of the textile effluent, mainly because it contains azo, reactive and disperse dyes, which are resistant to degradation and fading. Besides, textile wastewater has a high chemical oxygen demand (COD) and biological oxygen demand (BOD), which means that the wastewater has a high concentration of organic compounds that can deplete dissolved oxygen in water bodies. This is compounded by the fact that it contains toxic heavy metals like chromium, copper and zinc. Furthermore, the wastewater tends to exhibit very high or very low pH levels, either highly acid or highly alkaline, and high salinity since salts are used in dyeing. All these properties render the textile wastewater very hard to treat through the conventional treatment methods and require application of advanced treatment technologies that can facilitate effective treatment.

Fundamentals of Nanotechnology in Wastewater Treatment: Nanotechnology is the manipulation of materials on a nanoscale (1-100 nm) where they possess physical and chemical characteristics different to those of the bulk material. These properties are greater surface reactivity, higher adsorption capacity and better catalytic activity. Nanomaterials in wastewater treatment work by reacting with pollutants on the molecular scale. They are so small that they can enter and decompose complex contaminants better. Moreover, nano-materials can be designed to have particular surface properties to react to a specific pollutant, thereby enabling the treatment process to be more efficient and selective.

Classification and Role of Nanomaterials in Textile Wastewater Treatment: Nanomaterials that are used in the treatment of textile wastewater can be categorized into carbon-based nanomaterials, metal and metal oxide nanoparticles, polymeric nanocomposites and nanomembrane. Carbon nanotubes and graphene oxide are carbon-based nanomaterials and have a high adsorption capacity because of their high surface area that facilitates the removal of dyes and heavy metals. Metal and metal oxide nanoparticles (titanium dioxide, zinc oxide, etc.) are important in the photocatalytic degradation of organic pollutants, but have antimicrobial effects as well. Polymeric nanocomposites are a combin-ation of the benefits of polymers and nanoparticles,

which offer a higher level of stability and better adsorption capabilities. Nanomembranes, in turn, are employed in sophisticated filtration, whereby selective separation of contaminants occurs depending on their size and charge. Comprehe-nsively, these nanomaterials enhance the efficiency, selectivity and sustainability of textile wastewater treatment.

Mechanisms of Nanotechnology-Based Wastewater Treatment

Adsorption Mechanism: One of the most effective and popular mechanisms that is used in wastewater treatment based on nanotechnology is adsorption. Carbon nanotubes, graphene oxide, and metal oxide nanoparticles are a type of nanomaterials that have a very high surface area and high active sites, which also promote the pollutant adsorption on their surface. The elimination of the contaminants is made possible by different forms of interactions such as the electrostatic attraction, Van der Waals forces, and chemical bonding. The process is very effective at removing dyes, heavy metals and organic substances at very low concentrations and is therefore a very effective method of treating complex textile effluents.

Photocatalytic Degradation: Photocatalytic degradation is a highly developed oxidation process that involves the use of semiconductor nanoparticles like titanium dioxide (TiO_2) and zinc oxide (ZnO). These nanoparticles become activated to produce reactive oxygen species (ROS) when under the influence of ultraviolet or visible light, including hydroxyl radicals and superoxide ions. These highly reactive species decompose complex organic pollutants to simpler and less harmful substances such as carbon dioxide and water. This is particularly useful in the degradation of non-biodegradable dyes and toxic organic substances found in textile wastewater.

Membrane Filtration Mechanism: Nanotechnology has greatly enhanced the process of membrane filtration by designing nanostructured membranes whose pore sizes are in the nanoscale. The operation of these membranes is based on the concept of size exclusion and charge-based separation in which water molecules are allowed to move through the membranes whereas contaminants like dyes, salts and suspended solids are retained. Nanofiltration membranes are also highly efficient, consume less energy and are more selective than traditional filtration systems thus making them the most appropriate filtration systems in the treatment of textile wastewater.

Magnetic Separation Technique: The magnetic separation is carried out using magnetic nanoparticles, including iron oxide (Fe_3O_4) that can adsorb wastewater pollutants. Once adsorbed, the separation of these nanoparticles with the treated water is easily possible with the help of an outside magnetic field. The method makes the recovery process easier, requires less complicated filtration systems, and enables the reuse of nanomaterials, making it more efficient and cost-effective.

Advantages of Nanotechnology in Textile Wastewater Management

Nanotechnology has a great potential in treating textile wastewater because of the peculiarities of physicochemical processing at the nanoscale. The nanomaterials are good removers of dyes and heavy metals among other complex pollutants because of their high surface area-to-volume ratio, which allows them to collect the dye, heavy metals, and other complex pollutants at very low concentrations. Moreover, nanomaterials have high reaction kinetics that enhances speed in the treatment process, thereby increasing effectiveness. Their selective targeting properties to certain contaminants further boost their performance in terms of treatment. The processes based on nanotechnology also produce relatively lower slude, thus minimizing the secondary pollution and disposal problems. In addition, a high percentage of nanomaterials are recyclable and regenerable, making the process more cost effective in the long run. Nanotechnology is a sustainable and environmentally friendly solution to textile wastewater management due to the lessened use of harsh chemicals and the possibility of integration with environmentally friendly strategies, like green synthesis.

Challenges of Nanotechnology in Textile Waste water Management

Although it has a potential, there are a number of challenges in the application of nanotechnology in the treatment of textile wastewater that restrict its application at large scale. The high cost of the synthesis and processing of nanomaterials is one of the main issues because it may not be economically viable to all industries. Moreover, some nanoparticles may be poisonous, so these environmental and health concerns are a possibility because the release of nanoparticles into the ecosystem may have unforeseen effects. The unavailability of detailed regulatory guidelines and safety measures makes their use even more complicated. The other key challenge is that it is quite difficult to scale nanotechnology processes between the lab to industrial level with efficiency and cost-effectiveness. Moreover, concerns of recovery, stability, and performance of nanomaterials should be tackled to make them practically applicable. As such, although nanotechnology offers a very high-tech solution, it is necessary to overcome these difficulties to enable its sustainable and safe use.

Conclusion

Nanotechnology has disrupted the textile wastewater treatment process by providing very efficient, selective and sustainable treatment systems. It is a better option to the traditional approaches because of its capacity to target complex pollutants at the molecular scale. Even though issues of cost, safety, and scalability still exist, research and technological progress are likely to address these issues. Implementation of nanotechnology will be of great importance in attaining cleaner production, sustainability and responsible industrial development within the textile industry.

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Rising Demand for Cut Fillers in the Floral Industry

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Abstract

Floriculture is a fast-growing and profitable sector of horticulture with increasing demand in both domestic and international markets. Along with cut flowers, filler flowers play an important role in enhancing the beauty, volume, texture, and value of floral arrangements such as bouquets, garlands, weddings, and event decorations. In India, filler flowers are mainly produced in states like Karnataka, Tamil Nadu, Andhra Pradesh, and Uttarakhand, and they contribute significantly to exports to markets such as Europe, the USA, and Japan. This study highlights the importance and market potential of major filler flowers such as Limonium, Gypsophila, Mum Chrysanthemum, Solidago, and Stock. These fillers are widely preferred due to their long vase life, wide colour range, durability during transport, cost-effectiveness, and suitability for both fresh and dry flower arrangements. Many of these fillers also support sustainable and eco-friendly floriculture practices by requiring lower maintenance and fewer inputs. Overall, the rising global demand for filler flowers reflects changing consumer preferences toward mixed and textured floral designs. The increasing use of fillers not only improves the visual appeal of floral products but also enhances economic returns for growers and exporters, making filler flowers an essential component of the modern floriculture industry.

Introduction

Floriculture is rising, profitable, rapidly escalating industries of the world. Different types of cut flowers, cut filler, dry flowers and post-harvest products are demand in local and an international market. Cut flower arrangements are supported primarily by foliage filler crops. The cut fillers support the cut flower in various decorative things such as bouquets, garland etc. Cut filler are mostly grown in the region of Karnataka Tamil Nadu, Andhra Pradesh and Uttarakhand. The production of cut filler India is about 87700 tons of produce in 2023-2024. The demand is very both domestic market and an international market of Europe, USA and Japan. The global market cap of floriculture in India about the INR 292 million. The market growth rate increasing 10%.

What are cut Fillers?

- ✓ The backbone of an arrangement, foliage is used to set the shape and size of the arrangement, and to add texture whereas, Fillers are smaller flowers or plants that complement the focal flowers.

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- ✓ Fillers can add structure, bulk, and interest to bouquets.
- ✓ They can also add a textural contrast or colorful counterpoint.
- ✓ Some filler flowers can double as foliage, and can play different roles in a bouquet depending on the design.
- ✓ They provide essential structure, volume, and texture to floral arrangements, serving as a high-growth, profitable segment for farmers, especially during "lean" periods when flower production is low.

Importance of cut fillers in Floriculture Industry

Aesthetic Importance

Volume and Structural Support: Filler materials helps to add bulk to floral arrangements, enabling florists to create fuller, more luxurious designs while minimizing the use of costly focal flowers.

Texture and Visual Contrast: They enhance aesthetic appeal by introducing diverse shapes and colors ranging from spiky forms like thistle to delicate textures such as Limonium thereby creating contrast with primary blooms.

Background and Framing Effect: Cut foliage acts as a natural green backdrop that highlights the vibrancy of flowers while also concealing structural elements like floral foam and wiring.

Softening and overall harmony: Light-colored fillers, such as Baby's Breath and Waxflower, help tone down strong hues and contribute to a balanced, cohesive, and natural "garden-style" appearance.

Economic Importance

Enhanced Profitability for Growers: The commercial cultivation of fillers flowers is emerging as a highly profitable sector due to its low initial investment, lower production risks, and consistently high market demand, making it suitable for both small and large-scale farmers.

Continuous Market Supply: Unlike seasonal flowers, many filler plants such as gyphsophilla, mum chrysanthemum, Limonium etc., are available throughout the year, ensuring a stable and regular source of income.

Strong Export Opportunities: Premium-quality, well-graded cut fillers has significant demand in international markets, especially in regions like Europe, the United States, and Japan.

Scope for Value Addition: There fillers flowers also plays an important role in value-added products such as dried, bleached, and dyed arrangements, which enhance shelf life and increase overall market value.

Post Harvest Importance

Prolonged Vase Life: Several cut filler species, exhibit significantly longer vase life compared to fresh flowers, making them highly preferred by consumers seeking long-lasting decorative options.

Greater Transport Durability: Filler materials are generally sturdier than delicate blooms, enabling them to endure long-distance transportation and

handling with minimal damage.

Eco-Friendly Production: The cultivation of cut fillers typically requires fewer chemical inputs, less controlled heating, and lower energy consumption than greenhouse-grown flowers, making it a more sustainable and environmentally friendly option in the floriculture industry.

Brief about few Important Filler crops

Limonium: Limonium commonly known as Statice or Sea Lavender belongs to the family Plumbaginaceae and includes important species such as *Limonium sinuatum* (Annual Statice), *Limonium latifolium* (Perennial Statice) and *Limonium perezii*. Common varieties are Blue River, Yellow Sunbird, Iceberg, Gold Coast, Midnight Blue, American Beauty. It is high value for adding the volume, color good texture for bouquets. It has long life as a vase life since it remains bright fresh even dry for longer time is known as "Everlasting flower". It can maintain for 12- 24 months as wreath and arrangements. It is a popular, hardy filler flower that is used in both fresh and dried bouquets. Due to varietal, it is different in color such as the deep color white, pink, and yellow, along with fragrance free variety. It is eco- conscious and low maintainance flower for import purpose. The market value for the global export is Mexico with 3800 shipments with high significant holding after the Netherland. It prefers a light, well-drained sandy loam soils and is tolerant to salinity and drought conditions. It grows well in full sun and mild climate. The propagation of Limonium is commercially done through seeds. The seeds are first sown in plugtrays or potrays or nursery beds using cocopeat and the seedlings are ready for transplanting in the field after one month. Planting is done at a spacing of 30 × 30 cm or 45 × 45 cm depending on variety. Planting season varies with region but generally grown as a winter crop. Proper nutrition management plays a crucial role in achieving higher yield and quality in flower crops. Intercultural operations such as regular weeding are essential to minimize competition for nutrients and moisture, and mulching helps conserve soil moisture, regulate temperature, and suppress weed growth. Additionally, pinching of plants may be practiced to promote better branching and increased flower production. Harvesting should be done when the flowers are fully open but before pollen shedding to ensure maximum quality, making them suitable for both fresh and dried flower purposes; however, the yield largely depends on the variety and management practices adopted. In terms of post-harvest handling, these flowers exhibit excellent drying qualities, retaining their color even after drying, and can be processed using air drying or silica gel methods. Furthermore, they possess a relatively long shelf life compared to many other cut flowers, making them highly suitable for commercial use.

Gypsophilla: Gypsophila, commonly known as Baby's Breath, belongs to the family Caryophyllaceae and includes important species such as *G. elegans*, *G. paniculata*, *G. repens*, *G. muralis*, *G. pacifica*, and *G. acutifolia*, while popular varieties are Fun Time Ultra, Over Time, Cassiopeia, Dynamic Love, Orion, New Love, Million Stars, and Pink Fairy. Native to Europe and West Asia, it is widely used in borders, rock gardens, and as a filler in floral bouquets. Propagation is mainly done through seeds by direct or staggered sowing, as well as vegetatively through stem cuttings treated with growth regulators like IBA or NAA to enhance rooting. The crop prefers well-drained soil rich in organic matter and thrives under cool-season conditions, requiring protection from frost along with sunny weather and light rainfall. Planting is generally done with a spacing of 90 cm between rows and 35- 40 cm within rows, maintaining a plant density of about 3-4 plants per square meter. Growth regulators such as gibberellic acid (GA) promote flowering under long-day conditions, while CCC and MH help suppress excessive vegetative growth, and BA enhances flowering. Intercultural operations like mulching improve flowering and yield, staking supports tall stems, and pinching encourages uniform shoot growth. Harvesting is carried out when about 50% of the flowers are open, and stems are usually bunched in groups of five; however, the flowers are sensitive to ethylene. Post-harvest management includes treatment with silver thiosulfate (STS) to improve longevity and storage at 0-1°C under high humidity, although the vase life is relatively short but can be extended with preservatives. Tinting is used in gypsophila for adding the different color such purple, pink, gold. The crop is susceptible to diseases such as root rot, powdery mildew, stem rot, and crown rot, while common insect pests include mites, leaf miners, and aphids.

Blue Aster: Blue Aster (*Aster spp.*), belonging to the family Asteraceae, is a popular filler flower widely used in bouquets and floral arrangements, and is commonly known as Blue Aster or Michaelmas Daisy. It produces attractive daisy-like flowers in shades of blue, purple, pink, and white, adding texture and color to floral designs. Important species include *Aster amellus*, *Aster novi-belgii*, and *Aster novae-angliae*, while notable varieties are Blue Moon, Lady in Blue, Purple Dome, White Ladies, and Sapphire. The crop can be propagated through seeds, stem cuttings, and division, with division of clumps being the most commonly practiced method. It prefers well-drained, fertile loamy soil and thrives in cool to mild climatic conditions, requiring full sun to partial shade for optimal growth. Planting is usually carried out during spring or early winter, with recommended spacing of 30 × 30 cm or 45 × 45 cm. Proper nutrition is essential, and the application of farmyard manure improves plant growth, while balanced fertilization with nitrogen, phosphorus, and potassium enhances flowering. Intercultural operations such as regular weeding and irrigation are necessary for healthy plant development, and practices like pinching promote bushy growth and

increased flower production, while staking may be required for taller varieties. Harvesting is done when the flowers are partially open to ensure better quality and longer usability as cut flower fillers, with yield depending on the variety and cultural practices followed. Post-harvest, Blue Aster exhibits a moderate vase life, which can be improved with the use of floral preservatives, and storage under cool conditions helps extend shelf life. The crop is commonly affected by pests such as aphids, spider mites, and thrips, and diseases like powdery mildew and leaf spot, which need to be managed for successful cultivation.

Golden Rod: Golden Rod (*Solidago canadensis*), belonging to the family Asteraceae (Compositae), is a perennial herb widely used as a border, bedding, potted plant, and act as a cut flower or filler, characterized by its erect growth habit reaching 90-120 cm in height and producing numerous small yellow flower heads arranged in terminal panicles over an extended period. Popular varieties include Minuta, Golden Wing, Golden Mosa, Leraft, Lesden, Peter Pan, and Little Lemon. The crop is propagated through seeds, rhizomes, suckers, and cuttings, although commercial cultivation mainly relies on suckers and clump division. It can grow in a wide range of soils but performs best in well-drained, porous soil under mild climatic conditions, with flowering influenced by photoperiod. Land preparation involves ploughing to a depth of 25-0 cm, and planting is generally done during May-June with spacing of 60 × 60 cm or 30 × 30 cm in the first year. Nutrient management includes the application of FYM and organic manure along with recommended doses of 100-150 kg nitrogen, 100-150 kg phosphorus, and 50-100 kg potassium per hectare. Immediate irrigation after planting and regular weeding are essential for proper growth. Harvesting is carried out when about 25% of the flowers are open, yielding around 20-25 stems per square meter per season.

Mum Chrysanthemum: Mum chrysanthemum is preferred as a filler flower in the floral industry due to its spray type inflorescence, long vase life, year-round availability, wide colour range, durability during transport, and cost-effectiveness. These qualities make it one of the most reliable and commercially important filler flowers worldwide. While traditionally used as a focal flower, Mum chrysanthemums have seen a massive surge in demand as “fillers” because they offer volume, a wide color palette, and exceptional durability. Multiple small blooms on a single stem make them perfect for “bulking up” bouquet. Mum chrysanthemums typically last 10-20 days, outlasting most other filler flowers. This makes them the top choice for supermarket bouquets and subscription flower boxes. With rising shipping and production costs,

Mum chrysanthemums offer a high "visual-impact-to-cost" ratio. They allow florists to create lush, full-bodied arrangements while staying within consumer budgets. The global market for fresh Mum chrysanthemum bouquets was valued at approximately USD 42.53 Billion in 2025 with a projected growth rate (CAGR) of around 4-7% through2025-2035.Poland recently saw a 38.9% increase in Mum chrysanthemum imports, signalling a shift in Eastern European consumer preferences. In Japan, Mum chrysanthemums are already a dominant flower type culturally and commercially, contributing significantly to sales and exports. India exported fresh Mum chrysanthemums to multiple countries (e.g., Singapore, Georgia, Australia) with ~324 recorded shipments from Indian exporters. The year of 2024 witnessed the highest amount of fresh cut flower Mum chrysanthemum imports. Total 23 shipments weighing 179 Tons were imported during the year 2024. All the fresh cut flower Mum chrysanthemum importers accounted for 47 import shipments weighing 341 Tons.

Use of fillers in hand bouquet

Conclusion

The rising demand for cut fillers such as *Limonium*, *Gypsophila*, Blue Aster, *Solidago*, and Mum chrysanthemum clearly reflects their growing importance in the modern floral industry. These fillers not only enhance the aesthetic appeal, volume, and texture of floral arrangements but also provide cost-effective solutions for both florists and consumers. Their versatility, wide range of colors, and longer vase life compared to many primary flowers make them indispensable in bouquets, event decorations, and export markets. Additionally, the increasing popularity of dried flowers and sustainable floristry has further boosted their demand, as many fillers retain color and structure even after drying. With expanding market opportunities, ease of cultivation, and adaptability to diverse climatic conditions, cut fillers are emerging as a promising segment in floriculture, offering significant potential for growers, entrepreneurs, and the global floral trade.

Functional Characterization of Genes Associated with Flowering

Nivetha A. L., Lakshmipriya S., Arathi J. and Viji M. M.

Introduction

The transition from vegetative growth to flowering represents one of the most tightly regulated developmental switches in plants. This transition determines reproductive success, ecological fitness and agricultural productivity. Unlike passive organisms, plants actively integrate environmental cues such as photoperiod, temperature and stress with endogenous developmental signals to determine the precise timing of flowering. The functional characterization of flowering-related genes has been fundamental in uncovering the molecular mechanisms governing this transition.

Functional characterization involves identifying gene expression patterns, determining molecular interactions, analyzing mutant phenotypes and validating gene function through transgenic or genome-editing approaches. Through these methodologies, researchers have established that flowering regulation is controlled by interconnected pathways involving transcription factors, mobile signaling proteins, epigenetic regulators, micro RNAs and circadian clock components. These genetic networks collectively ensure that floral induction occurs only when environmental conditions and developmental competence are optimal.

Florigen and Floral Integrator Genes

The discovery and functional characterization of *FLOWERING LOCUS T (FT)* marked a milestone in flowering biology. *FT* encodes a small mobile protein that acts as the systemic flowering signal, or florigen. Expression studies demonstrated that *FT* is synthesized in leaf phloem tissues in response to inductive photoperiods and subsequently transported through the vascular system to the shoot apical meristem. Loss-of-function mutants of *FT* exhibit delayed flowering, while overexpression results in precocious floral initiation, confirming its role as a central integrator of flowering pathways. At the meristem, *FT* forms a transcriptional activation complex with *FD*, which induces downstream floral identity genes such as *APETALA1*, *LEAFY* and *SUPPRESSOR OF OVEREXPRESSION OF CONSTANS1*. These genes reprogram stem cell fate, initiating floral organogenesis.

In polyploid crops such as cotton, functional characterization of *FT* homologs has revealed conservation of florigen function despite genome duplication. Gene expression and transgenic studies indicate that *GhFT* integrates signals from photoperiod, hormone pathways and temperature responses. Gene duplication in cotton has allowed

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sub functionalization, where paralogs contribute to flowering regulation under distinct environmental conditions.

Photoperiodic Regulation and Circadian Clock Genes

The photoperiod pathway represents one of the primary mechanisms controlling flowering time. Functional characterization of *CONSTANS (CO)* established its role as a transcriptional activator of *FT* under long-day conditions. Circadian clock regulation ensures that *CO* expression peaks at specific times of the day, while light-responsive photoreceptors regulate its protein stability.

Mutant analyses demonstrated that disruption of *CO* leads to delayed flowering, whereas constitutive expression accelerates floral induction. In cereals, photoperiod sensitivity is controlled by homologous regulators such as *PHOTOPERIOD1 (PPD1)*. Functional studies of *EARLY FLOWERING 3 (ELF3)* revealed that it acts as a transcriptional repressor of *PPD1*, linking circadian rhythms to flowering time. Loss-of-function mutations in *ELF3* result in photoperiod-insensitive early flowering, highlighting the importance of circadian regulation in seasonal adaptation.

In rice, functional characterization of *Heading date 1 (Hd1)*, a *CO* homolog, revealed a unique dual regulatory role. *Hd1* promotes flowering under short-day conditions but represses floral induction under long days by inhibing the florigen gene *Hd3a*. This dual function illustrates evolutionary diversification of photoperiod regulators in different ecological contexts.

Vernalization and Epigenetic Regulation

In temperate species, flowering competence is achieved only after prolonged exposure to low temperatures, a process known as vernalization. Functional characterization of *FLOWERING LOCUS C (FLC)* demonstrated its role as a major floral repressor. Epigenetic silencing of *FLC* during cold exposure involves chromatin remodeling mediated by long noncoding RNAs such as *COOLAIR* and *COLDAIR*.

These RNAs recruit Polycomb Repressive Complexes, leading to histone modifications that stably silence *FLC* expression. This epigenetic memory ensures that flowering occurs only after winter has passed. In cereals, the vernalization response is mediated by the *VRN1–VRN2–FT1* regulatory network. *VRN2* represses flowering during autumn, while cold-induced *VRN1* suppresses *VRN2*, allowing activation of *FT1* in spring. Functional validation studies have shown that manipulation of *VRN* gene expression significantly alters flowering time and regional adaptability.

MicroRNA-Mediated Developmental Control

MicroRNAs play critical roles in regulating developmental phase transitions associated with flowering. Functional characterization of the *miR156-SPL* pathway demonstrated that high *miR156* levels maintain juvenile growth by repressing *SPL* transcription factors. As plants mature, *miR156* levels decline, allowing *SPL* expression to increase and promote floral transition.

Another key regulator, *miR172*, promotes flowering by repressing *APETALA2*-like genes that act as inhibitors of floral induction. Functional studies in wheat revealed that downregulation of *AP2*-like genes accelerates flowering, confirming the conserved role of *miR172* in developmental timing. These microRNA-mediated regulatory networks ensure synchronization between plant age and environmental cues.

Legume-Specific Flowering Regulators

In soybean, functional characterization studies identified *E1* as a central transcriptional repressor controlling flowering time. *E1* directly suppresses MADS-box genes known as *GmMDEs* through epigenetic silencing mechanisms involving histone modification. Under inductive short-day conditions, reduced *E1* expression permits activation of *GmMDE* genes, which subsequently promote expression of florigens *GmFT2a* and *GmFT5a*.

Functional analyses also revealed that *GmMDE* genes regulate plant architecture by repressing the shoot determinacy gene *Dt1*. This dual regulatory role demonstrates how flowering genes influence both reproductive timing and crop morphology.

Stress-Responsive and Alternative Splicing Mechanisms

In perennial crops such as citrus, functional characterization of the *CiFD* gene uncovered adaptive regulatory mechanisms involving alternative splicing. The *CiFDα* isoform interacts with florigen to promote flowering under favorable conditions. However, under drought stress, a truncated isoform, *CiFDβ*, is produced, which can activate floral identity genes independently of florigen. This mechanism provides a rapid reproductive response under environmental stress, illustrating how gene function diversification enhances ecological adaptability.

Pleiotropic Flowering Regulators and Developmental Integration

Functional characterization studies have demonstrated that flowering genes often exhibit pleiotropic effects on other developmental processes. For example, overexpression of *SmCOP1LIKE* in tomato accelerates flowering by upregulating florigen expression while simultaneously delaying fruit ripening through suppression of ethylene biosynthesis. Such findings highlight the interconnected nature of flowering regulation with broader developmental and metabolic pathways.

Conclusion

The functional characterization of flowering genes has revealed a conserved yet highly dynamic regulatory network controlling floral transition across plant species. Molecular studies involving gene expression analysis, mutant characterization, transgenic validation and epigenetic profiling have identified key regulators such as *FT*, *CO*, *FLC*, *VRN* genes, microRNAs and crop-specific transcription factors. These gene networks integrate environmental signals and developmental cues to ensure optimal reproductive timing. Understanding the molecular mechanisms underlying flowering regulati

-on is essential for developing crop varieties with improved adaptability, yield stability and resilience to climate variability. Advances in functional genomics and genome-editing technolo-gies are expected to further refine our ability to manipulate flowering pathways for sustainable agricultural production.

Drone Technology in Weed Management

Chandru B., M. Saravana Kumar and K. Pooja

Abstract

Drone technology has emerged as an innovative tool in modern weed management, offering precision, efficiency, and sustainability in agricultural practices. Unmanned Aerial Vehicles (UAVs) equipped with advanced sensors, cameras, and GPS systems enable real-time monitoring of crop fields and accurate identification of weed-infested areas. Through the integration of multispectral and hyperspectral imaging, drones can distinguish weeds from crops based on differences in spectral signatures. This allows for site-specific weed control, reducing the excessive use of herbicides and minimizing environmental impact. Additionally, drones facilitate targeted spraying, ensuring uniform application while saving time, labor, and resources. The adoption of drone-based weed management systems enhances crop productivity, supports precision agriculture, and contributes to sustainable farming. Despite challenges such as high initial costs and regulatory constraints, continuous technological advancements are expected to improve accessibility and effectiveness, making drones an essential component of future weed management strategies.

Introduction

Weed infestation remains one of the most persistent challenges in modern agriculture, significantly reducing crop yield, quality, and resource-use efficiency. Conventional weed control methods such as manual weeding, mechanical cultivation, and blanket application of herbicides are often labor-intensive, time-consuming, and environmentally unsustainable. In recent years, the integration of advanced technologies into agriculture, particularly under the framework of precision agriculture, has opened new avenues for efficient and sustainable weed management. Among these innovations, agricultural drones have emerged as a transformative tool.

Drone Technology

Drone technology encompasses unmanned aerial vehicles (UAVs) or Unmanned Aircraft Systems (UAS) operating without onboard pilots, relying on GPS, advanced sensors, AI, and robotics for flight and navigation. Drone are currently employed in India for a variety of purposes, including land and property surveys, precision agriculture, infrastructure inspection, disaster management, railway and highway monitoring, and defense applications. The maturation of an all-encompassing ecosystem that includes manufacturers, software and component developers, service providers, training facilities, certified pilots, start-ups, research organizations, and enabling digital platforms operating under a single regulatory framework is reflected in this increasing adoption.

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Tyes of Drone used for Weed Management

Multirotor Spraying Drones: eg. DIJ Agras T50/ T60, XAG P100 PRO. They feature multiple rotors for stability and precise hovering to perform site-specific spot spraying, minimizing herbicide waste.

Fixed Wing Mapping Drones: They have longer battery life and cover larger areas to identify weed infestations through high-resolution mapping.

Hybrid (VTOL) Drones: Combine vertical take-off and landing (like a helicopter) with fixed-wing flight efficiency, making them suitable for surveying large areas and landing in small spots.

Single Rotor Helicopter Drone: Offer higher payload capacities for carrying heavier tanks of herbicides over larger areas.

Common technologies and applications

Multispectral/Hyperspectral Sensors: These imaging sensors detect differences in light reflection between crops and weeds (e.g., near-infrared) to create, using tools like the Agremo Platform, precise weed maps.

Spot Spraying (Weed-It or Optical Spot Spraying): Drones with AI can distinguish weeds from crops in real time and apply chemicals only where needed.

Targeted Applications: Used for treating small infested patches, managing weeds in wet/ inaccessible areas, and slowing herbicide resistance by reducing, as seen with DJI Agriculture or XAG, overall chemical application.

Drone in Agriculture Weed Management

Drone technology, also known as Unmanned Aerial Vehicles (UAVs), offers a highly efficient and targeted approach to weed control. Equipped with high-resolution cameras, multispectral and hyper-spectral sensors, and advanced imaging systems, drones can accurately detect weed distribution, density, and species variability within crop fields. This real-time data enables site-specific weed management, allowing farmers to apply herbicides only where needed rather than across the entire field, thereby reducing chemical usage and minimizing environmental impact. The adoption of drone-based weed management is particularly relevant in regions facing labor shortages, rising production costs, and increasing concerns about environmental sustainability. Despite challenges such as regulatory constraints, high initial investment, and the need for technical expertise, drones represent a promising advancement toward sustainable and smart farming systems.

Fig. 1: Herbicide application by drone in rice and groundnut crops

Combining multiple techniques in the integrated weed management (IWM) strategy is a step toward reducing problems related to conventional approaches, such as herbicide resistance. UAV photography helps to better category results in early-season agronomic conditions where crop and weed seedlings have similar spectral signatures. Precision

farming approaches can efficiently manage weed problems while minimizing operating expenses and environmental damage by detecting weeds early in the season as a first and crucial stage.

Key Applications of Drone Weed Management

Weed Mapping and Detection: Drones equipped with multispectral, hyperspectral, or thermal cameras capture high-resolution imagery to distinguish weeds from crops. Machine learning and AI identify weed species and generate prescription maps.

Targeted Herbicide Application: UAVs (Unmanned Aerial Vehicles) enable "spot spraying" only on infested areas rather than entire fields, reducing chemical usage.

Accessibility and Efficiency: They are ideal for wet, sloped, or inaccessible land, covering large areas quickly and reducing soil compaction from heavy machinery.

Application of UAV and Remote Sensing for Weed Management in Agriculture Crops: Crop or weed mapping is one of the efficient approaches to be taken in managing agricultural crops. Weed population displays spatial variation within the crop type; thus, mapping weed infestations in annual crop results in implications for site-specific herbicide applications and designing different management strategies, and analyzing weed ecology itself. Precision agriculture assimilates several technological appliances, which incorporate variable rate technology (VRT), remote sensing, global positioning systems (GPS), and geographical information systems (GIS). Remotely sensed data could be utilize hugely in agricultural sector applications at a wide range of scales, from the micro level towards the global survey of internationally significant crops. Remote sensing methods, such as thermal infrared (IR) sensors and light detection and ranging (LiDAR) technology, attained astonishing results in measuring vegetation canopy temperatures and heights in order to evaluate the biomass, chlorophyll, and nitrogen (N) contents at a discrete time. Additionally, remote sensing has been broadly employed to detect and map weeds in the agricultural sector.

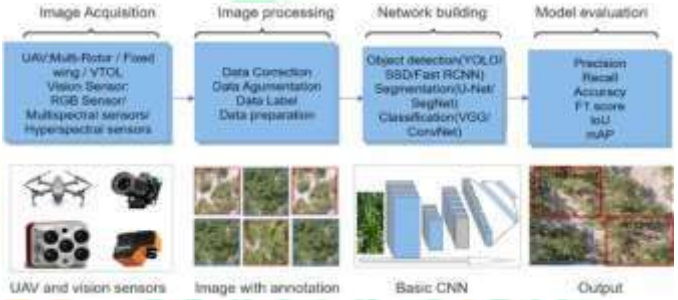

Fig. 2: Weed recognition and detection using UAV and AI image processing

Remote Sensing System in UAV: Remote Sensing Systems is a multi-disciplinary science that includes a combination of several fields, such as spectroscopy, optics, computers, photography, satellite launching, electronics, and communication. The successful operation of remote sensing requires several stages, such as:

- ✓ Emission of electromagnetic radiation (EMR) provided by sun or self-emission.
- ✓ Transmission of energy from source to earth surface.
- ✓ Interaction of EMR with the earth's surface, in the form of reflection and emission.

- ✓ Transmission of energy from the surface to sensor, and lastly.
- ✓ The output provided by the sensor. Remote sensing data encloses various forms, from ground-based sensors launched on tractors or other tools, to aerial imaging systems on data collected from satellite platforms.

Advantages in Drone Weed Management

Precision Spraying: UAVs can apply herbicides only to infested areas, reducing chemical usage, environmental impact, and saving money.

AI and Machine Learning: Deep learning models, such as YOLO, are used to analyze images in real-time, distinguishing between weeds and crops for highly targeted action.

High-Resolution Imaging: Multispectral sensors identify weeds based on specific spectral signatures.

Increased Efficiency: Autonomous drones can cover large areas rapidly, addressing agricultural labor shortages.

Current Trends and Technological Capabilities

Optimized Chemical Use: Studies indicate that 70% rate drone spraying can be highly effective, reducing costs.

Advanced Hardware: The market is growing with advanced models such as the DJI Agras T40 and XAG, which provide consistent, automated spraying, including the use of rotary atomizers.

Robotic Integration: Future methods include combining drone mapping with autonomous robots for mechanical weed removal.

Challenges and Limitations

Regulations and Safety: Adherence to rules such as FAA Part 107 and Part 137 is required, and spray drift must be managed.

Operational Limitations: Limited battery life, payload capacity, and reliance on clear weather can affect performance.

Technical Gaps: Detecting small, dense weeds in complex environments remains a challenge, necessitating further AI development.

Conclusion

The UAV-based weed management system represents a significant advancement in precision agriculture and trending agriculture by enabling accurate weed detection and targeted herbicide application. It reduces labor dependency, minimizes chemical usage, and enhances environmental sustainability while improving crop productivity. Despite challenges such as cost, technical expertise, and regulatory issues, continued technological improvements and wider adoption are expected to make UAVs an integral component of efficient and sustainable weed management systems in the future.

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Harnessing Molecular Docking for Sustainable Crop Protection

Lakshmipriya S., Arathi J., Nivetha A. L. and Viji M. M.

Introduction

As sessile, immobile organisms, plants must constantly protect themselves from a wide range of environmental threats. Global crop health and productivity are seriously threatened by abiotic and biotic stresses like drought, high salinity, and metal toxicity, as well as fungal pathogens and insect pests. In order to deal with these difficulties, plants produce a wide range of secondary metabolites, including flavonoids and alkaloids, which serve as natural defense and are essential in reducing oxidative damage. Even though plants naturally produce a variety of protective compounds, it is still very difficult to determine which particular molecule is most effective against a given stress.

Breaking the Bottleneck: Traditional approaches rely on extensive field and greenhouse experiments, which are time-consuming and costly. With thousands of metabolites and numerous plant proteins involved, trial-and-error methods become inefficient, creating a significant research bottleneck. To overcome this, scientists use *in silico* (computer-based) tools to rapidly screen large numbers of compounds cost-effectively. This approach helps identify the most promising candidates for specific stresses before moving to laboratory validation.

Molecular docking: Molecular docking is a computational technique used to predict how a small molecule (ligand) binds to a protein (receptor), including where it binds and how strong the binding is. It helps identify the most stable binding orientation (pose) and the strength of interaction (binding affinity).

- ✓ Ligand - small molecule
- ✓ Receptor/target - protein you dock against
- ✓ Binding site - Region of protein where ligand binds
- ✓ Complex - Protein + ligand together
- ✓ Pose - one possible orientation of the ligand in the binding site

Molecular docking plays a key role in predicting biological activity, understanding mechanisms of action, and supporting the discovery of bioactive compounds. It also helps provide molecular evidence for the activity of natural compounds.

Docking involves finding the most favourable binding mode(s) of a ligand to the target of interest; the steps are:

- ✓ Target Selection and Preparation
- ✓ Ligand Selection and Preparation
- ✓ Docking
- ✓ Evaluating Docking Results

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The best candidates identified through docking are validated experimentally and developed into practical crop protection or stress management solutions.

Models for molecular docking

Lock-and-Key Model: Proposed by Emil Fischer (1890), this model suggests that the ligand fits perfectly into the protein's active site, similar to a key fitting into a lock. It assumes both structures are rigid and highly specific.

Induce-fit model: Introduced by Daniel Koshland (1958), this model states that both the ligand and protein undergo slight structural changes to achieve an optimal fit, making the interaction more dynamic and realistic.

Conformational ensemble model: This model proposes that proteins exist in multiple pre-existing conformations. The ligand binds to the most suitable form, and the protein can shift between these states due to its inherent flexibility.

Table 1: Databases for protein structure and ligand

Category	Database	Purpose
Protein Structure	Protein Data Bank (PDB)	Provides 3D structures of proteins
	UniProt	Protein sequences and functional information
	AlphaFold Protein Structure Database	AI-predicted protein structures
Ligand	PubChem	Large repository of chemical compounds
	ZINC Database	Ready-to-dock compounds for screening
	ChEMBL	Bioactive molecules with drug-like properties

Case Study: Molecular Docking for Abiotic Stress Tolerance

A recent study (Choudry *et al.*, 2022) applied molecular docking to understand how plant metabolites help in combating metal-induced abiotic stress. The study focused on aluminium (Al^{3+}) and manganese (Mn^{2+}) toxicity, which are major constraints in acidic soils.

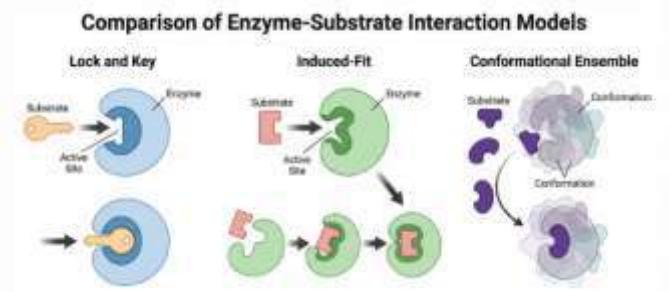

Fig. 1: Models for molecular docking

Key antioxidant enzymes such as DHAR and MDHAR were selected as target proteins, and various plant metabolites, including ascorbic acid, glutathione, jasmonic acid, and indole acetic acid, were used as ligands. Docking results revealed that these metabolites showed stronger binding affinity compared to toxic metal ions and could interfere with their interaction sites on the enzymes. This indicates a potential protective mechanism where plant metabolites prevent enzyme inhibition under stress conditions. The study suggests that enhancing the levels of such metabolites through breeding or genetic approaches could improve stress tolerance in crops.

Advantages

- ✓ Time-saving and cost-effective compared to field and lab experiments
- ✓ Enables screening of thousands of compounds quickly
- ✓ Helps in early prediction of biological activity
- ✓ Reduces unnecessary experimental trials

- ✓ Supports target-specific research in crop improvement

Limitations

- ✓ Results are predictive, not always exact
- ✓ Depends on the accuracy of protein structures
- ✓ Cannot fully mimic complex plant cellular conditions
- ✓ Requires experimental validation (in vitro / in vivo)
- ✓ Limited by software algorithms and scoring functions

Conclusion

Molecular docking has emerged as a powerful tool bridging computational biology and agriculture. It enables researchers to rapidly identify promising compounds and understand their interaction with plant proteins under stress conditions. By integrating docking with plant breeding and biotechnology, it is possible to develop crops that are more resilient to abiotic and biotic stresses. Although it has certain limitations, its role in accelerating agricultural research makes it an essential approach in modern crop improvement.

Functional Characterisation of Genes Associated with Nutrient Uptake

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Introduction

Functional characterisation of genes associated with nutrient uptake refers to the identification and analysis of genes that regulate the absorption, transport, and utilization of essential nutrients in plants. These genes mainly encode transporter proteins, regulatory proteins, and signaling molecules involved in nutrient acquisition from soil. Plants possess numerous nutrient uptake-related genes, including nitrate, ammonium, phosphate, potassium, and micronutrient transporter genes. Major examples include nitrate transporter (NRT), phosphate transporter (PHT), potassium transporter (HAK/HKT/KUP) and ZIP/IRT metal transporter families. These transporter families are widely recognized as key players in nutrient uptake and translocation.

Objectives of Functional Characterisation

- ✓ To determine the biological role of nutrient uptake genes.
- ✓ To understand their expression pattern in different tissues and nutrient conditions.
- ✓ To study how these genes regulate nutrient absorption efficiency.
- ✓ To identify candidate genes for crop biofortification and nutrient-use efficiency improvement.

Experimental Approaches

Functional characterization typically follows a multi-tiered pipeline:

In Silico Analysis (Bioinformatics)

Before wet-lab work, researchers use computational tools to predict function.

Homology Modeling: Comparing the gene sequence against known transporters in model organisms like Arabidopsis thaliana.

Motif Identification: Finding conserved domains (e.g., transmembrane domains) that characterize specific transporter families like NRT (Nitrate), PHT (Phosphate), or SULTR (Sulfate).

Heterologous Expression Systems

To isolate the gene's function from the plant's complex background, it is expressed in a foreign system.

Yeast Mutants: Using yeast strains deficient in a specific nutrient transporter. If the plant gene rescues the yeast's ability to grow, its function is confirmed.

***Xenopus laevis* Oocytes:** Injecting frog eggs with gene-encoded cRNA to measure electrical currents (electrophysiology), which helps determine the rate of ion transport across the membrane.

In Planta Validation

Reverse Genetics

Knock-out/Knock-down: Using CRISPR/Cas9 or RNAi to disable the gene. If the plant shows nutrient

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deficiency symptoms, the gene is essential for uptake.

Overexpression: Creating transgenic lines that "over-produce" the transporter to see if it increases biomass or nutrient density.

Reporter Gene Assays: Fusing the gene's promoter to markers like GUS or GFP to visualize exactly which cells (e.g., root epidermal cells or xylem parenchyma) are responsible for uptake.

Genes associated with nutrient uptake

Nitrogen (N) Uptake and Regulation

Plants primarily take up nitrogen as nitrate (NO^{3-}) and ammonium (NH^{4+}) through specialized transport systems.

Transporters: Nitrate uptake is mediated by two main families: NRT1/PTR and NRT2. NRT1.1 (also known as CHL1) is a unique "transceptor" that acts as both a transporter and a sensor; its affinity for nitrate is regulated by phosphorylation via the protein kinases CIPK23 and CIPK8. NRT2.1 is the primary high-affinity transporter in *Arabidopsis* and requires the accessory protein NRT3.1 to function.

Transcription Factors (TFs): ANR1 is a MADS-box TF that regulates nitrate-inducible lateral root growth. NLP7 has been identified as a master regulator of nitrate signaling, and its absence leads to nitrogen-starvation phenotypes. Conversely, members of the LBD family (LBD37, 38 and 39) act as negative regulators of nitrate-responsive genes.

Metabolic Integration: Enzymes like Alanine aminotransferase (AlaAT) and Asparagine synthetase (ASN1) have been overexpressed to improve nitrogen use efficiency (NUE), often resulting in increased biomass or seed protein content.

Phosphorus (P) Scavenging and Transport

Because inorganic phosphate (Pi) is often immobile in soil, plants use complex strategies to enhance its availability and uptake.

Transporters: The PHT1 family consists of high-affinity Pi carriers expressed in roots. Over-expression of genes like *AtPHT1;1 or OsPT1* (in rice) has been shown to increase biomass and Pi accumulation under limiting conditions.

Regulatory Elements: PHR1 is a master transcription factor that controls a large set of Pi-stress-responsive genes. Its activity is positively regulated by SIZ1 through sumoylation. In rice, the TF OsMYB2P-1 also enhances tolerance to low Pi by modulating root architecture and Pi content.

Biotechnological Approaches: To release Pi from organic forms, plants utilize phytases (like AtPAP15) and exude organic acids through enzymes like citrate synthase. A novel approach involves the bacterial *ptxD* gene, which allows plants to metabolize phosphite (Phi), a form of phosphorus that most soil microorganisms and weeds cannot use.

Potassium (K) Uptake and Regulation

The potassium transporter gene family, comprising HAK (High-Affinity K^+ Transporter), HKT (High-Affinity K^+ Transporter/K^+ Transporter) and KUP (K^+ Uptake Permease) proteins, plays a vital role in potassium acquisition, transport, and homeostasis in plants. Potassium (K^+) is an essential macronutrient required for enzyme activation, osmo-

regulation, maintenance of cell turgor, stomatal movement, photosynthesis, and overall plant growth. Members of the HAK/KUP/KT family primarily function as high-affinity potassium transporters and are responsible for potassium uptake from the soil, especially under potassium-deficient conditions. Among them, *HAK5* is one of the well-characterized genes and is strongly induced during potassium starvation, enabling roots to efficiently absorb K^+ when external concentrations are low. In contrast, the HKT family mainly functions in sodium and potassium transport and is involved in maintaining ionic balance under salt stress conditions. For example, *HKT1* regulates sodium exclusion from shoots and contributes to salt tolerance by controlling Na^+ and K^+ distribution within the plant. These transporters are generally localized in root epidermal and vascular tissues, where they facilitate uptake from the rhizosphere and long-distance transport through xylem and phloem. The expression of potassium transporter genes is tightly regulated by potassium availability, abiotic stresses, and hormonal signals to ensure optimal potassium homeostasis. Therefore, the potassium transporter gene family is considered a major target in crop improvement programs aimed at enhancing nutrient efficiency and stress resilience in plants.

Iron (Fe) Uptake Strategies

Plants employ two distinct strategies to acquire iron, which is often poorly soluble in alkaline soils.

Strategy I (Reduction - Dicotyledonous plants): This strategy involves soil acidification by H+-ATPases (e.g., AHA2, AHA7) and the reduction of Fe^{3+} to Fe^{2+} by FRO2 (ferric chelate reductase). The Fe^{2+} is then taken up by the IRT1 transporter. These genes are regulated by TFs like FIT (in *Arabidopsis*) and FER (in tomato).

Strategy II (Chelation-Grasses): Cereal crops secrete phytosiderophores (MAs) to chelate iron. Key genes include *NAS* (nicotianamine synthase) and *NAAT* (nicotianamine aminotransferase) for MA biosynthesis, *TOM1* for MA efflux, and YS1/YSL transporters for taking up the Fe^{3+}-MA complexes.

Homeostasis and Biofortification: The TF IDEF1 acts as a sensor by binding iron directly and regulating downstream genes. For grain fortification, overexpressing ferritin an iron reservoir protein has proven effective for increasing iron storage in seeds.

Micronutrient uptake and regulation

The functional characterization of micro-nutrient uptake centers on maintaining a delicate equilibrium between acquiring essential metal ions and preventing cellular toxicity through strict homeostasis and sequestration. The ZIP (ZRT/IRT-like Protein) family serves as the primary gateway for metal entry, where transporters like IRT1 (Iron-Regulated Transporter) utilize a broad substrate specificity to facilitate the initial uptake of ferrous iron (Fe^{2+}), zinc (Zn^{2+}), and manganese (Mn^{2+}) from the rhizosphere into root epidermal cells. Once inside the cytoplasm, these reactive ions must be carefully managed to avoid oxidative damage. This is achieved through sequestration into the vacuole the plant's

primary storage organelle mediated by the VIT (Vacuolar Iron Transporter) family, which is crucial for loading iron into seeds, and the MTP (Metal Tolerance Protein) family, which acts as cation diffusion facilitators. MTP1, for instance, is vital for zinc detoxification by pumping excess ions into the vacuole to maintain low cytosolic concentrations. These systems are further supported by HMA (Heavy Metal ATPase) pumps, which utilize ATP to drive the long-distance translocation of metals through the xylem, and NRAMP transporters, which remobilize sequestered minerals from vacuoles during periods of nutrient deficiency. Together, these gene families form a dynamic network that ensures minerals are available for metabolic processes like photosynthesis and DNA synthesis while keeping free ion concentrations below toxic thresholds.

Nutrient Cross-Talk and Integrative Signaling Networks

In nature, plants frequently face multiple nutrient stresses simultaneously, leading to complex physiological and molecular cross-talk. Variations in one nutrient's availability can modify the uptake and signaling of others, creating synergistic or antagonistic relationships. For example, nitrogen supply promotes the activity of PHR1, a phosphate-starvation-induced transcription factor. PHR1 acts as a potential integrator for N, P, S, Zn, and Fe nutrient signals. Under Pi deficiency, PHR1 induces phosphate transporters while also serving as a transcriptional regulator for sulfate transporters and the iron storage protein FER1. Furthermore, nitrate-inducible NIGT1 proteins modulate phosphate uptake and starvation signaling by regulating *SPX* genes, highlighting the tight coordination between macro- and micronutrient homeostasis.

Applications in Crop Improvement

Functional characterization helps in:

- ✓ Developing nutrient-efficient crop varieties
- ✓ Biofortification of crops
- ✓ Reducing fertilizer dependence
- ✓ Improving yield under nutrient-poor soils

Conclusion

Functional characterization of nutrient uptake genes provides insight into molecular mechanisms controlling nutrient acquisition in plants. It enables identification of transporter and regulatory genes responsible for nutrient efficiency and supports genetic improvement strategies for sustainable agriculture and nutritional security.

Breaking Free from Plastics: The Rise of Seaweed Bioplastics: A Green Transition towards Cleaner, Safer and Biodegradable Alternatives

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Abstract

Plastic pollution has emerged as one of the most pressing environmental challenges of the 21st century, with millions of tons accumulating in oceans and terrestrial ecosystems each year. In this context, seaweed-based bioplastics have gained increasing attention as a sustainable and biodegradable alternative. Seaweeds are rich in natural polymers such as agar, carrageenan and alginate, which can be processed into eco-friendly materials. This article explores the potential of seaweed to replace conventional plastics by discussing its availability, production processes, environmental benefits, economic feasibility and current challenges. With growing global demand for sustainable materials, seaweed-based bioplastics present a promising pathway towards reducing plastic dependency and fostering a circular bioeconomy.

Introduction

Plastic has become an inseparable part of modern life due to its durability, low cost and versatility. However, these same properties have led to severe environmental consequences, particularly because plastics are non-biodegradable and persist in ecosystems for hundreds of years. It is estimated that over 8 million tonnes of plastic enter oceans annually, posing a serious threat to marine bio-diversity and human health (Jambeck *et al*., 2015). As awareness of plastic pollution grows, researchers and industries are actively searching for sustainable alternatives. Among these, seaweed has emerged as a highly promising candidate. Unlike land-based crops, seaweed does not require freshwater, fertilizers or arable land, making it an environm-entally friendly raw material. Its rapid growth rate and high polysaccharide content further enhance its potential as a renewable resource for bioplastic production (Rajendran *et al*., 2012).

Why Seaweed? A Natural Advantage

- ✓ Seaweed is gaining attention as an eco-friendly substitute for conventional plastics. It is marine-safe, grows 30-60 times faster than most crops and does not require freshwater, fertilizers or arable land, making it a highly sustainable resource.
- ✓ In India, species like *Kappaphycus alvarezii*, *Gracilaria* and *Sargassum* are cultivated along the coasts of Karnataka, Tamil Nadu and Kerala. With around 24,252 hectares of suitable area, the country can produce nearly 10 million tonnes of biomass annually.
- ✓ Seaweed is rich in natural polymers such as

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carrageenan, alginate and agar, which can be used to create strong, flexible, biodegradable films.

- ✓ Moreover, large amounts of seaweed especially *Sargassum* often go to waste along coastlines. Converting this unused biomass into bioplastics can support a circular, zero-waste coastal economy.

These compounds have excellent film-forming and gel-forming properties, which are essential for producing biodegradable plastics. Unlike petroleum-based plastics, seaweed-derived materials are naturally biodegradable and do not release toxic residues into the environment (Sudhakar *et al*., 2018).

From Ocean to Plastic: How It Works

Raw Material Collection and Preparation: Fresh seaweed (such as *Kappaphycus* or *Gracilaria*) is collected from coastal regions, washed thoroughly to remove salts and impurities and then dried and powdered.

Extraction of Biopolymers: The dried seaweed is treated with hot water or mild chemicals to extract polysaccharides like carrageenan or alginate. These biopolymers act as the base material for bioplastic production.

Preparation of Bioplastic Solution

The extracted polymer is mixed with:

- ✓ Water
- ✓ Plasticizers (like glycerol)
- ✓ Additives (for flexibility and strength)

This mixture forms a viscous solution suitable for film formation.

Film Formation (Casting or Molding): The solution is poured onto flat surfaces (casting) or processed through extrusion or compression molding to form thin films.

Drying and Solidification: The film is dried under controlled conditions, allowing water to evaporate and forming a flexible, biodegradable plastic sheet.

Final Processing and Application: The final product can be used for:

- ✓ Food packaging
- ✓ Biodegradable bags
- ✓ Agricultural mulch films

Environmental Benefits

Seaweed-based bioplastics offer several ecological advantages over conventional plastics:

Biodegradability: These materials degrade naturally within weeks to months.

Non-toxic: They do not release harmful chemicals during degradation.

Marine-safe: Even if disposed into oceans, they do not harm aquatic life.

Reduced Carbon Footprint: Lower greenhouse gas emissions compared to petrochemical plastics.

A study by European Bioplastics (2019) highlights that bioplastics can significantly reduce environmental pollution when adopted on a large scale.

Expected Outcome

Product (Seaweed-based bioplastic)	Cups	Straws	Bottles	Features
CO_2 Score	3/5	3/5	3/5	40-69% less CO_2 emissions
Waste Score	3/5	3/5	3/5	Recyclable or composted industrially
Sustainability Score (Avg. of CO_2 and waste score)	3/5	3/5	3/5	Sustainable
Marketability Score	5/5	5/5	5/5	The product is highly convenient, familiar and fits perfectly into consumers' lives without requiring any behaviour change

Economic Potential in India

India has a vast coastline of over 7,500 km, providing immense potential for seaweed cultivation. Coastal states such as Tamil Nadu, Gujarat and Karnataka are already involved in seaweed farming.

Table 1: Economic Overview of Seaweed-Based Bioplastics

Parameter	Estimated Value
Seaweed cost (fresh)	₹10-20 kg^{-1}
Processing cost (lab scale)	₹150-300 kg^{-1}
Processing cost (pilot scale)	₹80-120 kg^{-1}
Market price (bioplastic films)	₹500-1500 kg^{-1}
Growth cycle	30-60 days

Seaweed farming can generate additional income for coastal communities while supporting sustainable industrial development. With proper infrastructure and policy support, India can become a global leader in this sector.

Current Applications

Seaweed-based bioplastics are already being used in:

- ✓ Food packaging materials
- ✓ Edible films and coatings
- ✓ Carry bags and disposable items
- ✓ Biomedical applications (capsules, drug delivery systems)

Challenges and Limitations

Despite its promise, several challenges must be addressed:

- ✓ High initial production cost compared to conventional plastics
- ✓ Limited large-scale processing facilities
- ✓ Shorter shelf life in some applications
- ✓ Lack of awareness and policy support

Additionally, standardization of production processes and quality control remains a critical requirement for market acceptance.

Future Scope

The future of seaweed-based plastics looks promising due to increasing environmental regulations and consumer demand for sustainable products. Advances in biotechnology and material science are expected to improve the strength, durability and cost-effectiveness of these materials. Government initiatives promoting blue economy and sustainable agriculture can further accelerate adoption. Integration of seaweed farming with coastal livelihood programs can create a win-win situation for both environment and economy.

Conclusion

Seaweed holds immense potential as a sustainable alternative to conventional plastics. Its biodegradability, abundance and eco-friendly nature make it a strong candidate in the fight against plastic pollution. While challenges remain, ongoing research and technological advancements are steadily

bridging the gap between innovation and commercialization. With the right combination of policy support, industry investment and public awareness, the solution to plastic pollution may indeed be floating in our oceans.

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Revolutionizing Crop Health: Artificial Intelligence in Modern Plant Disease Detection

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Introduction

Agriculture is undergoing a technological transformation, and Artificial Intelligence (AI) is emerging as one of the most powerful innovations in plant health management. By integrating smart-phones, drones, sensors, and intelligent algorithms, AI is revolutionizing the way farmers identify and manage plant diseases. What once required laboratory testing and expert observation can now be achieved in real-time through mobile applications and automated monitoring systems. For agricultural nations like India, where crop productivity directly impacts food security and rural livelihoods, AI-based disease detection offers a timely solution to one of farming's greatest challenges early and accurate identification of plant diseases. This technological advancement is empowering farmers, researchers, and agricultural professionals to protect crops more efficiently and sustainably.

The Growing Threat of Plant Diseases in Agriculture

Plant diseases continue to be a major cause of agricultural losses worldwide. Scientific estimates suggest that plant pathogens are responsible for reducing global crop yields by nearly 30-40% annually, significantly threatening food production systems. Traditional disease detection methods such as microscopy, ELISA, and Polymerase Chain Reaction (PCR) have been widely used for diagnosis; however, these techniques are often expensive, time-consuming and dependent on laboratory infra-structure and trained specialists. In practical farming situations, especially in remote and rural regions, these conventional methods are not always feasible. Farmers frequently identify diseases only after symptoms become severe, resulting in delayed interventions and substantial crop damage. Climate change and global movement of agricultural commodities have further accelerated the spread of emerging plant pathogens, making rapid disease surveillance more critical than ever.

How Artificial Intelligence Enhances Disease Detection

Artificial Intelligence enables computers to mimic human decision-making by learning from large datasets. In agriculture, AI systems analyze images, environmental data, and crop health patterns to detect disease symptoms with remarkable precision. Machine learning algorithms such as Support Vector Machines (SVM), Decision Trees, and Random Forests are commonly used to classify diseased and healthy plants based on visual sympto-

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ms. These models can detect subtle disease patterns that may not be visible to the human eye. Deep learning, particularly Convolutional Neural Networks (CNNs), has become the most effective AI approach for image-based disease diagnosis. CNNs automatically learn visual features such as lesions, discoloration, texture abnormalities, and wilting from thousands of leaf and stem images, often achieving accuracy rates above 95% in controlled experiments. Studies using the widely known PlantVillage dataset have shown that deep learning systems can identify multiple crop diseases with extremely high classification accuracy.

Smartphone Applications: AI in Farmers' Hands

One of the most practical uses of AI in agriculture is through smartphone-based disease diagnosis applications. Mobile apps allow farmers to capture images of infected leaves and instantly receive probable disease diagnoses along with treatment recommendations. Applications such as Plantix and PlantVillage Nuru have demonstrated promising results in identifying diseases affecting crops like tomato, potato, maize, cassava, and rice. These tools make expert-level diagnostics accessible even to smallholder farmers who may lack nearby agricultural extension services. Such accessibility is particularly valuable in India, where millions of small and marginal farmers depend on immediate and affordable agricultural advice.

Drone and Satellite Monitoring for Large-Scale Disease Surveillance

While smartphone apps support individual plant diagnosis, drone and satellite technologies extend AI's capability to monitor disease outbreaks over large agricultural fields. Equipped with multispectral and hyperspectral cameras, drones capture aerial images that reveal plant stress and disease symptoms before they become visible from ground level. AI-powered computer vision systems process these aerial images to generate disease maps, identify infected zones and recommend targeted pesticide applications. This approach supports precision agriculture by reducing unnecessary chemical spraying, lowering production costs, and minimizing environmental impact. Large-scale plantation systems and commercial farms increasingly rely on drone-based monitoring for real-time crop health assessment.

IoT Sensors and Smart Greenhouse Integration

AI is also being integrated with the Internet of Things (IoT) to create intelligent agricultural environments. Smart sensors installed in fields and greenhouses continuously monitor variables such as:

- ✓ Temperature
- ✓ Humidity
- ✓ Soil moisture
- ✓ Carbon dioxide concentration
- ✓ Light intensity

This environmental data is analyzed by AI models to predict disease outbreaks before symptoms appear. For instance, elevated humidity and temperature may signal ideal conditions for fungal infections, allowing preventive action before disease onset. In greenhouse farming, AI systems can auto-

matically regulate ventilation, irrigation, and lighting to optimize plant health and suppress disease development.

Challenges Limiting AI Adoption in Agriculture

Despite its enormous potential, several challenges hinder the widespread adoption of AI in plant disease detection.

Limited Real-World Data: Many AI models are trained using laboratory or ideal-condition datasets, which may not accurately represent field conditions involving dust, poor lighting, overlapping leaves, and mixed infections.

Lack of Explainability: Farmers may hesitate to trust AI recommendations if the system cannot clearly explain why it diagnosed a disease.

Data Bias and Model Generalization: Models trained in one geographic or climatic region may fail when applied elsewhere due to differences in crop varieties, disease strains and environmental conditions.

Infrastructure Barriers: Limited internet connectivity, smartphone access, and digital literacy in rural regions remain obstacles for AI deployment.

Future Directions of AI in Plant Pathology

The future of AI in agriculture lies in building more robust, explainable and field-adapted diagnostic systems. Emerging research is focusing on:

Explainable AI (XAI): Making AI decisions interpretable to users

Edge Computing: Running AI directly on smartphones and portable devices without internet dependency.

Multimodal Systems: Combining image, weather, and soil data for better predictions.

Disease Forecasting Models: Predicting outbreaks before infection occurs.

As these systems improve, AI is expected to become an indispensable part of sustainable agriculture and integrated disease management.

Conclusion

Artificial Intelligence is redefining plant disease diagnosis by delivering rapid, scalable, and highly accurate disease detection solutions. From smartphone applications and drone surveillance to smart sensors and greenhouse automation, AI is enabling proactive crop protection and smarter farming decisions. Although challenges remain in terms of accessibility, trust, and field adaptability, continued innovation promises to bridge these gaps. For countries like India, where agricultural productivity is central to economic and food security, AI-powered disease detection represents not just technological progress but a pathway toward resilient and sustainable farming systems.

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From Stubble to Spirit: How Agricultural Waste Could Fuel the World's Clean Energy Future

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Abstract

Global energy systems are under mounting pressure to transition away from fossil fuels towards cleaner, renewable alternatives. Bioethanol a liquid fuel produced through the fermentation of sugars derived from organic matter represents one of the most promising and technically mature pathways in this transition. This article examines the full spectrum of bioethanol production technologies, from first-generation food-crop-based systems to fourth-generation genetically engineered microbial platforms, with emphasis on the biological, chemical, and physicochemical processes that underpin each approach. Key feedstocks are evaluated, including sugar- and starch-rich crops, lignocellulosic agricultural residues, and marine macroalgae, alongside the pre-treatment strategies necessary to unlock their fermentable sugar content. Fermentation configurations including Simultaneous Saccharification and Fermentation (SSF), Simultaneous Saccharification and Co-Fermentation (SSCF), Separate Hydrolysis and Fermentation (SHF), and Solid-State Fermentation (SF) are discussed in terms of their efficiency, scalability and economic viability. The first-generation technologies are commercially mature, they face sustainability challenges related to food security. Second- and third-generation approaches address these concerns through the use of non-food lignocellulosic biomass and algal feedstocks, respectively, though technical barriers around pre-treatment cost and complexity remain. Fourth-generation approaches, leveraging synthetic biology and CRISPR-based genetic editing, hold transformative potential but require further development before large-scale deployment. Overall, bioethanol emerges as a versatile and scalable component of the global renewable energy portfolio, capable of contributing to carbon neutrality, rural economic development, and energy security.

Introduction

Every year, tons of crop stubble, wood chips, seaweed, and food waste are discarded, yet these materials contain valuable energy. Bioethanol, produced by fermenting sugars in organic matter, is a non-toxic, biodegradable fuel that can significantly reduce greenhouse gas emissions when responsibly sourced. Its production methods have advanced from simple corn fermentation to sophisticated genetic engineering. The process is nearly carbon neutral, as plants absorb carbon dioxide and release it back when burned, unlike fossil fuels which add new carbon to the atmosphere. Bioethanol also boosts farm incomes, rural economies and energy independ-

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ence by converting agricultural waste into fuel. Leading producers like North America and Brazil blend bioethanol with petrol for transportation, but the industry faces pressure to expand sustainably, driving ongoing innovation.

Generations of Bioethanol Production

First Generation: Starting with Food Crops: The initial bioethanol industry used food crops such as sugarcane, corn, and wheat for fuel, with Brazil and the U.S. leading in sugarcane and corn ethanol production, respectively. As bioethanol output increased, competition with food supplies caused higher prices and occasional shortages, especially in developing countries. While first-generation bioethanol reduced fossil fuel reliance, it raised food security concerns, prompting the industry to seek sustainable alternatives.

Second Generation: Turning Waste into Fuel: Second-generation bioethanol avoids the food-versus-fuel issue by using agricultural and forest wastes, such as wheat straw, rice husks, corn stover, sugarcane bagasse and wood chips. This lingo-cellulosic biomass is plentiful, inexpensive, and not food-related. Norway's Borregaard Company is a leading producer of second-generation ethanol. Lignocellulosic materials are much more complex than sugars or starches, consisting of a rigid matrix of cellulose, hemicellulose, and lignin that resists breakdown. Accessing fermentable sugars requires costly pre-treatment and enzymes, but research aims to lower these costs with improved enzyme engineering and process integration.

Third Generation: Farming the Sea: Third-generation bioethanol uses seaweed and marine algae, which grow quickly without farmland, fresh water or fertilizers. Some species, like *Enteromorpha,* are up to 70% carbohydrates by dry weight and ideal for fermentation. Macroalgae such as *Ascophyllum, Porphyra, and Palmaria* also offer high carbohydrate content. Algal biomass can yield 46,000 to over 140,000 litres of ethanol per hectare much more than land crops. The challenge is that algal sugars are not immediately available for fermentation. An optimised pre-treatment step is needed to liberate them, adding complexity and cost to the process. Research into optimising algal cultivation and harvesting at scale is ongoing.

Fourth Generation: Engineering Life Itself: Fourth-generation methods use genetic engineering, especially CRISPR/Cas9, to alter microorganisms for more efficient fuel production. Genetically modified cyanobacteria have been created to produce ethanol, butanol, isobutanol, and modified fatty acids. However, the technology is new, and scaling up remains difficult.

Key Feedstocks and Their Characteristics

Bioethanol feedstocks include

Sugar-rich crops (sugarcane, sweet sorghum, molasses, sugar beet): Easily processed as sugars are ready for fermentation.

Starch-rich crops (corn, wheat, cassava): Require enzymatic conversion of starch to sugars before fermenting.

Lignocellulosic biomass (straw, crop residues,

wood wastes): Most complex but abundant and doesn't compete with food production.

Pre-treatment of Lignocellulosic Biomass: Ligno-cellulosic biomass needs to be broken down before fermentation. Plant cell walls, made of cellulose, hemicellulose, and lignin, are hard to convert into fuel. Pre-treatment methods help overcome this challenge.

Physical Methods: Mechanical milling using techniques such as ball milling, wet milling, and vibratory milling physically shreds the biomass into smaller particles, increasing the surface area available for subsequent chemical or enzymatic attack. Pyrolysis, a high-temperature treatment above 300°C, rapidly decomposes the cellulose structure, producing gases and a carbon-rich char that can be further processed to yield fermentable sugars.

Physicochemical Methods: Steam explosion is one of the most widely used pre-treatment techniques. Biomass is blasted with high-pressure steam at temperatures between 160°C and 290°C, then the pressure is suddenly released essentially exploding the material apart from the inside. Variants include the liquid hot water method, which uses compressed hot water to dissolve hemicellulose, and Ammonia Fiber Explosion (AFEX), which combines liquid ammonia with steam explosion for particularly effective delignification. CO_2 explosion offers a more cost-effective alternative with impressively high conversion rates.

Chemical Methods: Acid pre-treatment, using dilute acids at concentrations of 0.2%-2.5% at elevated temperatures, breaks down the biomass structure to liberate sugars. Alkaline pre-treatment uses bases to dissolve lignin and hemicellulose, causing the cellulose to swell and become far more accessible to enzymes. Wet oxidation treats the biomass with water and oxygen at high temperatures, while organosolv pre-treatment uses organic solvents to extract and isolate lignin for potential reuse.

Biological Methods: Enzymatic hydrolysis uses biological catalysts to break down plant material in two stages. First, endoglucanases and exoglucanases attack the surface of solid biomass, releasing short oligosaccharide chains into solution. Then, cellobio-hydrolase converts these chains into cellobiose, and finally β-glucosidases cleave cellobiose into individual glucose molecules ready for fermentation. Biological methods are slower but highly specific and generate fewer toxic by-products than chemical approaches.

Fermentation Configurations: Once fermentable sugars are obtained from lignocellulosic biomass pre-treatment, the process of bioethanol production begins. Several fermentation strategies have been established to convert these sugars into bioethanol, with each method offering distinct advantages as well as certain limitations. These strategies are selected based on factors such as process efficiency, cost-effectiveness, and the nature of the feedstock used for fermentation.

Simultaneous Saccharification and Fermentation (SSF): SSF combines enzymatic breakdown and yeast fermentation in a single vessel. This approach

prevents inhibitory compounds from building up, reduces processing time, and cuts capital costs. It has become one of the most widely studied methods for converting both lignocellulosic and starchy feedstocks into ethanol and other biofuels.

Simultaneous Saccharification and Co-Fermentation (SSCF): Lignocellulosic biomass releases both hexose (C_6) and pentose (C_5) sugars during hydrolysis. SSCF is designed to ferment both types simultaneously, using microorganisms that can handle both sugar streams under shared temperature and pH conditions. This maximises the yield from each unit of biomass processed.

Separate Hydrolysis and Fermentation (SHF): The more traditional SHF approach keeps enzymatic hydrolysis and fermentation in separate vessels. This allows each step to be optimised independently. The drawback is that inhibitory compounds produced during hydrolysis can carry over and reduce fermentation efficiency.

Solid-State Fermentation (SF): In solid-state fermentation, microorganisms grow directly on the surface of solid biomass with little or no free water. This unusual environment eliminates the need for sugar extraction steps and produces less wastewater during processing. The result is lower distillation and purification costs a real advantage at industrial scale where energy and water efficiency directly affect profitability.

Future prospects

The integration of genetic engineering, synthetic biology, and advanced pre-treatment chemistry is expanding the potential for bioethanol production. The primary challenge involves scaling these technologies efficiently, reducing associated costs, and positioning bioethanol as renewable energy option. High oil price and geopolitical instability have accelerated the shift towards sustainable biofuels to reduce dependency on fossil fuel. India is transitioning from EBP (Ethanol Blending Program) program towards an era of E20 nationwide.

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Healing the Earth: How *Trichoderma* is Replacing Chemicals in Modern Agriculture

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Abstract

Trichoderma species are beneficial soil fungi that play a vital role in sustainable agriculture. They improve soil fertility, promote plant growth, and protect crops from a wide range of diseases. These fungi suppress harmful microorganisms through mechanisms such as antibiosis, mycoparasitism, and competition for nutrients. In addition to disease control, *Trichoderma* enhances plant tolerance to environmental stresses like drought, salinity, and temperature fluctuations. It is widely used as a biofertilizer, biocontrol agent, and seed treatment, thereby reducing dependence on chemical fertilizers and pesticides. Due to its eco-friendly nature, effectiveness, and affordability, *Trichoderma* has become an important component of modern sustainable farming systems.

Introduction

Trichoderma is a group of filamentous fungi commonly found in soil and in association with plant roots. These fungi are known for their rapid growth and their ability to survive in diverse environmental conditions. They are widely distributed in agricultural soils, forests, and even aquatic environments. Most species of *Trichoderma* are non-pathogenic and establish beneficial relationships with plants. One of the most important characteristics of *Trichoderma* is its ability to parasitize other fungi, a phenomenon known as mycoparasitism. In agricultural systems, *Trichoderma* improves plant health by suppressing plant pathogens and enhancing plant growth. It stimulates root development and increases nutrient uptake, leading to better crop performance. Furthermore, it activates plant defense mechanisms, enabling plants to withstand both biotic stresses caused by pathogens and abiotic stresses such as drought and salinity.

Importance and Characteristics of *Trichoderma*:

Trichoderma species are considered important plant growth-promoting fungi present in the rhizosphere, the region of soil surrounding plant roots. They play a significant role in improving plant growth and protecting plants from soil-borne diseases.

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These fungi enhance nutrient availability by solubilizing minerals and improving nutrient recycling in the soil. In addition to nutrient enhancement, *Trichoderma* produces growth-promoting substances and induces systemic resistance in plants. This leads to improved plant vigor and better resistance against diseases. Several species, including *Trichoderma* harzianum, *Trichoderma* viride, and *Trichoderma* asperellum, have been extensively studied and are widely used in agriculture due to their beneficial effects. Another important characteristic of *Trichoderma* is its ability to decompose organic matter and detoxify harmful substances in the soil. This contributes to improved soil health and fertility, making it an essential component of sustainable agricultural practices.

Role in Enhancing Stress Tolerance: Plants are often exposed to unfavorable environmental conditions such as drought, salinity, extreme temperatures and heavy metal contamin-ation. These stresses can lead to the production of reactive oxygen species, which damage plant cells and reduce growth. *Trichoderma* helps plants cope with such stresses by improving their antioxidant defense systems. It reduces the accumulation of harmful reactive oxygen species and enhances the plant's ability to tolerate adverse conditions. Studies have shown that plants treated with *Trichoderma* exhibit better growth, higher photosynthetic activity, and improved survival under stress conditions. The fungus also influences plant hormone regulation, which further contributes to stress tolerance. As a result, crops treated with *Trichoderma* show increased resilience and productivity even under challenging environmental conditions.

Impact on Soil Microbiome: The soil microbiome, particularly in the rhizosphere, is a complex and dynamic system that plays a crucial role in plant health. *Trichoderma* significantly influences this microbial community by promoting beneficial microorganisms and suppressing harmful ones. It improves nutrient cycling and modifies the composition of fungal and bacterial populations in the soil. Advanced techniques such as next-generation sequencing and molecular methods have shown that *Trichoderma* can increase microbial diversity and enhance soil biological activity. Although its impact on fungal communities is more pronounced, *Trichoderma* also affects bacterial populations by promoting beneficial groups and altering overall microbial balance. These changes contribute to improved soil health and better plant growth.

Role as a Biocontrol Agent: *Trichoderma* is widely recognized as an effective biocontrol agent against plant pathogens. It protects plants through several mechanisms, both direct and indirect. Direct mechanisms include mycoparasitism, where *Tricho-derma* attacks and destroys pathogenic fungi, and antibiosis, where it produces antibiotics that inhibit pathogen growth. It also competes with pathogens for nutrients and space, limiting their ability to survive. Additionally, *Trichoderma* produces enzymes such as chitinases and glucanases that break

Table : *Trichoderma* strains effects on plant growth and development through different mechanisms

Crop	*Trichoderma* strains	Effects	References
Brassica and lettuce (*Brassica rapa* and *Lactuca sativa* var. *crispa*	*Trichoderma hamatum* RW309	Production of indole-3-acetic acid, P solubilization and nutrient mineralization	Asghar and Kataoka (2021)
Arabidopsis thaliana	*Trichoderma atroviride and Trichoderma virens*	Production of abscisic acid (ABA)	Contreras-Cornejo *et al*. (2015)
Arabidopsis thaliana	*Trichoderma virens*	Production of indole-3-ethanol, indole-3-acetaldehyde and indole-3-acetic acid	Contreras-Cornejo *et al.* (2009)
Tomato *(Solanum lycopersicum)*	*Trichoderma harzianum*	Production of harzianic acid	Cai *et al.* (2013)
Arabidopsis thaliana	*Trichoderma viride, Trichoderma aggressivum* and *Trichoderma asperellum*	Production of VOCs such as 6-pentyl-2H-pyran-2-one (6PP), 3-methyl-1-butanol, 2-methyl-1-propanol, 1-hexanol	Lee *et al*. (2016)
Tomato *(Solanum lycopersicum)*	*Trichoderma atroviride*	Production of VOCs 2-heptanone, 2-pentyl furan (2-PF) and 6-pentyl-2H-pyran-2-one (6-PP)	Rao *et al*. (2022)

down the cell walls of harmful fungi, leading to their destruction. Indirectly, *Trichoderma* enhances plant defense by inducing systemic resistance. This process activates the plant's immune system, enabling it to resist future pathogen attacks more effectively. The production of volatile organic compounds further contributes to pathogen suppression and plant protection.

Role in Plant Growth Promotion: *Trichoderma* promotes plant growth through multiple mechanisms. It enhances seed germination, stimulates root development, and improves nutrient uptake. These effects lead to increased plant biomass and higher crop yields. The fungus produces several growth-promoting substances, including plant hormones such as indole acetic acid and abscisic acid. It also releases volatile organic compounds that stimulate plant growth and development. These compounds influence root architecture and improve the overall health of the plant. As a result, plants treated with *Trichoderma* show improved growth, better flowering and higher productivity compared to untreated plants.

Role in Soil Health and Biofertilizer Application: *Trichoderma* plays a crucial role in maintaining soil health by acting as a biofertilizer. It decomposes organic matter, releases essential nutrients, and improves soil structure. This enhances the availability of nutrients to plants and supports the growth of beneficial microorganisms. It is commonly applied as a seed treatment, soil amendment, or compost additive. The use of *Trichoderma* -based biofertilizers reduces the need for chemical fertilizers and contributes to environmentally sustainable farming practices.

Economic and Agricultural Importance: The growing concern over the environmental impact of chemical fertilizers and pesticides has increased the importance of *Trichoderma* in agriculture. It offers a cost-effective and eco-friendly alternative for improving crop productivity and managing plant diseases. The use of *Trichoderma* supports organic farming and sustainable agriculture by reducing chemical inputs and improving soil health.

Its increasing commercialization and global acceptance highlight its significance in modern agricultural systems.

Preparation of *Trichoderma* -Based Biofertilizers

The effectiveness of *Trichoderma* -based biofertilizers depends on proper formulation and application. Suitable strains must be selected, and appropriate carrier materials should be used to maintain the viability of the fungal propagules. These biofertilizers are available in both solid and liquid forms and can be easily applied in agricultural fields. Proper storage and handling are essential to ensure their effectiveness and long shelf life.

Conclusion and future prospects

Trichoderma has emerged as a powerful tool for sustainable agriculture due to its ability to promote plant growth, control plant diseases, and improve soil health. Its eco-friendly nature and multiple benefits make it an ideal alternative to chemical inputs. The integration of *Trichoderma* into agricultural practices can help achieve higher crop productivity while maintaining environmental balance. Future research should focus on improving its formulations and understanding its interactions with other beneficial microorganisms to maximize its potential in sustainable farming systems.

For future-oriented agricultural production, the integration of *Trichoderma*-cultured bioorganic fertilizers is crucial for ensuring soil health and biodiversity. Ongoing research and development activities should focus on refining formulation and application methods to ensure the durability, efficacy and compatibility of *Trichoderma*-based products across various agricultural systems. Exploring potential interactions between *Trichoderma* and other beneficial microorganisms presents a novel strategy for simultaneously addressing plant diseases and enhancing soil health.

Improvement of Post-Harvest Quality Traits in Vegetable Crops through Modern Breeding

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Abstract

Post-harvest losses in vegetables are a major challenge affecting food security, market value, and farmer income. Improving post-harvest quality traits through modern breeding has become essential to enhance shelf life, reduce losses, and maintain nutritional value. Advanced breeding techniques such as marker-assisted selection, genomic selection, and genome editing enable precise improvement of traits like firmness, color retention, and resistance to spoilage. These approaches help develop varieties with better storage and transport tolerance. Additionally, modern breeding enhances biochemical attributes such as antioxidants and vitamins. Integration of biotechnology accelerates the development of superior vegetable varieties. Despite challenges, these innovations offer promising solutions. Thus, modern breeding plays a key role in ensuring quality and sustainability in vegetable production.

Introduction

Vegetables are highly perishable commodities that undergo rapid deterioration after harvest. Post-harvest losses in vegetables can range from 20% to 40%, especially in developing countries. These losses occur due to physiological, biochemical and microbial factors. Improving post-harvest quality traits such as shelf life, firmness, color, and nutritional value is essential for reducing losses. Traditional breeding methods have contributed to quality improvement, but they are often slow and less precise. Modern breeding techniques offer efficient solutions to enhance post-harvest traits. These approaches enable the development of vegetable varieties that can withstand storage and transportation stresses. Thus, modern breeding plays a vital role in improving post-harvest quality and reducing food wastage.

Importance of Post-Harvest Quality Traits: Post-harvest quality traits determine the marketability and consumer acceptance of vegetables. Traits such as freshness, texture, color, and nutritional content influence consumer preference. Poor post-harvest quality leads to significant economic losses for farm-

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ers and supply chains. Improved quality traits enhance storage life and reduce spoilage during transportation. They also ensure better nutritional value for consumers. Maintaining quality is especially important in export markets where long-distance transport is involved. Therefore, improving post-harvest traits is essential for both economic and nutritional benefits.

Physiological and Biochemical Factors Affecting Quality

Post-harvest deterioration in vegetables is mainly due to physiological and biochemical changes. Respiration and transpiration lead to loss of moisture and freshness. Ethylene production accelerates ripening and senescence in many vegetables. Enzymatic activities cause softening, discoloration, and degradation of nutrients. Microbial growth further contributes to spoilage and decay. Environmental factors such as temperature, humidity, and handling conditions also influence post-harvest quality. Understanding these factors is crucial for developing improved varieties with better storage characteristics.

Role of Conventional Breeding in Quality Improvement

Conventional breeding methods such as selection and hybridization have been used to improve post-harvest traits. Breeders select plants with desirable characteristics like firmness and longer shelf life. Hybrid varieties often exhibit better quality traits due to heterosis. However, conventional breeding is time-consuming and depends on natural variation. It may not always achieve precise improvement of complex traits. Despite these limitations, it remains an important foundation for modern breeding programs.

Marker-Assisted Selection for Post-Harvest Traits

Marker-assisted selection (MAS) is a powerful tool for improving post-harvest quality traits. It uses molecular markers to identify genes associated with desirable characteristics. MAS allows early selection of plants with improved shelf life, firmness, and disease resistance. This technique increases the efficiency and accuracy of breeding programs. It reduces the time required to develop new varieties. MAS is particularly useful for traits controlled by multiple genes, such as fruit quality and storage ability.

Genomic Selection and Advanced Tools

Genomic selection uses genome-wide markers to predict the performance of plants. This approach helps breeders select superior genotypes with better post-harvest traits. Advanced tools such as high-throughput sequencing and bioinformatics support genomic selection. These technologies enable precise analysis of complex traits. Genomic selection accelerates breeding programs and improves efficiency. It is an important advancement in developing high-quality vegetable crops.

Genome Editing for Quality Enhancement

Genome editing technologies such as CRISPR-Cas9 allow precise modification of genes related to post-harvest quality. These tools can be used to

Table 1: Modern Breeding Approaches for Improving Post-Harvest Traits

Breeding Technique	Target Trait	Benefit	Example Crops
Marker-Assisted Selection	Firmness, shelf life	Faster selection	Tomato, pepper
Genomic Selection	Storage quality	High accuracy	Cabbage, carrot
Genome Editing	Ripening control	Precision improvement	Tomato, cucumber
Hybrid Breeding	Quality traits	Higher yield & quality	Brinjal, okra
Biofortification	Nutritional quality	Improved health value	Spinach, carrot

delay ripening, improve firmness, and enhance nutritional content. Genome editing enables targeted improvement without introducing foreign genes. It is faster and more efficient than traditional methods. This technology holds great potential for developing vegetables with extended shelf life. Continued research is needed to fully exploit its benefits.

Breeding for Extended Shelf Life

Shelf life is one of the most important post-harvest traits in vegetables. Breeding programs focus on developing varieties that maintain freshness for longer periods. Traits such as reduced respiration rate, delayed ripening, and improved cell structure contribute to extended shelf life. These improvements reduce losses during storage and transportation. Longer shelf life also increases market opportunities for farmers. Modern breeding techniques play a key role in achieving these goals.

Nutritional Quality Improvement

Modern breeding also focuses on enhancing the nutritional quality of vegetables. Traits such as higher vitamin content, antioxidants, and minerals are targeted. Biofortification through breeding improves the health benefits of vegetables. It helps address malnutrition and micronutrient deficiencies. Improved nutritional quality increases consumer demand and market value. These advancements contribute to better public health and food security.

Challenges in Improving Post-Harvest Traits

Improving post-harvest quality traits presents several challenges. These traits are often complex and controlled by multiple genes. Environmental factors also influence their expression. High costs and technical requirements of modern breeding tools can limit adoption. Regulatory issues and public acceptance may affect the use of advanced technologies. There is a need for multidisciplinary approaches to address these challenges. Collaboation among researchers and stakeholders is essential.

Future Prospects of Modern Breeding

The future of post-harvest quality improvement lies in integrating advanced technologies such as artificial intelligence and precision breeding. These innovations will enhance the accuracy and efficiency of breeding programs. Research is focused on developing vegetables with multiple quality traits. Climate-resilient and high-quality varieties will be essential for sustainable agriculture. Increased investment and policy support will drive innovation. Modern breeding will continue to play a key role in reducing post-harvest losses.

Conclusion

Improving post-harvest quality traits in vegetable crops is essential for reducing losses and ensuring food security. Modern breeding techniques offer efficient and precise solutions for enhancing

shelf life, nutritional value, and overall quality. Approaches such as marker-assisted selection, genomic selection, and genome editing have transformed crop improvement. Despite challenges, these technologies hold great potential for sustainable agriculture. Continued research and adoption of modern breeding methods will help improve vegetable quality and reduce wastage.

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Gut Microbiome Manipulation in Honey Bees: Implications for Pollinator Health and Sustainability

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Introduction

Honey bees constitute one of the most economically and ecologically significant groups of pollinators, underpinning global agricultural productivity and biodiversity conservation. It is estimated that a substantial proportion of food crops depend directly or indirectly on insect-mediated pollination, with honey bees contributing the largest share. However, over the past few decades, honey bee populations have undergone a marked decline, driven by a combination of anthropogenic and environmental stressors, including pesticide exposure, habitat degradation, climate change, and the proliferation of pathogens and parasites (Engel *et al.*, 2016; Motta and Moran, 2024). Recent longitudinal field investigations have further underscored the severity of colony losses in managed apicultural systems, thereby highlighting the urgent need for innovative, sustainable, and ecologically compatible interventions (Anderson *et al.*, 2024). In this context, the manipulation of the bee-associated microbiome, particularly through the engineering of gut symbionts has emerged as a promising frontier in pollinator health management.

The Bee Gut Microbiome: Composition and Functional Significance

The gut microbiome of honey bees is characterized by a relatively low taxonomic diversity but high functional specialization. It is predominantly composed of a conserved set of bacterial taxa, including *Snodgrassella alvi*, *Gilliamella apicola*, *Bifidobacterium* spp., and *Lactobacillus* spp., which are socially transmitted within colonies and establish stable host–microbe associations (Engel *et al.*, 2016). These microbial communities play indispensable roles in host physiology and health.

Nutritional Metabolism and Digestive Efficiency: Gut symbionts facilitate the degradation of complex dietary substrates, particularly recalcitrant pollen-derived polysaccharides. Through intricate metabolic interactions and cross-feeding networks, these microorganisms convert otherwise indigestible compounds into bioavailable nutrients, thereby enhancing host nutritional efficiency and promoting growth (Zheng *et al.*, 2017).

Immune Modulation and Pathogen Resistance: The gut microbiota exerts a profound influence on host immune competence by modulating signalling pathways and inducing the expression of antimicrobial peptides. Experimental studies have demonstrated that microbiota-depleted bees exhibit heightened susceptibility to opportunistic pathogens,

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including *Serratia marcescens* and *Nosema ceranae* (Engel *et al.*, 2016).

Detoxification and Environmental Adaptation: In addition to nutritional and immunological functions, gut microbes contribute to the detoxification of xenobiotic compounds, including agricultural pesticides. However, exposure to such chemicals can disrupt microbial homeostasis, leading to dysbiosis and compromised host resilience (Motta andoran, 2024).

Regulation of Host Physiology and Behaviour: Emerging evidence indicates that the gut microbiome influences host metabolic pathways, developmental processes, and behavioural traits, including foraging efficiency and learning capacity, thereby underscoring its integrative role in host biology (Zheng *et al.*, 2017).

Microbiome Disruption and Its Implications: Anthropogenic interventions, particularly the use of antibiotics in apiculture and widespread pesticide application, have been shown to perturb the gut microbiome of honey bees. Such disturbances result in microbial dysbiosis, characterized by reduced diversity and functional imbalance, ultimately leading to increased mortality and disease susceptibility (Raymann *et al.*, 2017). Given these implications, the restoration and stabilization of the native microbiome have become central objectives in contemporary pollinator health research.

Probiotic Interventions: Potential and Constraints

Probiotic supplementation has been explored as a strategy to re-establish microbial balance and enhance bee health. Evidence suggests that host-adapted (native) microbial strains confer greater benefits in terms of immune enhancement and physiological performance compared to non-native formulations (Alberoni *et al.*, 2016). Nevertheless, the efficacy of probiotics remains variable. Empirical studies have demonstrated that commercially available, non-native probiotics often fail to establish persistent colonization or confer sustained benefits, particularly following antibiotic-induced dysbiosis (Anderson *et al.*, 2024). Furthermore, the potential ecological risks associated with microbial dissemination to wild pollinator populations warrant careful consideration.

Engineering Gut Symbionts: Advances in Synthetic Biology

Recent advancements in synthetic biology have enabled the targeted engineering of gut symbionts, offering unprecedented opportunities to enhance their functional capabilities. Unlike conventional probiotics, engineered symbionts can be designed to perform specific, high-efficiency tasks within the host environment.

Metabolic Enhancement and Nutritional Optimization: Genetically modified symbionts can be engineered to augment digestive processes, synthesize essential nutrients, and optimize metbolic pathways, thereby improving host growth and fitness (Zheng *et al.*, 2017).

Detoxification of Xenobiotics: The introduction of genes encoding detoxifying enzymes enables engine-

ered bacteria to degrade harmful agro-chemicals, mitigating their adverse effects on bee health (Leonard *et al.*, 2020).

Development of Biosensing Systems: Engineered microbial systems can function as biosensors, capable of detecting physiological or environmental changes and initiating context-specific responses. This represents a significant advancement toward the development of adaptive and responsive micro-biome-based interventions (Navarro-Escalante *et al.*, 2025).

Symbiont-Mediated RNA Interference (smRNAi): Mechanisms and Applications

Symbiont-mediated RNA interference (smRNAi) represents a transformative innovation in microbiome engineering. In this approach, engineered gut bacteria are utilized as delivery systems for double-stranded RNA (dsRNA), which activates gene-silencing pathways in the host or associated pathogens.

This technology has demonstrated efficacy in:

- ✓ Suppressing viral pathogens
- ✓ Controlling *Varroa destructor* infestations
- ✓ Reducing *Nosema ceranae* infections (Leonard *et al.*, 2020). The specificity, sustainability, and reduced environmental impact of smRNAi make it a highly promising alternative to conventional chemical control strategies.

Conclusion

The engineering of bee gut microbiota represents a paradigm shift in pollinator health management, offering a sustainable and targeted approach to mitigating the multifaceted challenges facing honey bee populations. By enhancing microbial functions related to nutrition, immunity, and detoxification, this strategy holds considerable promise for improving colony health and resilience. Although several technical, ecological, and regulatory challenges remain, ongoing advances in this field are likely to enable the development of practical, scalable solutions. Ultimately, microbiome engineering has the potential to play a pivotal role in safeguarding pollinator populations and ensuring the sustainability of global agricultural systems.

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New Product Development and Technology Commercialization

Sandeep Kumar and Nikita

Abstract

The knowledge intensive nature of new product development (NPD) may have increased recently due to the move toward more open innovation procedures that actively transmit technology both internally and outward. Although the body of research has shown that knowledge is essential for NPD performance knowledge produced by NPD can also have an effect on external technology exploitation such as when businesses use technology out licensing to commercialize their technologies rather than just using it internally. The process of turning scientific discoveries and technical advancements into commercially viable goods or services is known as technology commercialization. New technology enhanced crop varieties farm equipment and value-added food items are frequently developed by agricultural universities research facilities and innovation centers. These inventions can more successfully reach farmers industries and consumers through appropriate commercialization tactics like licensing, patenting, start-up incubation, and public-private collaborations. Technology transfer methods and extension systems are crucial for connecting research organizations with end users. Digital advisory platforms, training courses, field tests, and demonstrations all aid in raising awareness and promoting the uptake of recently created technology. Through funding incubation facilities and capacity-building initiatives for researchers and entrepreneurs, government policies and institutional support also encourage innovation.

Introduction

New Product Development (NPD) and technology commercialization are key drivers of innovation, economic growth, and competitiveness in today's knowledge-based economy. External technology commercialization and external technology exploitation synonymously refer to commercializing technologies exclusively or in addition to their application in a firm's own products, for example by means of outlicensing (Lichtenthaler, 2007; Teece, 2006). Technology commercialization goes far beyond a marginal transfer of residual technologies (Chesbrough, 2003; Kline, 2003). In particular, firms often license technology because of limited complementary assets for internal technology exploitation (Arora *et al.*, 2001 and Teece, 2006). Accordingly, outward technology transfer often constitutes a key dimension of corporate strategy (Chesbrough, 2007; Fosfuri, 2006). By means of licensing, firms attempt to achieve both strategic and monetary benefits. Strategic benefits include establishing industry standards or gaining access to

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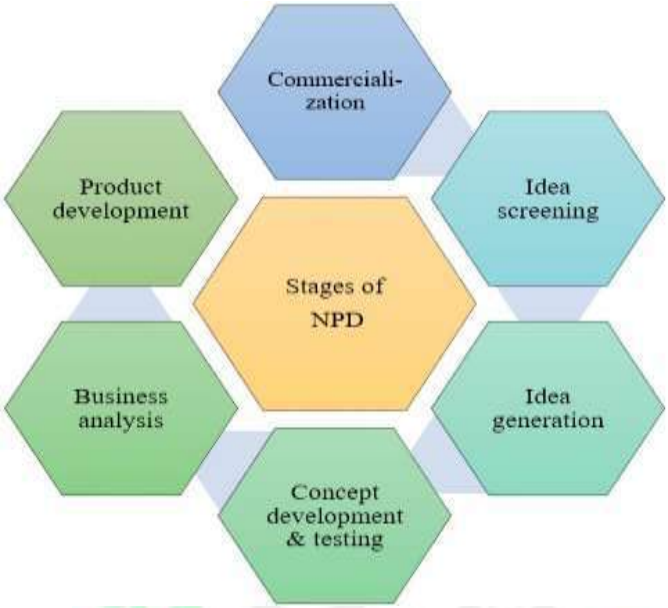
external knowledge (Arora *et al*., 2001; Grindley and Teece, 1997). Concerning monetary benefits, various pioneering firms, for example, IBM and Dow Chemical, have generated hundreds of millions of dollars in annual licensing revenues (Arora *et al.,* 2001).



Technology Commercialization

The process of turning scientific discoveries, research findings, and technical advancements into commercially viable goods or services is known as "technology commercialisation." By ensuring that discoveries created in labs are successfully launched into the market, it serves as a link between research institutions, industries, and end consumers. The main goal is to use new technology to create social and commercial value.

Objectives of Technology Commercialization

- ✓ To convert research findings into practical applications
- ✓ To generate revenue and economic growth
- ✓ To enhance technology adoption among users (e.g., farmers)
- ✓ To promote innovation and entrepreneurship
- ✓ To improve productivity and sustainability

Linkage between NPD and Technology Commercialization

New Product Development (NPD) and technology commercialization are closely interconnected processes that together ensure the successful transformation of innovative ideas into marketable products. While NPD focuses on the creation and development of new products through systematic stages such as idea generation, design, and testing, technology commercialization emphasizes the introduction of these developed products into the market and their widespread adoption. The linkage between NPD and commercialization lies in their complementary roles. NPD generates innovations based on market needs and technological feasibility, whereas commercialization ensures that these innovations reach end users effectively and generate economic value. Without proper commercialization, even the most advanced products developed through NPD may fail to achieve impact, remaining confined to laboratories or pilot stages.A strong connection between these two processes requires continuous interaction among researchers, developers, marketers, and end users. Feedback from the market plays a crucial role in refining products during the NPD stages, making them more user-

centric and demand-driven. Similarly, insights gained during commercialization help improve future product development cycles. In agriculture, this linkage is particularly important, as technologies such as improved seeds, farm machinery, and digital advisory tools must not only be developed but also effectively transferred and adopted by farmers. Factors such as market demand, institutional support, financial resources and extension services significantly influence this relationship. Moreover, the integration of Information and Communication Technologies (ICTs) has strengthened the linkage by enabling faster communication, real-time feedback, and efficient dissemination of innovations. Digital platforms, mobile applications, and e-extension services help bridge the gap between innovation and adoption.

Role of ICT in NPD and Technology Commercialization

Information and Communication Technology (ICT) plays a transformative role in enhancing the efficiency, speed, and effectiveness of both New Product Development (NPD) and technology commercialization. In the modern digital era, ICT tools enable seamless integration of research, innovation, market analysis, and communication, thereby strengthening the entire innovation cycle from idea generation to market adoption.

Application in Agriculture

The increasing productivity, sustainability, and farmer livelihoods, the application of New Product Development (NPD) and technology commercialisation in agriculture has profoundly changed the industry. Innovative agricultural goods and technologies must be developed and successfully disseminated in order to meet the growing need for food security and effective resource utilization.

Role of Startups and Institutions

Institutions and startups are essential in advancing technological commercialisation and New Product Development (NPD). By creating user-centric, market-focused solutions and quickly introducing new technology to the market, startups stimulate innovation. Particularly in agriculture, they introduce cutting-edge solutions like AI, IoT, and digital platforms. Research, funding, training, and policy frameworks are some of the ways that institutions including government agencies, universities and research groups support innovation. Startups can grow their ideas into successful businesses with the aid of incubators and accelerators. In addition to facilitating technology transfer and ensuring that innovative products are successfully commercialised and widely adopted, collaboration between startups and institutions also strengthens the innovation ecosystem. The collaboration between start-ups and institutions enhances technology transfer, reduces the gap between resea-

rch and market, and ensures wider adoption of innovations, leading to sustainable development and economic growth.

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Hydrochar: A Potential Amendment for Soil Health Improvement and Sustainable Agriculture

Chauhan Aditi, Susheel Singh and Trupti Vyas

Abstract

Hydrochar is a carbon-rich material produced at moderate temperatures (180-250 °C) under saturated pressure via Hydrothermal Carbonization (HTC) of wet organic wastes like agricultural residues, food waste, and sewage sludge. Unlike biochar, it is suitable for high-moisture feedstocks and supports sustainable waste management. Soil application of hydrochar can improves physical properties (structure, porosity, water retention), chemical properties (nutrient retention, CEC, slow-release N, P, K), and biological activity by providing a habitat for beneficial microorganisms. It also contributed to climate change mitigation and carbon sequestration. However, some constraints still exist, particularly in improving production methods and fully understanding the prolonged impacts. This makes it necessary to carry out more research and field studies to ensure its safe and effective use.

Introduction

Hydrochar is emerging as a promising material for promoting sustainable agriculture and effective waste management. It is produced via hydrothermal carbonization (HTC), which involves treating organic biomass such as agricultural residues, food waste, and sewage sludge at moderate temperatures (180-250 °C) under saturated pressure in water. This process is comparable to natural coal formation but occurs over hours instead of millennia, making it a rapid and resource-efficient approach (Libra *et al*., 2011). The resulting product is a carbon-rich, porous material with numerous agronomic and environmental benefits. Unlike conventional composting or pyrolysis-based biochar, HTC can process wet feedstocks, which constitute a large portion of municipal and agro-industrial waste. This enables hydrochar to transform potential pollutants into a valuable soil amendment, enhancing waste valorisation (Reza *et al*., 2014). Hydrochar enhances soil physical properties by improving structure, porosity, aggregate stability, and water-holding capacity, which supports better aeration and moisture retention. Chemically, it increases cation exchange capacity (CEC), improving nutrient retention and reducing leaching, and can also act as a slow-release source of N, P, and K (Masoumi *et al*., 2021). Biologically, hydrochar promotes microbial activity and key processes such as nutrient mineralization, thereby improving soil fertility and crop productivi-

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ty. Its high carbon content aids in long-term carbon sequestration and climate change mitigation, while also helping immobilize contaminants. Overall, hydrochar supports sustainable agriculture and circular economy practices.

Key Benefits of Hydrochar

Soil Conditioning and Fertility: Hydrochar improves soil structure, porosity, and aeration, supporting better root growth and crop productivity. Enhances water-holding capacity, reducing drought stress. Acts as a slow-release source of essential nutrients (N, P, K), minimizing nutrient leaching and improving nutrient use efficiency (Masoumi *et al*., 2021).

Carbon Sequestration and Climate Mitigation: Contains stable carbon that resists microbial decomposition, remaining in soil for long periods. Helps reduce greenhouse gas emissions, contributing to climate change mitigation and adaptation strategies.

Soil Remediation: Improves soil buffering capacity. Can immobilize heavy metals and organic pollutants, aiding in detoxification of contaminated soils.

Sustainable Waste Management: HTC can process high-moisture feedstocks like food waste, sewage sludge, and crop residues without drying. Reduces energy consumption and diverts organic waste from landfills, lowering methane emissions and leachate formation. Produces nutrient-rich process water, which can be recycled or further treated.

Reduction of Chemical Fertilizer Dependence: Integrating hydrochar in agriculture can lower the need for synthetic fertilizers, reducing costs and environmental impact.

Support for Regenerative and Circular Agriculture: Promotes eco-friendly, regenerative farming systems, especially in degraded or nutrient-deficient soils. Aligns with circular bioeconomy principles, converting waste into a valuable input that enhances soil health, crop productivity, and economic resilience.

Applications of Hydrochar

Hydrochar has a wide range of applications across different fields, highlighting its multi-functional nature and environmental significance. In agriculture, it is used to improve soil fertility and increase crop yields by enhancing soil structure and making nutrients more available to plants. Its strong adsorption capacity enables it to bind heavy metals and organic pollutants, making it effective for environmental remediation, particularly in the treatment of contaminated soils and wastewater. In the energy sector, hydrochar can be utilized as a feedstock for biofuel production or directly as a renewable energy source. Furthermore, it contributes to sustainable waste management by converting organic residues into a useful product, thereby supporting circular economy principles. This transformation of waste into value-added material not only reduces environmental burden but also promotes resource efficiency (Libra *et al*., 2011).

Role of Hydrochar in Soil Health

Hydrochar plays an important role in enhancing soil health by positively affecting its

physical, chemical, and biological characteristics. Due to its distinctive properties, including a porous nature, large surface area, and nutrient-enriched composition, it serves as an effective soil amendment, particularly in degraded and nutrient-poor soils. Its incorporation into soil systems contributes significantly to overall soil quality and sustainability.

Effect on Soil Physical Properties

The addition of hydrochar improves key physical properties of soil that are essential for plant growth and efficient water management:

Soil Structure and Porosity: Hydrochar promotes better aggregation of soil particles due to its porous and lightweight structure. This leads to improved aeration and facilitates easier root penetration, while also enhancing gas exchange within the root zone.

Reduction in Bulk Density: Because of its low density, hydrochar helps in lowering the bulk density of compacted or heavy soils. This creates a more favorable environment for root growth and simplifies tillage operations.

Water Holding Capacity (WHC): Hydrochar increases the soil's capacity to retain moisture, which is particularly beneficial in sandy or drought-affected soils. Improved water retention ensures better moisture availability to crops during critical growth stages and reduces the need for frequent irrigation.

Erosion Control: By improving soil aggregation and surface stability, hydrochar minimizes soil loss caused by wind and water erosion. This helps in conserving topsoil and maintaining essential nutrients within the soil system.

Effect on Soil Chemical Properties

Hydrochar significantly modifies the soil's chemical environment, thereby improving nutrient dynamics and buffering capacity:

Nutrient Retention and Availability: Hydrochar contains essential macro- and micronutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium. It acts as a gradual nutrient source, minimizing losses through leaching and volatilization (Masoumi *et al.*, 2021).

Cation Exchange Capacity (CEC): The presence of functional groups like carboxyl and hydroxyl on hydrochar surfaces enhances the soil's cation exchange capacity. This improves the retention and exchange of important nutrient ions such as ammonium, potassium, and calcium.

pH Regulation: Depending on the type of feedstock and production conditions, hydrochar can help in stabilizing soil pH. It may reduce acidity or buffer extreme pH levels, thereby creating a more favorable environment for nutrient uptake.

Contaminant Immobilization: Hydrochar has the ability to bind heavy metals such as lead, cadmium, and zinc, as well as organic pollutants. This reduces their mobility and toxicity, making hydrochar useful for remediation of polluted soils.

Effect on Soil Biological Activity

Hydrochar contributes to improving soil biological health, which is essential for sustainable soil functioning:

Microbial Biomass and Diversity: It provides a suitable habitat and carbon source for beneficial soil

microorganisms, resulting in increased microbial population and diversity.

Soil Enzyme Activity: The application of hydrochar enhances the activity of key soil enzymes like dehydrogenase, urease, and phosphatase, which are involved in nutrient cycling and microbial metabolism.

Support to Symbiotic Organisms: Hydrochar promotes the activity of plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, which improve nutrient uptake and enhance plant tolerance to stress conditions.

Soil Organic Carbon (SOC) Enrichment and Carbon Sequestration

Stable Carbon Pool: Hydrochar contains a high proportion of stable organic carbon that decomposes slowly, contributing to long-term carbon storage in soils.

Carbon Sequestration Potential: Its application helps in capturing and storing atmospheric carbon dioxide in the soil, thereby playing a role in climate change mitigation.

Improved Microbial Carbon Efficiency: Hydrochar enhances microbial utilization of organic matter, leading to more efficient carbon cycling within the soil system.

Support for Plant Growth and Yield

By improving soil physical, chemical, and biological properties, hydrochar indirectly supports plant growth by:

- ✓ Promoting better seed germination and root development
- ✓ Enhancing uptake of nutrients and water
- ✓ Reducing stress under adverse conditions such as drought and salinity
- ✓ Increasing overall crop productivity and biomass yield

Challenges and Research Needs

Although hydrochar shows great promise, its large-scale application is still limited by certain challenges. These include the need to better understand its long-term environmental effects, optimize hydrothermal carbonization conditions for different types of feedstocks, and improve its economic viability. Ongoing research is also focused on modifying hydrochar properties to suit specific agricultural and environmental applications.

Conclusion

Hydrochar has emerged as a multifunctional and eco-friendly material with significant potential to tackle major global environmental issues. Its role in enhancing soil quality, promoting carbon sequestration, managing organic waste and supporting sustainable agricultural practices highlights its importance in advancing environmental sustainability. Owing to its diverse applications in agriculture, pollution remediation, energy generation and waste valorization, hydrochar serves as an effective tool for encouraging circular economy approaches and reducing the impacts of climate change. Its adoption can contribute to building more sustainable and resilient production systems. Nevertheless, additional research is essential to refine production techniques, assess long-term effects on

soil and the environment, and improve its economic viability. Strengthening these aspects will be crucial for the safe and widespread implementation of hydrochar in practical applications.

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Cowpea: A Controversial Crop

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Abstract

Cowpea is considered to be a potential crop since years for its wide range of use in many measures. But keeping aside its wide usage pattern, the crop has always sparked a debate of confusion among the agriculturists about choosing a side for it. The wide range of usage in this crop gives it an identity of an agronomic crop as well as a horticultural crop. In the following chapter it is discussed in details about the aspects of the variability of this crop and some criteria which sustains its usage in both agronomic and horticultural aspect.

Introduction

Cowpea (*Vigna unguiculata*) is an annual plant that belongs to the Fabaceae family of peas and is cultivated for its edible legumes. The plants are commonly grown in warm climates worldwide and are believed to be native to West Africa. Cowpeas are widely planted not just as a food crop high in protein but also as a hay crop, green manure, or cover crop. Cowpeas are usually trailing or climbing vines with three leaflets on their compound leaves. At the tips of long stalks, the white, purple, or pale-yellow flowers typically grow in pairs or threes. Depending on the cultivar, the long, cylindrical pods can reach lengths of 20-30 cm (8-12 inches). The plants can withstand drought and are heat-adapted. Cowpeas are utilised for heart and intestinal health, diabetes management, and energy production, among other health advantages. They are high in fibre, protein, and important vitamins and minerals including iron, folate, and antioxidants that support healthy skin and lower inflammation.

Cowpea is a multipurpose, adaptable legume with unique horticultural and agronomic characteristics that determine how it is grown and utilised worldwide. From the horticultural approach concentrates on fresh consumption and particular quality traits like pod appearance, texture, and taste for vegetable markets and home gardens, whereas the agronomic approach concentrates on the crop's resilience, soil benefits, and dry grain yield for large-scale production.

What are the controversies?

In horticulture base the cowpea is treated as a crop of tender green pod, immature seed and fresh vegetable for its palatability and nutritional richness. In horticultural production systems cowpea is a short duration, high market demand, suitable for kitchen gardens and all-season cultivable crop. It is often cultivated as fresh market supply and dietary source along with generating a moderate farm income.

Whereas, in agronomic base cowpea has a significance in pulse and fodder crop rather than a

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fresh output. It is extensively cultivated for long durations for mature dry seeds to sell as pulses and the plant extracts are used as fodder for cattle feeds and green manuring. It also serves as a medium for nitrogen fixation in soil which makes it highly suitable for sustainable agriculture.

Controversies relating to Academic Curriculum

As the crop sustains in both the subjects of Agronomy and Horticulture hence:

- ✓ Its inclusion in academic curricula often creates confusion in subject clarification.
- ✓ Research recommendation may differ depending on the purpose it is grown.
- ✓ Crop management practices, harvesting time and post-harvest techniques may differ.

Key Facts

- ✓ Cowpea is one of the few crops that is cultivated as food, fodder and manure at the same time.
- ✓ Breeding programmes of cowpea has a wide approach for more varietal trials and on farm breeding to increase its productivity.
- ✓ Its widely adaptable climatic approach makes it convenient to be cultivated in most of the regions of world.
- ✓ It is drought tolerant and low input crop making it suitable for climate resilient agriculture.
- ✓ In small holder farming it is mixed with other vegetable crops than growing as a single crop.
- ✓ It has a different economic value depending on the purpose it is being sold either as a vegetable or a pulse.
- ✓ The controversy around cowpea reflects the broader challenge of classifying multifunctional crops in agriculture.

Conclusion

The cowpea is a distinct and multifaceted crop whose importance transcends the boundaries of a particular agricultural line of work. Its classification is debatable because of its use as a vegetable crop in horticulture and as a pulse, fodder, and soil-enriching crop in agronomy. This overlap should be seen as a strength that emphasizes the crop's adaptability and significance in sustainable farming rather than as a point of controversy. Cowpea is a perfect example of an interdisciplinary crop that bridges the gap between horticulture and agronomy because of its capacity to assist soil health, income generation, and nutrition.

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Balvinder Singh's Dairy Journey from Kalaundi Punjab

Suhani

In a small vilage of Kalaundi, Balvinder Singh made a successful dairy business which he started with only a few local beed buffaloes on rented land. Today he has 50 cows and 54 buffaloes and Supply approx. 1,200 litres milk to dairy companies such as Verka and Amul every day. He belonged to a family of marginal farmers and smallholdings. He had a crop failure and debt problems in 2010. Inspired by the White Revolution in Punjab, he sold his tractor in 2015 and bought two high-quality Murrah buffaloes along with some Sahiwal dairy cows. He also received training on scientific feeding and breeding through the local department.

He is now able to produce feed for his dairy animals using two acres of land (thereby reducing feed costs by approximately 40%). He also uses artificial insemination (AI) method and has improved both the genetic quality of his herd. By implementing AI technique he has able tp increased the amount of milk production per buffalo daily, from 8 litres to over 25 litres per buffalo. Balvinder reinvests profits back into his dairy operation at a rate of 10 additional animals per year. The secret to the success of Balvinder's dairy operation is that he feeds his dairy animals a balanced diet consisting of green fodder, concentrates, and minerals, and has a regular veterinary check-up of livestocks that also reduced the amount of veterinary medications utilized.

Everyday Balvinder supply 800 liters of milk to the milk plant located at near by locations and 400 liters to Amul. With his sales of Rs 2.5 lakh (monthly) priced at Rs 45-50 per liter, he earns 60% profit after all expenses. With this income, he has been able to pay for his son's education, buy a new tractor, and even provide training to youth in his village. This is the potential of dairy farming for marginal farmers in Punjab.

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AgriTech Evolution: Cultivating Intelligence in Agriculture

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Abstract

Information technologies have transformed the field of agriculture in many ways, enabling farmers to improve efficiency, productivity and sustainability. Precision farming, automated farming, biotechnology, data analytics and sustainable agriculture are some of the key areas where modern technologies have had a significant impact. Precision farming technologies, such as GPS, drones and sensors help the farmers to monitor and analyze their crops, soil and weather conditions with high precision, leading to optimized crop yield and reduced wastage. Automated machinery and robotics increase crop productivity, reduce labour-costs and minimize environmental impact. Overall, the modern technologies have played a crucial role in advancing the agriculture field, helping farmers to increase efficiency, productivity and sustainability while producing high-quality and safe food.

Introduction

In the era of information technology, today, the role of information technology sector has entered every aspect of human life. Information technology has recognized as a powerful tool in a wide range of activities carried out by either organizations or individuals so that the information technology may affect and occur in most human activities. The usage of technology in agriculture domain has resulted in digital agriculture, precision agriculture, analytics for crop yield, *etc*. Precision agriculture is emerging as a result of the strategic integration of smart sensors and advanced data analytics to guide agricultural decisions in their application to factors, such as fertilizers, water, pesticides, insecticides, seed, *etc*. (Bhakta *et al*., 2019). These technological advances are playing a central role in the transformation of agricultural practices, offering solutions to optimize inputs, increase productivity and mitigate environmental impact (Abioye *et al*., 2020). These advances include the development of information technology systems, the use of cloud computing and wireless sensor networks and the application of AI techniques, such as machine learning (Sharma *et al*., 2021). The drone's technology often referred to as unmanned aerial vehicles (UAVs) have made impressive advancements. They have transformed agricultural practices, offering farmers substantial

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Precision agriculture tools

GPS and GIS	GPS and GIS technologies, when combined with other digital tools play a crucial role in monitoring and optimizing agricultural practices, facilitating precision farming and sustainable food production.	Ghosh and Kumpatla (2022)
Sensor	Integrated NPK sensors within Wireless Sensor Networks (WSNs) play a pivotal role in optimizing nutrient management to enhance crop productivity and sustainability.	Musa *et al*. (2023)
Remote sensing	Land use, land cover and other thematic data are periodically provided by remote sensing data gathering technologies, such as satellites and aerial photos.	Trivedi *et al*. (2020)
Drones	Drones can be utilized to identify and monitor water resources across fields more effectively.	Parsaeian *et al*. (2020)
Biotechnology	With the help of biotechnology farmers can produce more crops with fewer resources, and consumers can have a more abundant and affordable food supply.	Das *et al*. (2023)
Automated machinery and robotics	Tractors and agricultural machinery in general are large and powerful. They tend to degrade soil and make it more difficult to traverse.	Tazzari *et al*. (2020)

Application of Drones

Analysis of soil and monitoring of field	Drones used for monitoring various farming aspects, including crop health (insect damage, nutrient deficiencies and pest-related color changes), vegetation (leaf area, treatment efficiency, phenology and yield) and plant growth (leaf area index, density and height.	Debangshi (2021)
Seed planting with drones	Drones can facilitate seed sowing. Additionally, these drone systems can shoot seed pods, along with essential plant nutrients, directly into well-prepared soil, effectively reducing the time required for planting.	Marzuki *et al*. (2021)
Crop spraying	Drones are environment friendly and minimize human contact with hazardous chemicals. Their spraying capacity is up to five times more rapid as compared to conventional techniques.	Pathak *et al*. (2020)
Crop monitoring	Drones save time and labor by swiftly assessing crop conditions.	Hafeez *et al*. (2023)
Irrigation	Drones offer crucial data for planning, allowing farmers to combine drone data with weather forecasts, soil type and crop needs to create an effective irrigation schedule.	Barbedo (2019)
Crop surveillance	Drones efficiently capture extensive farmland data, including soil moisture, nutrient content and plant health, enabling precise input application and reducing waste.	McCarthy *et al*. (2023)
Livestock monitoring	Livestock technology, such as wearable Radio Frequency Identification (RFID) tags or remote sensors that collect physiological or behavioral data and notifies irregularities, automates ongoing monitoring and offers more comprehensive information in comparison to manual approaches.	Herlin *et al*. (2019)
Tree/crop biomass estimation	Drones can capture high-resolution aerial imagery of fields and forests for precise biomass estimation.	Kachamba *et al*. (2016)

cost reductions, enhanced operational effectiveness and increased profitability (Debangshi *et al.*, 2021).

Precision agriculture

Precision agriculture was developed in the mid-1980s with an objective to enhance crop productivity and quality while simultaneously reducing operational expenses and minimizing environmental pollution as well as enhancing the utilization of resources and minimizing uncertainties associated with monitoring farm responses to spatial and temporal variations. Precision agriculture is modern agricultural practice that employs technologies, such as remote sensing, Geographical Information System (GIS) and Global Positioning System (GPS) usually used to increase productivity and profitability (Niu *et al.*, 2019). Precision agriculture helps to provide the farmers with real-time information about their farms and livestock as

needed, enabling them to make precise decisions in a timely manner that will increase yield and reduce wastage of limited resources.

GPS and GIS

Utilization of global positioning system (GPS) and global information system (GIS) in precision agriculture further enhances data collection and analysis for informed decision-making in crop management as well as precise location tracking, mapping and informed decision-making in crop management, optimizing resource utilization (Tagung *et al*., 2022). A farming GIS database can provide information on field topography, soil types, surface drainage, subsurface drainage, soil testing, irrigation, chemical application rates and crop yield. Once analyzed, this information is used to understand the relationships between the various elements affecting a crop on a specific site (Bharteey *et al*., 2019). GIS-enabled cloud technology serves as a decision support system for soil fertility management, utilizing soil test and crop response data to provide accurate fertilizer recommendation, and this enables farmers to optimize fertilizer usage and maximize crop yield. Geo-information technologies are becoming a key factor in precision fertilization, as a basis for integrating discrete spatial data of soil sampling and their spatial prediction. Geospatial technologies form the foundation of precise agriculture, a paradigm shift in the agricultural industry (Trivedi *et al*., 2021). GPS enables farmers to precisely locate particular sites in the field year after year for the purpose of gathering soil samples or keeping an eye on crop conditions (Hao *et al*., 2019).

Sensor technologies

Variable rate technologies, guided by sensor information, allow for the precise application of water and fertilizers based on the specific needs of different areas within a field. Wireless sensor network to monitor parameters, such as temperature, humidity and soil moisture, ensuring automatic control of climatic conditions (Savitha *et al*., 2022). Soil sensors constantly monitor soil conditions to guide precise irrigation and fertilization practices, avoiding overuse of resources and ensuring optimum nutrient availability for crops.

Remote sensing

Remote sensing data are used to distinguish crop species, locate stress conditions, identify pests and weeds and monitor drought, soil and plant conditions. Various technologies encompassed within sensing technologies, including remote sensing techniques, such as satellite imagery, aerial photography and drones, as well as ground-based sensors like weather stations, soil moisture sensors and nutrient sensors (Sishodia *et al*., 2020). Remote sensing (RS) technology offers the capability to monitor dynamic conditions of the soil, plants and the area under cultivation with high accuracy, achieving 95% accuracy in assessing the cultivated area and 90% accuracy in identifying single crop cultivation areas within 10 days timeframe.

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Soil Pollution Mitigation through Technological Innovations, Remediation and Management

Ramdas Yadav, Robin Kumar, Ruby Yadav and Raghvendra Kumar Kushwaha

Abstract

With rapid industrialization, excessive use of agrochemicals, and improper waste management, soil pollution is emerging as one of the major environmental problems, adversely affecting the quality of the soil as well as human life and the environment. The current paper is intended to explore the role of technologies and managerial methods in addressing soil pollution problems and restoring the quality of soil for future use. Nanotechnology, bioremediation, phytoremediation, and sensors are some of the latest technologies that show great potential in detection and remediation of soil pollution. They play a key role in degrading soil pollution by promoting decomposition and soil fertility. In addition, technologies like precision agriculture and organic waste recycling help in managing the pollution problem effectively. It is evident from the results obtained in this research that with the help of appropriate technology and management measures, soil pollution can be successfully mitigated and maintained. Thus, application of these remedial measures helps restore soil pollution and ensure the availability of healthy soils for future generations to ensure sustainability.

Introduction

The earth's surface has a dynamic natural body called soil, which is a vital resource for sustaining plant growth (Kushwaha and Varma, 2023). Pollution is the result of harmful substances into the environment, causing undesirable changes in air, water, and soil. Soil, often called a “universal sink,” absorbs a variety of contaminants resulting from human activity, such as industrial processes, mining, waste disposal, and pharmaceutical use. Heavy metals are among these pollutants. Synthetic chemicals, and biological agents like pathogens and parasites, it may have detrimental effects on human health. Contamination of soil can have an impact on plant and animal life, often requires an inter-disciplinary approach to understand. Fields like chemistry, biology, public health, and geology must collaborate to identify pollutants, assess their effects, and develop solutions like bioremediation or phytoremediation. Polluted soil can cause illnesses and long-term health hazards through the food chain, so addressing soil pollution is essential for the health of ecosystems and the general people (Havugimana *et al.*, 2017). Today's productivity is heavily influen-

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ced by the quality of the soil. The use of chemicals, fertilizers, trash, and metals, among other things, has increased the importance of soil contamination concerns. Soil contamination or pollution is a result of land degradation caused by the presence of xenobiotics (man-made substances) or other alterations in the natural soil environment (Mitral *et al.*, 2022). The step to look after the resources includes the sustainable management of natural resources which ensures the minimum and sufficient amount of resources to be used and also the amount required in further cases will be available (Kushwaha and Dayal, 2023).

What is Soil Pollution?

The outermost layer of the earth's crust is called soil. The soil is where we live and where we receive our nourishment. Soil contamination has been caused by unsustainable agriculture, rapid industrialization, urbanization, and population growth. The undesirable changes in biological, chemical, and physical properties of soil that are detrimental to all living things are referred to as soil contamination. Pollutants that are in direct contact with soil for a comparatively longer amount of time are what distinguish soil pollution from air and water pollution (Katyayan *et al.*, 2019). "Soil pollution refers to anything that causes contamination of soil and degrades the soil quality."

Soil Pollution Sources

Agricultural Activities: Sustainable agriculture major objective is to avoid diminishing natural resources so that future generations can make good use of them. More production or meeting human needs is the primary objective of farming (Kushwaha and Dayal, 2023). Excessive application of insecticides and fertilizers is among the most significant contributors to contamination of the soil in farming regions. These chemicals can gather in the soil over time, causing toxicity to soil micro-organisms and affecting the development of plants. Improper disposal of livestock waste and agricultural byproducts can also result in contamination of the soil with harmful bacteria and chemicals. Pesticides also harm plants and animals by contaminating the soil. These chemicals get deep inside the soil and poison the ground water system. Runoff of these chemicals by rain and irrigation also contaminate the local water system and is deposited at other locations (Mishra *et al.*, 2016). Poor management and careless use of soil and water resources have a negative impact on the environment and may be fatal for both humans and other animals (Kushwaha and Varma, 2023).

Fig. 1: How soil pollute through Agricultural Activates

Industrial Activities: The most significant gases are carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2), which are produced by combustion in industry and automobiles and are hazardous to the environment.

Food processing facilities generate both liquid and solid waste. Products can be in the form of gases, liquids, or solids. The textile industry's Heavy metals including cadmium, lead, and boron found in sewage sludge are contaminating nearby ecosystems, particularly irrigation soils. This contamination has reduced rice yields by 80% over 20 years, from 4-6 tons per hectare to just 1 ton. The heavy metals accumulate in plant roots and tissues, decreasing soil productivity and harming human health. Proper waste management and treatment are crucial to mitigate these long-term environmental and agricultural impacts (Havugimana *et al.*, 2017).

Fig. 2: Industrial Activities leading to soil pollution

Urbanization: Human activities are largely blamed for the widespread degradation of land, with the amount of productive land rapidly declining due to development projects such as urban expansion, industries, transportation infrastructure (roads, railways, airports), and more. Pollution of surface soils is a growing concern, as it is contaminated by various materials including vegetable and animal waste, paper, wood, plant debris (twigs and leaves), discarded clothes, household sweepings, and numerous non-biodegradable substances like plastic bags, bottles, and other plastic waste, as well as glass bottles, broken glass, and cement fragments. In Indian cities alone, it is estimated that 50,000 to 80,000 metric tons of solid waste are generated daily. If this waste is not collected and properly managed, it can lead to several serious issues, including.

Fig. 3: Urbanization leading to soil pollution.

Mining Activities: Mining operations often disturb the soil and can introduce harmful substances like mercury, arsenic, and cyanide into the environment. These pollutants can accumulate in the soil, affecting plant and animal life (Virta, 2002).

Fig 4: Mining Activities leading to soil pollution

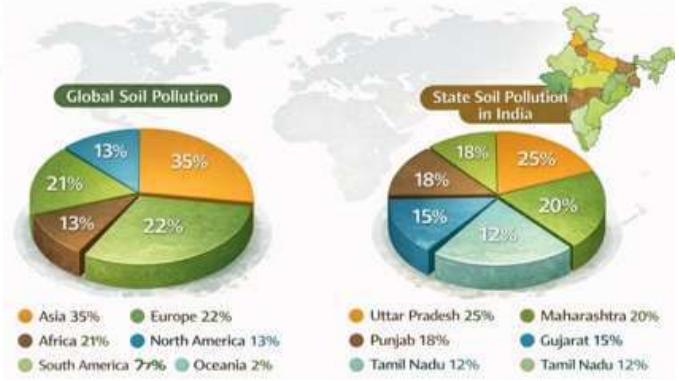

Fig. 5: Global and Indian status of soil pollution

This chart offers a comparison of soil pollution worldwide as well as in Indian states through the use of pie charts. According to the global pie chart, Asia accounts for the largest percentage of soil pollution at 35%, Europe at 22%, and Africa at 21%. North America and South America are at 13% each, whereas Oceania is the least polluted continent at 2%. As per the pie chart on soil pollution in Indian

states, Uttar Pradesh leads at 25%, Maharashtra at 20%, Punjab at 18%, and Gujarat at 15%. Tamil Nadu accounts for 12%.

Effect on Soil Living Microorganisms and Human life of Soil Pollution: The problem of soil pollution is a major factor impacting soil bacteria and humans. The presence of heavy metals, industrial waste products, and other toxic compounds decreases the variety of microorganisms and impacts the natural soil processes of decomposition, recycling nutrients, fixing nitrogen. As a result, soil fertility reduces along with the productivity of crops. Toxic chemicals may have a detrimental effect on the microorganism balance by encouraging the growth of more harmful forms. Polluted soils affect people through the contamination of food supplies and the environment at large. Diseases associated with contaminated soil include cancers, respiratory diseases and neurologic syndromes.

Fig. 6: Effect on soil living microorganisms and human life of soil pollution

Toxic metals like cadmium, lead, chromium, arsenic, mercury and nickel accumulate in the soil and negatively impact microbial processes, soil physicochemical properties, crop productivity and human health through food chain transfer. The goal of the current study is to determine the level of heavy metal contamination in soils as well as athe effectiveness of modern, sustainable management techniques for reducing metal toxicity and enhancing soil health (Kushwaha, 2026). Soil pollution entails hazardous chemicals in the form of heavy metals, pesticides, and industrial pollutants that affect the quality of soil as well as decrease its microorganism population. Soil pollution affects natural soil activity, which may even lead to the entry of the soil contaminants into the human body through the food chain and water sources causing various health issues. Heavy metal pollution poses long-term risks to soil sustainability and food safety (Kushwaha, 2026).

How to Control the Soil Pollution?

Controlling soil pollution requires a multi-faceted approach that involves both preventative and remedial measures. The source of soil contamination is the accumulation of harmful substances like chemicals, heavy metals, pesticides, waste, and organic matter in the soil, which may negatively impact plant, animal, and human health. Here's a detailed guide about how to control soil pollution;

Prevention of Soil Pollution: Preventing soil pollution includes proper disposal of wastes, using environmentally friendly farming techniques, promoting sustainable urban development, and formulating strict laws. Proper management of wastes and maintenance of landfills prevent pollution. Utilizing organic fertilizers and pesticides prevent contamination.

Green areas and planned constructions help prevent pollution. Moreover, implementation of environmental laws and creating awareness among people play a very important role in preventing soil pollution.

Fig. 7: Prevention Strategies for Soil Pollution

Remediation of Polluted Soil: The process of remediation of contaminated soil entails procedures aimed at the removal and neutralization of pollutants for the enhancement of soil fertility. Remediation procedures include methods like bioremediation whereby contaminants are broken down using living organisms like plants and microbes. Soil washing is another method that helps to get rid of contaminants like heavy metals.

Fig. 8: Soil Pollution Remediation Techniques

Technological Innovations for Soil Pollution Control

Nanotechnology: Researchers are exploring nanomaterials for soil remediation. Nanoparticles can be used to remove or neutralize pollutants like heavy metals, oil, and pesticides more efficiently than traditional methods.

Geochemical Stabilization: This involves the application of geochemical techniques to reduce the mobility of heavy metals in the soil and stabilize them. Thus, less likely to contaminate the environment.

Restoration of Contaminated Sites

Revegetation: After cleaning a polluted site, the soil should be restored with appropriate vegetation. This helps in soil stabilization, erosion control, and improving soil quality. Native kinds of plants are commonly preferred, as they are more resilient to local conditions and can help restore the natural ecosystem.

Erosion Control: Erosion can exacerbate soil contamination by spreading pollutants to surrounding areas. Measures like planting grass cover, building terraces, and using organic mulch can prevent soil erosion and further contamination.

Conclusion

Mitigation of soil pollution demands a comprehensive strategy that involves technology, remediation techniques, and sustainable practices. Utilization of innovative methods such as bioremediation, nanotechnology, and precision agriculture is a good way of restoring polluted soils without causing additional harm. Similarly, there needs to be proper policymaking, monitoring, and community education in efforts aimed at mitigating soil pollution. A combination of science, governance,

and sustainable practices will ensure long-term health of the soil in future.

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Emerging Machine Vision Technologies Driving Next-Generation Smart Farming

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Abstract

Agriculture plays a vital role in ensuring global food security and economic growth, yet it faces challenges such as labour shortages, rising food demand, and sustainability concerns. To address these issues, modern farming is increasingly adopting advanced technologies like precision agriculture, robotics, and data-driven systems. Machine vision has become a crucial component of agricultural automation, enabling machines to capture and analyze visual information for applications including crop monitoring, weed detection, disease identification, harvesting, and navigation. Various vision systems such as RGB, depth, multispectral, hyperspectral, thermal, and LiDAR are used based on specific needs. Despite limitations, machine vision improves accuracy, reduces labour dependence, and promotes sustainable farming practices.

Introduction

Agriculture is fundamental to human survival and the global economy, supplying food, fibre, and essential raw materials to populations around the world. As of 2023, agricultural land use includes vast areas of cropland and pasture, with cropland alone accounting for approximately 1.6 billion hectares dedicated to sowing and cultivation activities (FAO, 2024). To meet the increasing food requirements of a rapidly growing global population, cropland areas have expanded in many regions, accompanied by increases in both sown and harvested land. At the same time, modern agriculture is undergoing a significant transformation driven by technological advancements, mechanization, and data-based approaches such as precision farming, agricultural robotics, and digital decision-support tools. These innovations aim to enhance productivity, optimize resource use, and reduce negative environmental impacts.

Agricultural production involves numerous labour-intensive operations, including land preparation, planting, irrigation, crop monitoring, weed management, pest and disease control, and harvesting. Traditionally, these activities depend heavily on manual labour and visual assessment by farmers, which can be slow, inconsistent, and susceptible to human error. Accuracy in these operations is crucial,

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as even minor errors in timing or input application can lead to substantial reductions in yield and crop quality. As farm sizes continue to increase and productivity demands grow, conventional farming practices often struggle to meet modern requirements, emphasizing the need for automation and intelligent decision-making technologies. In recent years, machine vision has become an important enabling technology in advanced agricultural systems, particularly within agricultural robotics and precision farming applications. Machine vision enables machines to capture visual data through cameras and interpret it using image processing and artificial intelligence methods. In agricultural settings, these systems allow robots and automated equipment to visually recognize crops, weeds, soil conditions, and surrounding field environments in real time (Yadav *et al*., 2026). By replicating aspects of human visual perception, machine vision supports automated analysis, reliable object identification, and informed decision-making, all of which are essential for intelligent and efficient farm operations.

Need for Machine Vision in Agriculture:

Conventional agricultural practices rely largely on human observation for tasks such as crop inspection, disease identification, and harvesting decisions. These approaches are often time-consuming and subject to variability and error. Machine vision provides a more efficient alternative by delivering fast, accurate, and continuous visual assessment of crops and field conditions. This capability enables timely interventions, improves operational consistency, and supports the adoption of precision agriculture techniques.

Machine Vision Systems Applied in Modern Agriculture

Machine vision systems play a crucial role in modern agricultural automation by enabling accurate sensing, analysis, and decision-making. Different machine vision systems are used in agriculture to support monitoring, analysis, and automation across various farming operations. RGB vision systems rely on standard colour cameras and are widely used for crop monitoring, fruit detection, weed identification, and yield estimation.

Fig. 1: Machine Vision Based Workflow in Precision Agriculture

Depth and stereo vision systems provide three-dimensional information, allowing accurate measurement of plant height, volume, and spatial positioning, which is useful for navigation and harvesting tasks. Multispectral and hyperspectral vision systems capture information beyond visible light, enabling detailed assessment of plant health, stress, and disease conditions that are not detectable by the human eye, although hyperspectral systems are mainly limited to research due to high cost and

computational demands. Thermal vision systems detect temperature variations to identify water stress and irrigation issues, supporting efficient water management. LiDAR-based systems generate precise 3D field maps and assist in obstacle detection and canopy analysis. When integrated with artificial intelligence, these vision systems enable automated decision-making, thereby improving accuracy, adaptability, and efficiency in modern agricultural robotics (Yadav *et al*., 2025). Figure 1 illustrates the machine vision-based workflow in precision agriculture.

Applications of Machine Vision in Agricultural Robotics

Table 1: Vision-based Applications in Agriculture

Application Area	Role of Machine Vision	Key Benefits
Crop Monitoring and Growth Evaluation	Assesses plant growth, canopy condition, and crop uniformity in real time	Early stress detection and timely crop management
Weed Identification and Targeted Spraying	Identifies weeds and differentiates them from crops for targeted control	Reduced chemical use and operational costs
Detection of Diseases and Pests	Detects early symptoms of crop diseases and pest infestations	Lower yield losses and improved crop quality
Vision-Guided Harvesting	Locates produce, estimates maturity, and guides automated picking	Efficient harvesting with reduced labour requirement
Autonomous Navigation and Field Operations	Enables robots to detect rows, obstacles, and field boundaries for safe movement	Reliable autonomous operation with minimal supervision

Machine vision has become a core technology for agricultural robots and automated farm equipment, allowing them to carry out demanding agricultural tasks with greater accuracy and reliability. By analysing visual data in real time, these systems support decision-making throughout the entire crop production cycle, from early field operations to final harvesting. The key application areas of machine vision in agricultural robotics are illustrated in Fig. 2 and Table 1.

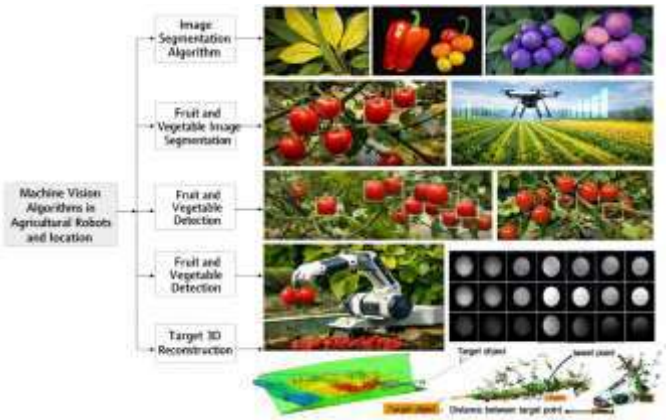

Fig. 2: Machine Vision System Architecture for Smart Farming Applications

Benefits of Machine Vision Systems in Agriculture

The adoption of machine vision technologies has significantly improved efficiency and productivity in agricultural operations. By enabling accurate visual analysis, these systems allow farmers and robotic platforms to perform field tasks more quickly and precisely. Machine vision reduces reliance on manual labour, which is particularly important in regions facing labour shortages. It also supports precise application of agricultural inputs such as fertilizers, pesticides, and irrigation water, minimizing waste and lowering production costs. Furthermore, vision-based monitoring helps reduce human error in tasks such as crop inspection, disease identification, and harvesting, leading to improved crop quality and yield consistency.

By promoting targeted interventions and reducing chemical overuse, machine vision contributes to environmentally sustainable farming practices (Raghavendra *et al*., 2025).

Challenges and Limitations of Machine Vision Systems

Despite its advantages, implementing machine vision in agriculture presents several challenges. Variations in lighting conditions, such as shadows and reflections, can reduce image quality and detection accuracy. Crop occlusion by leaves, soil, or branches further complicates visual analysis. High initial costs of cameras, sensors, and computing hardware limit adoption by small-scale farmers. In addition, machine vision systems require large, well-labelled datasets and significant computational resources, while environmental factors like dust, rain, and fog affect system reliability.

Future Scope and Conclusion

Future advancements in machine vision are expected to further strengthen its impact on agricultural robotics and precision farming. Improvements in artificial intelligence and deep learning will enhance detection accuracy and system reliability under varying field conditions. The availability of low-cost, energy-efficient sensors and edge computing solutions will promote wider adoption among small and medium-scale farmers. Integration with technologies such as the Internet of Things, GPS, and satellite systems will support more connected and intelligent farming operations. In conclusion, machine vision has become a key driver of automation and sustainability in agriculture, playing an important role in improving productivity and ensuring long-term food security.

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Navigating Sustainability and Resilience in the Indian Himalayas: Sustainability on the High Edge

Atul Chaudhary

The Indian Himalayas, encompassing states like Himachal Pradesh and Uttarakhand, represent a region of unparalleled natural beauty, rich biodiversity and profound cultural significance. Often referred to as the "Third Pole" and the "Water Tower of Asia," these majestic mountains are a critical source of freshwater for billions downstream, regulate regional climate, and harbour diverse ecosystems. However, this vital region is at a critical juncture, facing complex and escalating challenges that threaten its ecological integrity and the livelihoods of its inhabitants. Achieving sustainability and resilience in the Himalayan region is not merely an environmental ideal but a pressing necessity for the long-term well-being of both mountain communities and the broader subcontinent.

Fig. 1: The majestic Nanda Devi and Trisul peaks viewed from Auli, Uttarakhand sentinels of a rapidly changing ecosystem

The Fragile Balance: Compounding Challenges to Sustainability

Key Climate & Environmental Data: Himachal Pradesh & Uttarakhand

Indicator	Data / Figure	Source
Temperature rise (Himalayas vs. global)	1.5°C vs. 1.1°C above pre-industrial levels	ICIMOD / IPCC
Glacier retreat rate (Gangotri, Yamunotri)	>50 metres per year	GSI / MoEFCC
Himalayan glacier volume loss by 2100 (high emission)	70-80% of current volume	ICIMOD, 2023
Glacier volume loss limited at 1.5°C warming	~30% of current volume	ICIMOD, 2023
Forest cover lost (HP, 2001–2021)	4,820 hectares	Global Forest Watch
Waste generated (Dharamshala annually)	25 tonnes	HP State Govt.
Cloudburst incidents (HP, 2025 monsoon)	46 events; Mandi district worst-hit	HP Disaster Mgmt.
Landslides reported (HP, 2023)	>100 major landslides	HP Govt. Reports
Economic losses from disasters (HP, 4 years)	₹46,000 crore total	HP Finance Dept.
Economic losses (HP, 2025 monsoon alone)	₹4,000-4,800 crore; 448 lives lost	HP Disaster Authority
Rainfall/snowfall deficit (Uttarakhand, Dec 2025)	100% deficit highest in a decade	IMD / UK Govt.
Open dumpsites across IHR	228 sites identified	CPCB / IMI
Polluted river stretches in IHR states (2018)	66 stretches (BOD basis)	CPCB

Ecological Degradation Drivers

Population Pressure and Resource Extraction: A burgeoning human population places immense pressure on natural resources. Traditional practices such as subsistence agriculture, shifting cultivation, extensive livestock grazing, and the demand for

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fodder and fuelwood contribute significantly to deforestation and forest degradation, particularly in lower altitude areas. Overharvesting of non-timber forest products (NTFPs) and medicinal plants also inflicts severe damage, especially in alpine meadows.

Unplanned Infrastructure Development: Rapid, often unregulated, infrastructure development is a major contributor to environmental instability. The proliferation of hydropower projects in Himalayan River valleys has had severe negative impacts leading to extensive deforestation, habitat fragmentation and significant soil erosion. Construction activities, including blasting and tunnelling, exacerbate geological vulnerabilities, triggering landslides and drying up natural springs. The 2021 Chamoli disaster, where a glacial breach destroyed two hydroelectric projects and claimed over 200 lives, tragically underscored the risks of building in such fragile ecologies (NDMA, 2021).

Unsustainable Tourism: The Himalayas draw millions of visitors annually, but unchecked tourism growth has led to severe environmental consequences. Overcrowding and poor waste management result in massive quantities of plastic polluting pristine areas, trekking routes, and river systems like the Ganga.

IMI Spotlight: The Himalayan Cleanup (THC) - Waste Crisis Data: The Himalayan Cleanup, anchored by IMI and Zero Waste Himalaya since 2018, is the largest grassroots waste audit in the Indian Himalayan Region.

THC 2018-2022 (Cumulative)

- ✓ 200+ cleanup sites across all 12 IHR states
- ✓ 15,000+ volunteers mobilized
- ✓ 97% of trash collected was plastic (2018-2021 average)
- ✓ 228 open dumpsites recorded across the IHR

THC 2024 Key Findings

- ✓ 80% of waste linked to single-use food & beverage packaging
- ✓ 70% of collected plastics are non-recyclable with no market value
- ✓ Current national policies fail to address unique mountain ecosystem challenges

THC 2025 Key Findings

- ✓ 217,854 pieces of plastic waste collected 93% of total waste
- ✓ 47% of plastic waste non-recyclable; 53% recyclable but unprocessed
- ✓ Food packaging = 93% of all plastics audited
- ✓ 52% of food packaging is non-recyclable highlighting the limits of recycling alone

Declaration (Mountain Legislators' Meet 2021): Committed to the vision of a Zero Waste Himalaya and called for stringent policies against single-use plastics in the IHR.

Figure 2: Plastic waste audit during The Himalayan Cleanup (THC) campaign

Source: IMI Annual Report 2021-22; THC 2024 & 2025 Reports; UNEP-IMI Counter Measures II.

Climate Change Impacts: The Himalayan region is experiencing climate change impacts at an accelerated rate. Average temperatures in the Himalayas are rising faster than the global average at 1.5°C compared to 1.1°C globally since pre-industrial times (IPCC, 2022).

Glacier Retreat & GLOFs: Accelerated warming is causing glaciers like Gangotri and Yamunotri to retreat rapidly, exceeding 50 metres per year in some areas. This leads to altered seasonal river flows and an increased risk of Glacial Lake Outburst Floods (GLOFs). Under high-emission scenarios, ICIMOD projects that 70-80% of current Himalayan glacier volume could disappear by 2100 (ICIMOD, 2023).

Extreme Weather Events: Climate change has intensified monsoon patterns, leading to erratic and extreme rainfall. Uttarakhand witnessed the catastrophic 2013 Kedarnath floods and the 2021 Chamoli disaster. Himachal Pradesh recorded 46 cloudburst incidents during the 2025 monsoon season alone with Mandi district being particularly hard-hit. Over 100 major landslides were reported in HP in 2023 (HPSDMA, 2023-25).

Droughts and Dry Spells: Both states are experiencing prolonged dry spells and failed snowfall, impacting agriculture, horticulture, and leading to water scarcity. December 2025 saw a 100% deficit in rainfall and snowfall in Uttarakhand the highest in a decade (IMD, 2025).

Major Disaster Events - Timeline

Year	Event	Location	Impact
2013	Kedarnath Flash Floods / Cloudbursts	Uttarakhand	~6,000 lives lost; massive infrastructure damage
2021	Chamoli Glacial Breach (GLOF)	Uttarakhand	200+ lives lost; 2 hydro projects destroyed
2023	Monsoon Landslides	Himachal Pradesh	>100 major landslides; ₹10,000+ crore losses
2025	Monsoon - Cloudbursts & Floods	Himachal Pradesh	448 lives; ₹4,000-4,800 crore losses; 46 cloudbursts
Dec 2025	Drought / Zero Snowfall	Uttarakhand	100% rainfall/snowfall deficit - decade worst

Figure 3: Aftermath of the 2021 Chamoli glacial outburst flood a stark reminder of the risks of unplanned development in GLOF-prone zones.

Building Adaptive Capacity: Strategies and Innovations: Addressing the complex challenges in the Indian Himalayas requires a multi-pronged approach that integrates policy, technology, and community engagement. Both state governments and organisations such as the Integrated Mountain Initiative are implementing strategies to build adaptive capacity.

Policy and Governance

Himalayan-Specific Regulations: There is a critical need for legally binding Himalayan Mountain Codes that replace generic plains-based norms with slope-

sensitive, geology-aligned standards for land-use and construction. IMI has consistently advocated for a "mountain lens" in national policymaking recognising that policies designed for plains cannot be applied to fragile mountain ecosystems (IMI, 2021).

SDGs Integration: Both Himachal Pradesh and Uttarakhand are actively working towards the UN Sustainable Development Goals. Uttarakhand achieved the top rank in the NITI Aayog SDG India Index 2023-24 (NITI Aayog, 2024). Himachal Pradesh developed "Drishti Himachal Pradesh-2030," a vision document outlining a roadmap for sustainable growth in eco-tourism and renewable energy.

National Mission on Sustaining Himalayan Ecosystem (NMSHE Phase-II): This initiative aims to pivot from passive observation to active, evidence-based policymaking, aligning State Action Plans on Climate Change (SAPCC) with rigorous district-level vulnerability maps (Ministry of Science & Technology, 2023).

Technological Innovations

Early Warning Systems: Himachal Pradesh has installed Doppler radars in Shimla, Chamba, and Mandi to predict abnormal weather conditions, river flow, and snow melting. Early warning systems for GLOFs combining satellite-linked sensors, lake-level sensors and community-based alert dissemination have been operationalised in Sikkim and are being scaled across the wider Himalayan region (HP Deptt. of Revenue & Disaster Management, 2024).

Sustainable Waste Management Technology: The Digital Deposit Refund System (DDRS), piloted in Kedarnath, has prevented approximately 163,000 plastic bottles from entering the ecosystem since 2018 (Pragya, 2022).

Soil Bioengineering: Strategic planting of vegetation and organic materials to stabilise soil has proven effective in mitigating landslides, as demonstrated in Nog village, Himachal Pradesh. This nature-based approach reduces runoff and erosion while offering co-benefits such as carbon absorption and habitat creation (CSWCRTI, 2022).

Community-Led Initiatives

Community-Based Disaster Response: Training local Disaster Response Teams, mapping local hazards, and conducting evacuation drills are crucial. The Disaster Management System (DMS) Himalaya, developed by Pragya, empowers remote communities through customised disaster communications, pre-disaster early warning (Go-Risk), and post-disaster needs assessment (RnR-Comm).

Clean Energy and Indigenous Stewardship: Organisations like Global Himalayan Expedition (GHE) help remote communities build self-sustainable, low-carbon villages through decentralised DC solar grids and improved cookstoves, reducing reliance on firewood. Local communities act as "guardians" of the Himalayas possessing invaluable traditional knowledge and serving as first responders to environmental changes.

Springshed Management and Nature-Based Solutions: Scaling up springshed management is

crucial for ensuring sustainable water security. Springs are drying up across the IHR due to deforestation and groundwater depletion. IMI's work with state chapters identifies and supports community-led spring revival initiatives as a priority climate resilience strategy (IMI & ICIMOD, 2022).

Conclusion: A Blueprint for a Sustainable and Resilient Himalayan Future

The Indian Himalayas a region of immense ecological and socio-economic importance face an urgent imperative to reconcile development with environmental preservation. The compounding pressures of population growth, unplanned infrastructure, unsustainable tourism, and accelerating climate change demand a concerted and integrated approach to ensure sustainability and resilience across Himachal Pradesh and Uttarakhand. The path forward requires a fundamental shift in collective mindset from an extractive model to one that prioritises ecological well-being and community empowerment. This involves enforcing Himalayan-specific land-use policies, investing in resilience-led planning, and leveraging technological innovations for early warning and sustainable resource management. Crucially, it means recognising and strengthening the pivotal role of civil society organisations such as the Integrated Mountain Initiative (IMI), which has since 2011 built a pan-Himalayan platform for evidence-based dialogue, legislative advocacy, and grassroots action. IMI's Zero Waste Himalaya campaign, its annual Sustainable Mountain Development Summits, and its work with UNEP on plastic pollution in Himalayan rivers represent the kind of sustained, multi-stakeholder collaboration that the region urgently needs. As the Supreme Court has warned, unchecked ecological damage could lead to the disappearance of these vital mountain states. The choice before us is clear: to embrace a blueprint for a sustainable and resilient Himalayan future characterised by foresight, collaborative action and an unwavering commitment to balancing human prosperity with the health of our planet. In the Himalayas, sustainability is not merely an ideal; it is the last line of defence.

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Quality Seed Production

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Abstract

Quality seed production forms the backbone of modern agriculture by ensuring the availability of high- quality, genetically pure, and viable seeds to farmers. As agriculture shifts from subsistence to market-oriented farming, the demand for reliable seeds with superior yield potential, disease resistance, and adaptability has increased significantly. This article explores the concept of quality seed production, its importance, major steps involved, quality control measures, and challenges faced by the seed industry. Emphasis is placed on how scientific management, regulatory frameworks, and skilled human intervention work together to deliver seeds that ultimately determine crop performance and food security.

Introduction

Seeds are more than just planting material; they are the starting point of life in agriculture. Every successful harvest begins with a good seed, making seed quality one of the most critical factors influencing crop productivity. In traditional farming systems, farmers often saved seeds from their own fields. While this practice worked for generations, it could not meet the demands of modern agriculture, which requires uniformity, higher yields, resistance to pests and diseases, and adaptability to changing climates. Quality seed production emerged to address these needs. It is a specialized and carefully regulated process aimed at producing seeds of known genetic identity and high physiological quality on a large scale. Unlike grain production, seed production focuses not only on yield but also on maintaining genetic purity, germination capacity, and physical health of the seed.

This makes it a knowledge-intensive and management driven agricultural enterprise.

Concept and Scope of Quality Seed Production: Quality seed production refers to the organized multiplication of genetically pure seeds of improved varieties under controlled conditions, followed by processing, testing, certification, and marketing.

The scope of quality seed production includes:

- ✓ Production of breeder, foundation, certified, and hybrid seeds
- ✓ Maintenance of genetic purity and varietal identity
- ✓ Seed processing, storage, and packaging
- ✓ Quality assurance through testing and certification

Distribution through formal seed systems: It encompasses a wide range of crops, including cereals, pulses, oilseeds, vegetables, forage crops, and ornamentals.

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Importance of Quality Seed Production: The importance of Quality seed production cannot be overstated, as it directly influences agricultural productivity and food security.

Enhanced Crop Productivity: High-quality seeds ensure better germination, uniform crop stand, and vigorous plant growth, leading to higher yields.

Genetic Purity and Uniformity: Quality seed production maintains the genetic identity of varieties, which is especially crucial for hybrids and improved cultivars.

Adoption of Improved Technologies: New varieties developed through plant breeding reach farmers only through efficient seed production and distribution systems.

Economic Benefits: Seed enterprises generate employment and income for seed growers, processors, and marketers, contributing to rural development.

Risk Reduction for Farmers: The Certified seeds reduce uncertainty in crop performance, giving farmers greater confidence at the time of sowing.

Steps Involved in Quality Seed Production

Selection of Variety and Seed Source: The process begins with selecting a suitable variety and obtaining seeds from an authentic source. Breeder or foundation seeds are used to ensure genetic purity.

Selection of Suitable Area and Field: Seed crops require specific agro-climatic conditions. Fields should have fertile soil, good drainage, and a history free from volunteer plants or related crops that may cause contamination.

Isolation: Isolation is critical to prevent unwanted cross- pollination. Depending on the crop, isolation can be maintained by distance, time (staggered sowing), or physical barriers.

Isolation distance: 3 m

Land Preparation and Sowing: Proper land preparation ensures good seedbed conditions. Sowing is done at the recommended time, spacing, and seed rate to promote healthy crop growth.

Crop Management: This includes irrigation, nutrient management, weed control, and plant protection measures.

Special attention is given to maintaining plant health and uniformity. This includes irrigation, nutrient management, weed control, and plant protection measures.

Roguing: Roguing involves the removal of off-type, diseased, or undesirable plants at different growth stages. It is a critical operation to maintain genetic purity.

Harvesting and Post-Harvest Handling: Seed crops are harvested at physiological maturity. Care is taken to avoid mechanical damage, moisture absorption, or mixing with other seeds.

Seed Processing and Storage: Seeds are cleaned, graded, treated, and dried to safe moisture levels. Proper storage conditions are essential to maintain viability and vigor.

Quality Control and Certification: Quality assurance is a defining feature of quality seed

production. Seeds undergo laboratory testing for germination percentage, physical purity, moisture content, and seed health. Certification agencies monitor field operations and processing units to ensure compliance with established standards. Certified seeds are labeled and sealed, providing assurance to farmers regarding quality and authenticity.

Challenges in Quality Seed Production:

Despite its importance, seed production faces several challenges:

- ✓ Climatic uncertainties affecting seed yield and quality
- ✓ High costs of production and certification
- ✓ Risk of genetic contamination
- ✓ Storage and transportation losses
- ✓ Limited awareness among farmers in some regions
- ✓ Addressing these challenges requires continuous research, training, policy support, and adoption of modern technologies.

Conclusion

Quality production is a cornerstone of modern, sustainable agriculture. It transforms scientific innovations in plant breeding into practical solutions that reach farmers' fields in the form of high-quality seeds. By focusing on genetic purity, physiological quality, and rigorous management practices, quality seed production ensures reliable crop performance and contributes directly to food security and economic growth. As agriculture faces challenges such as climate change, population growth, and shrinking natural resources, the role of quality seed production becomes even more significant. Strengthening seed systems through innovation, skilled human involvement and supportive policies will not only benefit farmers but also safeguard the future of global agriculture. In essence, investing in quality seeds is an investment in the foundation of life and livelihoods.

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Structural Equation Modeling (SEM): An Analytical Tool

Komal Gambhir

Introduction

For assessment of association between variables in a study area, researchers have basically used statistical techniques such as multivariate regression analysis and analysis of variance. According to Haenlein and Kaplan (2004), the above methods have three major limitations viz; (1) they assume that all variables are measured with perfect accuracy; (2) all the variables should be directly observable; and (3) they are constrained by the assumption of a simple model structure i.e. the model is unbiased and efficient. Therefore, to overcome from the above limitations, Structural Equation Modeling (SEM) is used which is helpful for estimation of complex relationships and interaction between observed and latent (unobserved) variables. Unlike regression analysis, both direct and indirect effects can be measured using structural equation modeling (SEM). Hence, it is also known as causal modeling or covariance modeling. It has been widely used in behavioral science viz; psychology, social science, etc where we have to deal with complex relations among variables. SEM combines aspects of factor analysis, route analysis, and multiple regressions into a single framework for evaluating intricate theoretical models (Kline, 2016; Hoyle, 2012). It gives researchers the means to simultaneously assess proposed causal links, validate measurement validity, and model latent constructs. A number of popular models, including as multivariate regression, linear regression, path analysis, confirm-atory factor analysis, and structural regression, are regarded as special examples of SEM. Several kinds of correlations can be stated within SEM:

- ✓ Between variables that may be observed (like regression)
- ✓ Between observable and latent variables (e.g., confirmatory factor analysis)
- ✓ Between latent variables (structural regression, for example)

Assumptions of Structural Model Equation (SEM)

Structural equation model have same assumptions of regression models as the later models work together under SEM (Bayram, 2013). The following are the assumptions for SEM:

- ✓ The observations must be distributed normally.
- ✓ The latent variables should also follow normal distribution
- ✓ There should be linear relationships between latent variables and also between observed and latent variables.
- ✓ There should be no outliers in the observation
- ✓ Multiple measurements variables must be used to measure each latent variable.
- ✓ There must no relation between the independent

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variables in the structural equation model.

- ✓ A minimum sample size of 150 is recommended for structural equation models (Bentler and Chou, 1987).
- ✓ It is assumed that there is no correlation between error terms in the structural equation modeling method.

Components of SEM

Observed variables: Manifest variables that can be measured directly.

Latent variables: Unobserved variable that cannot be measured directly.

Measurement model: It depicts how observed or manifest variables or indicators represent the constructs. It uses confirmatory factor analysis approach.

Structural model: Indicates the degree of interdependence between the constructs and the correlations between latent and observable variables.

Path diagrams: It is a visual flowchart that depicts the direct and indirect relations among indicators and constructs.

Steps in SEM

Model specification: Model specification is the process of identifying correlations between variables based on theoretical basis and prior research. In order to specify a model, one must identify the constructs and the observable indicators that correspond to them, explain the structural relationship of the latent variable (construct), and make a path diagram to show the relationships.

Model Identification: In a structural-equation model, a parameter is considered identified if it can be calculated; if not, it is underidentified (or unidentified). If there are more known data points (observed variances and covariances) than unknown parameters that need to be estimated, the model is identified.

Model estimation: For model estimation, the value of the parameters is calculated. The most common estimation methods used are Maximum Likelihood method, generalized least squares method, weighted least squares method and partial least squares method.

Model Evaluation: To ascertain how effectively the chosen model captures the observed data, it is crucial to assess the model's fit. The fit indices include the chi-square test, the standardized root mean square residual (SRMR), the comparative fit index (CFI), and the root mean square error of approximation (RMSEA).To obtain a thorough evaluation of model fit, it is crucial to employ several fit indices.

Model Modification: Modifications might be required if the original model does not fit well. This can be done through adding or removing the pathways as per modification indices and theoretical reason. To prevent overfitting, model updates should be based on theory rather than just statistical criteria.

Software programs: Structural Equation Modeling (SEM) software enables researchers to analyze complex relationships between observed and latent variables, with popular choices including IBM SPSS Amos (graphical), Mplus (extensive features), SmartPLS (partial least squares), and R packages

like lavaan. These tools handle measurement models, confirmatory factor analysis (CFA), and structural regressions.

Advantages

- ✓ SEM allows for the analysis of complex relationships between multiple variables.
- ✓ SEM can be performed using various software packages, including SPSS and AMOS.
- ✓ SEM provides a clear and interpretable representation of the relationships between variables.

Limitations

- ✓ SEM assumes normality, linearity, and homoscedasticity of the data.
- ✓ SEM requires a large sample size to produce reliable results.
- ✓ SEM requires careful specification of the measurement and structural models to avoid model misspecification.

Conclusion

A potent statistical method for examining intricate interactions between variables, structural equation modeling has been applied extensively in many different domains. Researchers find it to be an appealing tool due to its adaptability, accessibility, and interpretability. To make certain reliable and precise outcomes, it is important to be aware of its limitations and to precisely define the measurement and structural models.

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Climate in Crisis: How Changing Weather Patterns are Reshaping Agriculture and Horticulture in Himachal Pradesh

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A Silent Transformation in the Himalayan Food Systems

Climate change is not merely a global phenomenon; it is a reality in the mountainous Himachal Pradesh. Instead of the reliable snowfall, gradual thawing of spring and predictable monsoons, farmers are now experiencing unpredictable weather, dwindling winters and unpredictable extreme events. Even small shifts in climatic conditions in this hill state where agriculture and horticulture are the major source of rural livelihoods have been magnified. Fields which used to have a consistent crop of wheat and maize are now vulnerable to irregular rain patterns and extended dry seasons. Meanwhile, the fruit economy that the state is known to have worldwide, particularly, apple growing, is experiencing a radical change. It is not only environmental change that is taking place, but structural change in the food production, maintenance and security in the Himalayan region.

Changing Climate Trends in Himachal Pradesh

Scientific observations and studies carried out on the region suggest evident climatic changes throughout the state:

- ✓ Increased average temperatures, especially in mid- and high-hill areas.
- ✓ Decreased snow and less winter chilling.
- ✓ Unpredictable monsoon cycles that have heavy downpours.
- ✓ More common droughts, landslides, and hail-storms. Of particular importance to such changes is in mountainous areas where agriculture is already limited by topography, depth of soils and availability of water. Agro-climatic equilibrium which supported the various types of cropping systems in the past is being strained.

Quantifying the Damage: From Global Trends to Local Reality

Research carried worldwide indicates that temperatures are lowering crop production, yet on the Himachal Pradesh, these effects are heightened by altitude sensitive ecosystems. Farmers claim that they are experiencing reduced yields of staple crops as well as rising unpredictability in the seasonal patterns. Observations in the region over a long period indicate:

- ✓ Unproductivity of the conventional crops such as wheat and maize.
- ✓ Increased crop failures due to untimely rains and dry spells

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- ✓ Weakening of agricultural profitability, particularly of smallholders. These patterns reflect the situation worldwide but are aggravated by the ecological susceptibility of the state.

Impact on Agricultural Crops: A System under Stress

In Himachal Pradesh, there is an increasing impact of increased temperatures and unpredictable rainfall on agricultural crops. Let us take the case of wheat, which is very sensitive to heat when forming the grain. An increase in temperature reduces the length of growth resulting in a decrease in grain size and yield. Likewise, maize is affected by moisture stress at critical stages of its growth, particularly in situations where the monsoon rains are late or inconsistent. The issue of water has risen to one of the most urgent problems. The conventional rain-fed agriculture systems can no longer be relied upon because the rainfall patterns have changed to be short and intense precipitation rather than constant rainfall. These rains are high in nature which means that they do not absorb but run off leading to erosion of soils and low supply of water to crops. Conversely, extended dry seasons leave fields dry, and farmers are forced to rely on scarce irrigation water. Another increasing issue is soil degradation. The heavy rainfall in hilly areas promotes landslides and soil erosion, which removes the fertile topsoil needed to support crop growth. In the long term, this decreases soil productivity and dependency on external inputs like fertilizers, which raises the cost of cultivation. The dynamics of pests and diseases are also evolving. Warmer climate is allowing pests to last longer and extend into high altitudes to places they have never been before. This has contributed to the rise in crop infestations, leading to farmers requiring more chemical inputs, which again affect the soil health and environment. Most importantly, the conventional cropping schedules are turning out to be untrustworthy. Previously, farmers used to stick to a fixed sowing and harvesting pattern, but today they face difficulties adapting to the changing seasons. Late monsoons, early summers, and sudden rainfalls turbulence the growth of crop which in most cases leads to low yields or total failure of the crop.

Impact on Horticulture: The Apple Economy at Risk

The economy of Himachal Pradesh is sustained by horticulture especially apple farming. Nevertheless, it is a very climate-dependent industry that is experiencing unprecedented difficulties today. Apples, pears, peaches, and plums are examples of temperate fruits which require sufficient chilling during winter so that they can flower and bear fruits. Warmer winters in recent years have had a great impact of cutting the chilling hours and particularly in low altitudes. It has led to abnormal flowering, low fruit set, and low yields. In most regions, the growing of apples is no longer profitable, so farmers are turning to other crops or relocating orchards to higher altitudes. Variations in temperature in the spring only exacerbate the situation. Early warming can also cause the flowering to be premature and the blossom is damaged by late frost. Even a single frost event can

destroy an entire season's crop. Also, the fluctuation in temperatures impacts pollination, resulting in poor quality of fruits that are unable to meet market standards. Increasing temperatures in the process of fruit development are also affecting quality. Poor color development, less firmness and less sugar are becoming more evident in Apples. These reforms have a direct impact on market value in that consumers and export markets require produce of high quality. Alterations in rain patterns are additional stressors. The surplus rainfall during the harvesting period causes the fruits to crack, develop fungal infections and when there is a drought, the fruits turn out to be small and less juicy. The humidity encourages diseases such as the apple scab and makes the use of pesticides more important and makes production more expensive. One of the most obvious and noticeable changes is the relocation of apple growing to a higher altitude. Previously productive areas previously used in the production of apples have become less productive and regions that are colder and at the higher altitudes are becoming new areas of cultivation. Nonetheless, this is a gradual process which is costly and not possible to all farmers.

Global Inequality Reflected in Local Realities

Climate change is a global phenomenon that is, however, not equally distributed. In states such as Himachal Pradesh small and marginal farmers are the worst hit. Having little technological access, irrigation, and financial resources, they are not better placed to deal with changing circumstances. Farmers are becoming economically vulnerable due to declining yields, higher input costs and higher risks. This does not only have an impact on livelihoods, but also poses a threat to the socio-economic stability of rural communities.

Food Security at Risk in Mountain Regions

The cumulative effect of the falling agricultural productivity and the quality of horticulture is a significant risk to food security. Less local production will lead to reliance on foreign markets, which will expose food systems to fluctuations in prices and supply shocks. These alterations have extensive consequences in nutrition, income, and well-being in a state where a big part of people are reliant on agriculture.

Adaptation: The Path Forward

Farmers in Himachal Pradesh are already adapting in many different ways: changing the type of crops, moving to water-conserving methods, and diversify into less climate-sensitive crops. There is some hope with the introduction of low-chill apple varieties, better irrigation systems, and farming practices that are resistant to climatic change. Nevertheless, adaptation might not be enough. There is an increasing demand of: Strong policy support - Research and extension services, Climate-resilient infrastructure and Community-based resource management

Conclusion: A Critical Moment for the Himalayas

Himachal Pradesh is redefining agriculture and horticulture due to changing climate. What used

to be a predictable and stable system has now become filled with uncertainty and risk. The effects can be seen in the falling agricultural product output, changing orchard areas and poor quality of produce. It is not merely an environmental issue but a matter of life, food security, and sustainability of the region. The solution to this crisis lies in the response of farmers, scientists and policymakers to save agriculture in the Himalayas. The change has begun. It is now a matter of time to be smart and take decisive action in order to save the already vulnerable agricultural infrastructure in this mountainous country before changes become irreversible.

Gender Dimensions of Agroforestry: Recognizing Women's Contributions to Sustainable Land Use

R. K. Meena, Tulika Kumari and Rashmi Sinha

Abstract

Agroforestry is the integration of trees, crops, and livestock for sustainable land-use which enhances biodiversity, soil health, and rural livelihoods. Women play a vital role in this system but their role is unrecognized. They act as custodians of traditional knowledge, selecting and managing multipurpose tree species and preserving biodiversity. They are engaged in nursery management, planting, protection, and monitoring of trees, contributing to successful agroforestry practices. Women also enhance food security by collecting, processing, and utilizing diverse forest products, improving household nutrition. Additionally, they generate income through the sale of agroforestry products, supporting economic empowerment. Despite these contributions, women face challenges such as limited land rights, restricted access to resources and training, time constraints, and social barriers. Strengthening land rights, improving access to credit and education, and promoting gender-inclusive policies are essential for women recognition. Recognizing their contributions is crucial for sustainable development and climate resilience.

Introduction

Agroforestry is a traditional land use system that integrates trees, crops, and livestock on the same land and contributes to the solution of environmental problems in agriculture (Pantera *et al.*, 2021). Agroforestry presents significant economic opportunities for women as they are often involved in the collection and processing of non-timber forest products such as fruits, herbs, and medicinal plants (Mandal *et al.*, 2025). Women play multidimensional role in agriculture and allied sectors and comprise around 43 per cent of agricultural labour force of developing countries. The female share ranges from about 20 per cent in Latin America to 50 per cent in Eastern and Southeastern Asia and sub-Saharan Africa (FAO, 2011). Despite of their indispensable contribution, they face discrimination and remain as disadvantaged and vulnerable group of the society. Despite progress in gender equality initiatives, women in many developing countries continue to face structural barriers such as limited education, lack of employment opportunities, restricted mobility and unequal access to resources (Fatima and Athar, 2025). The determinants such as economic condition, income levels, education, social relations, gender equality, power of decision-making, access to media, government assistance/development initiatives, cultural norms and beliefs, geographical aspects and women's participation are influencing women's status. All the identified determinants are crucial and

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significant in determining women's empowerment (Kaur, 2024). Recognizing women's contributions in agroforestry is not only a matter of gender equality but also a key factor in achieving sustainable development. Women's involvement leads to improved resource management, increased agricultural productivity, enhanced household well-being and greater resilience to climate change. Ignoring their role can result in ineffective policies and missed opportunities for sustainable growth. Therefore understanding the role of women in agroforestry is essential for designing inclusive and effective sustainable development strategies.

Role of women in management of agroforestry system

Women are often the primary holders of indigenous knowledge related to plants, trees, and ecosystems (Kurtkoti and Joshi, 2024). This knowledge includes understanding which tree species are suitable for specific soils, climates, and purposes such as food, medicine, fuel, or fodder. In agroforestry systems, women use this knowledge to select and manage multipurpose trees that complement agricultural crops. Women are usually responsible for identifying medicinal plants and herbs within agroforestry landscapes (Howard, 2003). They know the seasonal cycles, growth patterns, and uses of various species. This knowledge is passed on from generations to generations, making women key agents in preserving biodiversity and promoting sustainable land use. Women are actively involved in various stages of tree cultivation in agroforestry systems. Their responsibilities include:

Nursery management: Women often raise seedlings, ensuring proper care and selection of species.

Planting and watering: They contribute significantly to planting trees and maintaining them during early growth stages.

Pruning and protection: Women help in protecting young plants from grazing animals and ensure their healthy growth.

Their continuous interaction with the land allows them to monitor changes in plant health and environmental conditions. This involvement ensures the success of agroforestry practices at the grassroots level. Besides, they are typically responsible for feeding, watering, and caring for animals and agroforestry supports livestock rearing. Trees provide fodder, shade, and shelter for livestock, and women manage these resources efficiently. They collect leaves and grasses from agroforestry systems to feed animals, ensuring productivity and health. This integration enhances the overall efficiency of farming systems and supports diversified livelihoods.

Contribution of women towards food and income security

Agroforestry systems provide a diverse range of food products such as fruits, nuts, leaves, and roots. Women play a central role in managing and utilizing these resources to ensure household nutrition. They collect fruits, edible leaves, and other forest-based foods that supplement diets, particularly during periods of food scarcity (Mandal *et al.*, 2025).

Women also process and store these products, ensuring year-round availability. By integrating trees with crops women provide and enhance dietary diversity as they are at the forefront of this process. In many rural households, women are responsible for meal preparation, making them directly connected to food choices and nutritional outcomes. Their involvement in agroforestry helps improve family health and resilience against food insecurity. Agroforestry also provides opportunities for women to generate income through the sale of forest and farm products like fruits, firewood, medicinal plants, honey and other non-timber forest products. Women often participate in local markets, selling surplus produce and contributing to household income. In some cases, they form self-help groups or cooperatives to collectively market agroforestry products, increasing their bargaining power and financial independence. Economic empowerment through agroforestry enables women to invest in education, healthcare, and improved farming practices. It also enhances their decision-making power within households and communities.

Women in environmental conservation

Women's involvement in agroforestry contributes significantly to environmental sustainability. They play a key role in:

Soil conservation: By promoting tree planting, women help in reducing soil erosion and improve soil fertility.

Water management: Trees planted and maintained by women help in retaining soil moisture and regulating water cycles.

Biodiversity conservation: Women often cultivate a variety of plant species, maintaining ecological balance. Their daily interaction with natural resources fosters a sense of responsibility toward environmental conservation. Women's practices in agroforestry are often aligned with sustainable and eco-friendly principles.

Challenges faced by women in agroforestry

Despite their significant contributions, women face several challenges that limit their full participation and benefits from agroforestry:

Limited Access to Land: In many regions, women do not have ownership rights to land. This restricts their ability to make decisions about tree planting and land management. Without secure land tenure, women may lack incentives to invest in long-term agroforestry practices (Torquebiau, 2024).

Lack of Access to Resources and Training: Women often have limited access to agricultural extension services, credit and financial support and access to improved seeds and technologies (Barooah *et al.*, 2023). This lack of access hinders their ability to adopt advanced agroforestry techniques and improve productivity.

Time Constraints: Women bear the burden of multiple responsibilities, including household chores, childcare and farming activities. This workload limits the time they can dedicate to agroforestry practices or participate in training programs.

Social and Cultural Barriers: In some societies, cultural norms restrict women's participation in

decision-making processes. Their contributions may be undervalued, and they may have limited voice in community-level planning and resource management (Kaur, 2024).

Strategies to enhance women's role in agroforestry

To fully realize the potential of women in agroforestry, several strategies can be implemented:

Strengthening Land Rights: Ensuring legal access of women to land can encourage long-term investments in agroforestry practices.

Capacity Building and Training: Providing women with training on modern agroforestry techniques, nursery management, and marketing can enhance their skills and productivity.

Access to Credit and Markets: Facilitating access to financial services and market opportunities can help women expand their agroforestry enterprises and increase income.

Promoting Gender-Inclusive Policies: Governments and organizations should design policies that recognize and support women's roles in agroforestry. This includes involving women in decision-making processes and ensuring equal opportunities.

Supporting Women's Groups and Cooperatives: Encouraging the formation of self-help groups and cooperatives can strengthen women's collective power and improve access to resources and markets.

Conclusion

Women play a multifaceted and indispensable role in agroforestry practices. From managing tree cultivation and preserving traditional knowledge to ensuring food security and contributing to income generation, their contributions are central to the success of agroforestry systems. Despite facing numerous challenges, women continue to demonstrate resilience and innovation in managing natural resources. Empowering women through access to land, resources, education, and decision-making opportunities can significantly enhance the effectiveness of agroforestry practices. As the world moves toward sustainable and climate-resilient agriculture, recognizing and strengthening the role of women in agroforestry is essential. Their knowledge, skills, and dedication make them vital agents of change in building a more sustainable future.

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Digital Marketing Platforms Transforming the Agriculture Sector

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Abstract

Digital marketing platforms are transforming agriculture by reducing market fragmentation and improving access to information and buyers. Platforms like eNAM and AgriBazaar enable better price discovery and direct farmer-buyer linkages. Social media, agritech advisory services, and online input marketplaces further support decision-making and productivity. Government initiatives have accelerated digital adoption in the sector. Despite challenges such as digital illiteracy and infrastructure gaps, these platforms enhance efficiency, transparency, and farmer income, contributing to a more resilient agricultural system.

Introduction

Agriculture has traditionally been characterized by fragmented markets, information asymmetry, and dependence on intermediaries (Birthal *et al.*, 2017; Chand, 2016). Farmers often faced challenges in accessing reliable market information, fair prices, and wider consumer bases. With the rapid advancement of digital technologies, the agricultural sector is now experiencing a significant transformation (Aker, 2016; Mittal & Mehar, 2016). Digital marketing platforms are emerging as powerful tools that bridge the gap between farmers and markets, enabling direct communication, efficient transactions, and improved decision-making (Aker, 2016). In India, the push towards digital agriculture has been supported by increasing smartphone penetration, internet connectivity, and government initiatives (Gulati *et al.*, 2020). Platforms such as eNAM and AgriBazaar are redefining how agricultural produce is marketed and traded (Reddy, 2018). These innovations are not only enhancing market efficiency but also empowering farmers by giving them greater control over pricing and sales (Birthal *et al.*, 2017).

E-commerce and Agri Marketplaces: E-commerce platforms dedicated to agriculture have revolutionized the way farmers sell their produce (Trebbin, 2017). Traditional mandi systems often limited farmers to local buyers, restricting competition and price discovery (Chand, 2016). Digital marketplaces now enable farmers to access a broader range of buyers across regions and even internationally (Birthal *et al.*, 2017). Platforms like eNAM integrate multiple agricultural markets into a unified national platform, allowing transparent price discovery and online bidding (Government of India, 2021). Similarly, AgriBazaar connects farmers directly with processors, exporters, and bulk buyers, reducing the role of intermediaries (Reddy, 2018). These platforms offer several benefits, including real-time

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price information, reduced transaction costs, and improved logistics support (Aker, 2016). They also promote standardization and grading of produce, which enhances quality and market competitiveness (Birthal *et al.*, 2017). As a result, farmers are better positioned to negotiate prices and maximize their income (Gulati *et al.*, 2020).

Social Media as a Marketing Tool: Social media has become an important digital marketing channel in the agriculture sector (Kumar and Sharma, 2020). Platforms such as Facebook, YouTube, and WhatsApp are increasingly being used by farmers, agri-entrepreneurs and farmer-producer organizations (FPOs) to promote agricultural products and services. Through these platforms, farmers can directly connect with consumers, share product details, and build trust through transparency (Mittal and Mehar, 2016). For example, videos showcasing organic farming practices or harvesting processes help consumers understand the quality and authenticity of products. WhatsApp groups are widely used for bulk selling, order management, and communication with buyers (Kumar and Sharma, 2020). Social media also facilitates knowledge sharing among farmers, enabling them to learn from each other's experiences (Aker, 2016). This peer-to-peer interaction strengthens community networks and promotes innovation in farming practices.

Agritech Advisory and Information Platforms: Access to timely and accurate information is crucial for effective agricultural marketing (Mittal & Mehar, 2016). Agritech platforms such as Kisan Suvidha and IFFCO Kisan play a vital role in providing farmers with essential data on weather conditions, market prices, pest management, and best agricultural practices (Government of India, 2020). These platforms help farmers make informed decisions regarding crop selection, harvesting time, and market entry (Aker, 2016). By integrating advisory services with market information, they enhance the overall efficiency of agricultural operations (Mittal and Mehar, 2016). Moreover, personalized recommendations based on location and crop type further improve productivity and profitability. The availability of such digital advisory services reduces dependence on traditional extension systems and ensures that farmers receive real-time support (Aker, 2016).

Online Input Marketplaces: Digital platforms are also transforming the way farmers access agricultural inputs (Gulati *et al.*, 2020). Online marketplaces like BigHaat and AgroStar allow farmers to purchase seeds, fertilizers, pesticides, and equipment from the comfort of their homes. These platforms offer a wide range of products, competitive pricing, and doorstep delivery, making input procurement more convenient and efficient (Trebbin, 2017). They also provide detailed product information, usage guidelines, and expert advice, helping

farmers choose the right inputs for their crops (Mittal and Mehar, 2016). By reducing the dependence on local dealers and ensuring access to quality inputs, these marketplaces contribute to improved crop yields and better farm management (Birthal *et al.*, 2017).

Role of Government and Institutional Support

The Ministry of Agriculture & Farmers Welfare has played a crucial role in promoting digital marketing platforms in agriculture (Government of India, 2021). Government initiatives focus on improving digital infrastructure, enhancing farmer awareness, and integrating various services through centralized platforms (Chand, 2016). Programs aimed at digitizing agricultural markets, providing financial support, and encouraging public-private partnerships have accelerated the adoption of digital technologies (Gulati *et al.*, 2020). Institutional support from research organizations, extension services, and cooperatives further strengthens the digital ecosystem (Aker, 2016). Such efforts ensure that even small and marginal farmers can benefit from digital marketing platforms, thereby promoting inclusive growth in the agricultural sector.

Benefits of Digital Marketing Platforms

- ✓ Improves market access by connecting farmers with a larger pool of buyers at domestic and global levels.
- ✓ Enhances price discovery, ensuring fair compensation for agricultural produce.
- ✓ Reduces the role of intermediaries, leading to lower transaction costs and higher profit margins.
- ✓ Provides real-time information and advisory services, enabling better decision-making.
- ✓ Ensures transparency and timely transactions through digital payment systems.
- ✓ Promotes direct farmer-consumer linkages, building trust and improving market relationships.
- ✓ Improves product traceability, especially for organic and high-value agricultural products.

Challenges and Limitations

Despite their potential, digital marketing platforms face several challenges in the agriculture sector.

- ✓ Limited digital literacy among farmers, especially in rural areas, restricts the effective use of these platforms.
- ✓ Inadequate internet connectivity and infrastructure further hinder adoption.
- ✓ Trust issues, lack of awareness, and resistance to change also pose significant barriers. Additionally, logistical challenges such as transportation, storage, and quality assurance need to be addressed to ensure smooth operations.
- ✓ Policy and regulatory frameworks must evolve to support digital transactions, protect farmers'

interests, and ensure fair competition among platforms.

Future Prospects

The future of digital marketing in agriculture is promising, with advancements in technologies such as artificial intelligence, blockchain, and data analytics. These innovations have the potential to further enhance transparency, efficiency, and traceability in agricultural markets. Increasing investment in agritech startups and growing collaboration between public and private sectors are expected to drive innovation and expansion. As digital literacy improves and infrastructure develops, more farmers will be able to leverage these platforms for better market outcomes.

Conclusion

Digital marketing platforms are transforming the agriculture sector by bridging the gap between farmers and markets. They enhance market access, improve price realization, and empower farmers with information and technology. While challenges remain, continued efforts in infrastructure development, awareness creation, and policy support can unlock the full potential of these platforms. As agriculture moves towards a more digital and connected future, these platforms will play a critical role in ensuring sustainable growth, increased farmer income, and a resilient agricultural system.

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Nature's pH Guardian: Understanding Soil Buffering Capacity and Why Soil Resists pH Change

Sayambhu Biswaprakash Biswal

Introduction

When you pour a large bucket of vinegar on your farm, you may not have realized it until now, but your crops may not even notice any difference at all! How can that be? The answer is the soil's buffering capacity one of the most important concepts in soil science! The buffering capacity of soil is what allows the soil to buffer or "absorb" the effects of a sudden increase or decrease in either acidity or alkalinity, and keep the chemical equilibrium of the soil at the correct levels for the microorganisms, plants, and entire soil ecosystem. In general, the soil pH has a huge impact on crop production, microbial activity, and the availability of nutrients to crops. A pH unit change is equal to ten times change in the amount of acid in the soil. However, most soils have the ability to absorb both alkaline and acidic products in huge quantities, resulting in only minor to moderate pH changes. Learning about the buffering capacity of soil has very important, practical applications for everyone involved in agriculture, agronomy, or environmental management. The applications of this knowledge include predicting how soils will respond to pollution and/or excessive fertilizer use, as well as helping farmers determine how much lime to apply to acidic soils to improve their soils.

What is Soil Buffering Capacity?

Soils have buffering capabilities so they are able to resist changes in pH (acidity) when strong acids and bases (alkalinity) come into contact with them. Soils can be complicated and consist of multiple components. Cation Exchange Capacity (CEC) refers to the ability of clay particles and organic matter in a soil to adsorb and hold positively charged ions (cations) including: hydrogen, calcium, magnesium and potassium. The negatively charged surfaces of these two components provide exchange sites where hydrogen ions will be retained upon application of an acid to a soil so that the pH of the soil will not drop instantly.

Carbonate and Mineral Weathering Buffers refer to the process whereby acidity applied to calcareous soils (soils that contain high amounts of calcium carbonate) results in the dissolution of limestone particles to produce calcium and bicarbonate ions that can neutralize the acidity. Organic Matter as Buffer means that because soil organic matter contains many carboxyl and hydroxyl functional groups, it can donate or pick up protons depending upon the conditions of the particular soil. Thus, soils with a high percentage of humus will generally exhibit greater buffer capacity than similar soils having low amounts of humus, over a wider

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range of pH values.

Benefits in Agriculture

Well-buffered soil naturally maintains the optimum pH range of 6.0 to 7.5, where most essential plant nutrients are most readily available. By keeping nutrients from being immobile in insoluble form, well-buffered soil allows them to be readily accessible to plants. In poorly buffered soils, a single large rainfall event or heavy fertilizer application can result in extremely high pH levels that can make nutrients temporarily or permanently unavailable to plants. In addition to preventing large swings in pH, well-buffered soils also protect against the gradual increase in acidity caused by fertilizers that contain ammonium, acid rain, and the breakdown of organic matter. These three factors are responsible for significant worldwide soil degradation. Soils with high organic matter and clay content require much greater acid loads to achieve the same level of acidification than do sandy soils with little organic matter. After repeated applications of fertilizer to strongly buffered soils, very little pH movement will occur making these soils easier for farmers to manage with more stable soil characteristics without the need for continual pH correction.

The Effect on Crop Growth and Yield: Long-term studies have proven that liming acidic soils and maintaining pH levels between 6.0-7.0 significantly increases wheat grain yields by 15%-30% on average, primarily due to increased phosphate availability. Soils with good buffering capacity also help keep the pH level above 5.8, which provides legumes (e.g., soybeans, peanuts, and chickpeas) with an increased nodulation and biological nitrogen fixation rate, thus reducing reliance on synthetic nitrogen applications. Additionally, soils' natural buffering capacity helps regulate typical pH fluctuations induced by flooding (e.g., rice production) through self-buffering. Therefore, managing buffering capacity is essential for horticultural crops with narrow pH ranges (e.g., brassicas) to ensure optimum production through pH management.

Environmental Benefits: In addition to providing essential environmental benefits, soil buffering capacity has numerous ecological advantages. As the pH level declines, heavy metals (e.g., zinc, lead, cadmium) may become more soluble, and therefore more mobile, because they bind less strongly to particles in the soil. Well-buffered soils can delay or prevent further acidification, so the heavy metals are bound in a less mobile form and have a lower chance of being transported into groundwater or food chains. With regard to carbon sequestration, a neutral pH level of well-buffered soils creates a conducive environment for a high degree of microbial activity and diversity, both of which favour the continuous building of organic matter (humus) in the soil. The residual effects of acid rain damage in Sweden and the Northeast U.S.A. is a clear example of how the buffering capacity of catchment soils within watersheds influences the amount of acid deposition the watershed can retain prior to acidification of the streams and/or lakes that are present in the watershed.

Limitations: The amount of buffering produced cannot be continually produced. In addition, soils with a good buffer will eventually reach their maximum buffering capacity and that soil will become acidified due to excessive acid loading or depletion of organic matter. Measuring buffering capacity accurately can be challenging because useful tests for buffer pH have not yet been made widely available in developing countries. Also, pH of routine water tests does not measure all aspects of the soil's ability to buffer. Decreases in the ability of the soil to buffer as a result of soil degradation also are going on. Examples include: soil erosion; loss of organic matter and waterlogging. Research indicates that, over the past 50 years of farming, the amount of SOM has been reduced by 40-60% in many heavily cultivated regions of South Asia, sub-Saharan Africa, and Latin America; this loss of SOM clearly has weakened the natural ability to buffer of many soils.

Conclusion

Soil buffering capacity is one of nature's most amazing ways of reacting to instability in terms of chemistry; a built-in resilience system to protect the fragile but critical chemical make-up of the soil environment. This provides farmers with the information to make better decisions regarding rates for fertilizers and lime. This means accurately determining any issues with pH in their soil without unnecessarily over-using agronomic products. To environmentalists, it means that they should appreciate and recognize how soils can be utilized as a proactive defence against pollution and acidification. Due to the ever-increasing pressures of extreme weather conditions/climate changes and intensive farming practices on soils, preserving and re-establishing the soil's natural buffering capacity must be a high priority. The value of soil buffering capacity as an indicator of the resilience of the soils upon which all sustainable agriculture relies (not only as a chemical characteristic) is the very foundation of soil buffering capacity.

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Artificial Intelligence in Agriculture: Transforming Modern Farming

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Introduction

Agriculture is the backbone of many economies, especially in countries like India, where a large population depends on farming for livelihood. However, modern agriculture faces several challenges such as climate change, declining soil fertility, water scarcity, and increasing pest and disease pressure. Traditional farming practices alone are often insufficient to tackle these issues efficiently. In recent years, Artificial Intelligence (AI) has emerged as a transformative technology in agriculture. AI refers to computer systems that can analyze data, learn patterns, and make intelligent decisions. In farming, AI helps in improving productivity, reducing costs and ensuring sustainable use of resources. From crop monitoring to yield prediction and disease detection, AI is reshaping the way agriculture is practiced today.

Role of AI in Modern Farming

AI plays a crucial role in modern farming by providing data-driven solutions. It helps farmers and researchers make informed decisions based on real-time data. AI systems can analyze weather patterns, soil conditions, and crop health, enabling better farm management. For example, AI-based tools can predict rainfall patterns and suggest optimal sowing time. Similarly, AI can analyze soil data to recommend appropriate fertilizers, improving nutrient management. These applications help in increasing crop productivity while minimizing resource wastage.

Applications of AI in Agriculture

Table 1: Major Applications of AI in Agriculture and their Benefits

Application	AI Function	Benefit to Farmers
Precision Farming	Data analysis & monitoring	Reduced input cost
Disease Detection	Image recognition	Early control of diseases
Yield Prediction	Predictive modeling	Better planning and income stability
Smart Irrigation	Sensor-based decisions	Water conservation
Crop Monitoring	Remote sensing	Improved crop health management

Precision Farming: AI enables precision farming by using sensors, drones, and satellite data to monitor crop conditions. Farmers can apply water, fertilizers, and pesticides only where needed, reducing input costs and environmental impact.

Crop Disease Detection: AI-powered image recognition tools can detect plant diseases at early stages. This allows timely intervention and reduces yield losses.

Yield Prediction: AI models analyze historical data, weather conditions, and crop performance to predict

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yield accurately. This helps farmers plan better and manage risks.

Smart Irrigation: AI systems optimize water usage by analyzing soil moisture and weather data, ensuring efficient irrigation and conservation of water resources.

Advantages of AI in Agriculture

AI offers several advantages that make it highly valuable for modern farming. It improves efficiency by automating tasks and reducing manual labor. It enhances decision-making by providing accurate and timely information. AI also helps in reducing the use of chemicals, thereby promoting environmentally sustainable agriculture. Another important benefit is risk reduction. By predicting weather conditions and crop performance, AI helps farmers prepare for uncertainties and minimize losses.

Figure 1: Illustration showing the use of AI technologies such as sensors, drones, and data analytics in modern farming.

Challenges in Adoption of AI

Despite its benefits, the adoption of AI in agriculture faces certain challenges. These include high initial costs, lack of technical knowledge among farmers, and limited access to digital infrastructure in rural areas. Additionally, the availability of quality data is essential for AI systems to function effectively. To overcome these challenges, there is a need for awareness programs, training and government support to make AI technologies accessible to farmers.

Conclusion

Artificial Intelligence is transforming agriculture by making farming more efficient, precise, and sustainable. It helps in improving crop productivity, reducing input costs, and managing resources effectively. Although challenges such as cost and accessibility exist, increasing awareness and technological advancements are expected to promote wider adoption. In the future, AI will play a key role in ensuring food security and sustainable agricultural development.

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Indigenous Traditional Knowledge: A Sustainable Pathway for Climate Change Mitigation and Socio-Economic Resilience

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Introduction

Climate change represents one of the most significant global challenges of the 21st century, exerting profound impacts on agriculture, water resources, biodiversity, and rural livelihoods. While modern scientific advancements have contributed substantially to climate mitigation strategies, increasing attention is being directed toward Indigenous Traditional Knowledge (ITK) as a complementary and context-specific approach. ITK, developed over generations through continuous interaction with local ecosystems, embodies a repository of sustainable practices that can contribute meaningfully to climate change adaptation and mitigation.

Concept and Significance of Indigenous Traditional Knowledge

Indigenous Traditional Knowledge refers to the cumulative body of knowledge, practices, and belief systems developed by indigenous and local communities over time. It is deeply rooted in ecological understanding and is transmitted across generations through oral traditions and experiential learning. Unlike conventional scientific approaches that often rely on external inputs and standardized models, ITK is location-specific, adaptive, and closely aligned with natural processes.

The significance of ITK lies in its holistic approach to resource management, encompassing environmental sustainability, socio-economic stability and cultural preservation. In the context of climate change, ITK provides locally relevant solutions that enhance resilience and reduce vulnerability among rural communities.

Role of ITK in Climate Change Mitigation

ITK contributes to climate change mitigation through a range of sustainable practices, particularly in agriculture, water management, and biodiversity conservation.

Sustainable Agriculture and Food Security: Agricultural systems based on ITK emphasize diversity, resilience and ecological balance. Practices such as crop rotation, intercropping, and agroforestry contribute to soil fertility enhancement, pest regulation, and efficient resource utilization. These methods reduce reliance on synthetic inputs, thereby lowering greenhouse gas emissions associated with chemical fertilizers and pesticides. Traditional seed conservation practices further strengthen resilience by preserving locally adapted and climate-resilient crop varieties. These varieties often exhibit tolerance to drought, pests and diseases, ensuring food security under changing climatic conditions. Agroforestry systems, which integrate trees with crops, provide

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multiple benefits including carbon sequestration, improved soil structure, and diversified income sources.

Water Resource Management: Water management is another critical domain where ITK demonstrates significant relevance. Indigenous communities have historically developed efficient water conservation techniques such as rainwater harvesting, traditional irrigation systems, and watershed management practices. These systems are designed to optimize water use, reduce wastage, and ensure equitable distribution. Such practices are particularly valuable in regions experiencing water scarcity and erratic rainfall patterns due to climate change. By relying on locally available materials and community participation, these methods offer cost-effective and sustainable solutions for water security.

Socio-Economic Dimensions of ITK

The socio-economic implications of ITK are substantial, as it supports sustainable livelihoods, enhances economic resilience, and fosters community well-being.

Sustainable Livelihoods and Economic Diversification: ITK enables communities to diversify their income sources through integrated farming systems, forestry, and fisheries. Agroforestry, for instance, provides food, timber, and non-timber forest products such as medicinal plants and resins. This diversification reduces dependency on a single source of income and enhances resilience to climate-induced shocks. Moreover, the sustainable harvesting of natural resources ensures long-term economic stability while conserving ecosystems. Such practices align with the principles of circular economy and resource efficiency.

Cost-Effectiveness and Resource Efficiency: A notable advantage of ITK is its cost-effectiveness. Traditional practices rely primarily on locally available resources, reducing the need for external inputs. Techniques such as organic composting, mulching, and biological pest control minimize production costs while maintaining environmental integrity. This low-input approach is particularly beneficial for smallholder farmers, enabling them to sustain agricultural productivity without incurring significant financial burdens.

Social and Cultural Dimensions

ITK plays a vital role in strengthening social cohesion, preserving cultural identity and facilitating knowledge transfer.

Community Cohesion and Collective Action: Many ITK practices are community-based, involving collective management of resources such as land, water, and forests. These collaborative efforts foster social cohesion, trust, and mutual support, which are essential for effective climate adaptation.

Cultural Identity and Knowledge Transmission: ITK is intrinsically linked to cultural traditions, including rituals, festivals and conservation practices such as sacred groves. These cultural elements reinforce environmental stewardship and promote sustainable behavior. Intergenerational knowledge transfer is a key feature of ITK, ensuring continuity and adaptation over time. Elders play a crucial role

in imparting ecological knowledge to younger generations, who increasingly integrate traditional practices with modern innovations.

Environmental Sustainability and Ecological Benefits

The environmental sustainability of ITK is evident in its contributions to biodiversity conservation and ecosystem management.

Biodiversity Conservation: Indigenous practices such as rotational grazing, mixed cropping, and protection of sacred sites contribute to the conservation of biodiversity. These approaches maintain ecological balance and enhance ecosystem resilience.

Carbon Sequestration and Ecosystem-Based Management: Practices like agroforestry and forest conservation play a significant role in carbon sequestration. By increasing vegetation cover, these systems absorb atmospheric carbon dioxide, thereby mitigating climate change. Additionally, they improve soil health, prevent erosion, and support ecosystem stability.

Challenges in Integrating ITK into Climate Policy

Despite its recognized value, ITK faces several challenges in its integration into formal climate strategies.

Lack of Institutional Recognition: One of the primary barriers is the limited recognition of ITK within national and international policy frameworks. This marginalization restricts the participation of indigenous communities in decision-making processes related to climate action.

Intellectual Property and Ethical Concerns: Issues related to intellectual property rights pose significant challenges. The unauthorized use of traditional knowledge by external entities raises concerns about ownership, benefit-sharing, and ethical considerations. There is a need for legal mechanisms to protect the rights of indigenous communities.

Conclusion

Indigenous Traditional Knowledge represents a valuable and underutilized resource in addressing climate change. Its emphasis on sustainability, resilience and community participation aligns closely with the goals of climate adaptation and mitigation. By integrating ITK with modern scientific approaches, it is possible to develop holistic and context-specific solutions for environmental and socio-economic challenges. However, achieving this integration requires recognition of indigenous rights, protection of traditional knowledge, and inclusive policy frameworks. Strengthening the role of ITK in climate strategies will not only enhance resilience but also contribute to sustainable development and environmental conservation.

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Self-incompatibility (SI)

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Introduction

Self-incompatibility (SI) is a genetically controlled mechanism in flowering plants that prevents self-fertilization by inhibiting the growth or function of self-pollen. It promotes cross-pollination (allogamy) and maintains genetic diversity in plant populations. SI is present in nearly 40-60% of angiosperms and plays a vital role in plant evolution and crop improvement.

Concept and Mechanism of Self-Incompatibility

Self-incompatibility is controlled by S-genes (S-locus), which help the plant distinguish between "self" and "non-self" pollen. If the S-alleles of pollen and pistil match, fertilization is prevented.

Types of SI

Gametophytic SI (GSI)

- ✓ Controlled by haploid genotype of pollen
- ✓ Common in Solanaceae, Rosaceae
- ✓ Pollen tube growth inhibited in style

Sporophytic SI (SSI)

- ✓ Controlled by diploid genotype of parent plant
- ✓ Common in Brassicaceae
- ✓ Pollen rejected at stigma surface

Relevance of Self-Incompatibility

Self-incompatibility has both biological and breeding significance:

Genetic Significance

- ✓ Prevents inbreeding depression
- ✓ Maintains heterozygosity
- ✓ Enhances genetic variability

Evolutionary Importance

- ✓ Promotes adaptability to changing environments
- ✓ Ensures survival through cross-pollination

Agricultural Importance

- ✓ Essential in hybrid seed production
- ✓ Maintains vigour (heterosis) in crops

Methods to Overcome Self-Incompatibility

In plant breeding, SI can be a barrier when selfing is required. Several techniques are used to overcome it:

Bud Pollination

- ✓ Pollination before stigma becomes receptive
- ✓ SI mechanism not fully active

Mentor Pollination

- ✓ Mixing compatible pollen with self-pollen
- ✓ Compatible pollen helps bypass SI response

Delayed Pollination

- ✓ Pollination after stigma maturity declines

Environmental Manipulation

- ✓ Temperature changes or CO_2 treatment can suppress SI

Chemical Treatment

- ✓ Application of growth regulators (e.g., auxins, gibberellins)

Mutation and Polyploidy

- ✓ Mutation at S-locus can break SI

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- ✓ Polyploidy reduces SI expression

Molecular Techniques

- ✓ Marker-assisted selection
- ✓ Gene editing (e.g., CRISPR) to convert SI → SC

Advantages of Self-Incompatibility

- ✓ Promotes cross-pollination
- ✓ Maintains genetic diversity
- ✓ Avoids inbreeding depression
- ✓ Produces vigorous progeny
- ✓ Useful for hybrid seed production

Disadvantages of Self-Incompatibility

- ✓ Difficulty in maintaining pure lines
- ✓ Requires pollinators
- ✓ Seed set may be low under unfavorable conditions
- ✓ Complicates breeding programs
- ✓ Not suitable where uniformity is needed

Utilization in Crop Improvement

Self-incompatibility is widely exploited in plant breeding:

Hybrid Seed Production

- ✓ SI ensures natural cross-pollination
- ✓ Eliminates need for emasculation

Maintenance of Heterosis

Maintains hybrid vigor in crops like:

- ✓ Brassica (cabbage, cauliflower)
- ✓ Sunflower
- ✓ Rye

Population Improvement

- ✓ Maintains broad genetic base in breeding populations

Genetic Studies

- ✓ Helps in studying gene interactions and inheritance

Development of Synthetic Varieties

- ✓ SI plants used to produce synthetics with high variability

Transition to Self-Compatibility

Controlled breakdown of SI helps:

- ✓ Develop pure lines
- ✓ Improve breeding efficiency

Conclusion

Self-incompatibility is a crucial reproductive mechanism that maintains genetic diversity and promotes cross-pollination in plants. While it poses challenges in breeding, modern techniques allow its manipulation for crop improvement. Its strategic use in hybrid seed production and maintenance of heterosis makes it a valuable tool in Plant Breeding and Genetics (PBG).

More Milk, More Money: How IVF is Changing Farmers' Lives

Shreya Ash and Bhagya Laxmi Sahu

Abstract

India's dairy sector is undergoing a technological revolution. Currently accounting for over 5% of the national GVA, the sector is moving beyond traditional husbandry toward high-tech, indigenous solutions. This article details how the Department of Animal Husbandry and Dairying is utilizing sex-sorted semen to ensure 90% female calf births and genomic selection to identify elite livestock years earlier than previously possible. A central focus is placed on "Shashthi," India's first homegrown IVF media suite, which has reduced embryo costs by 33% and removed reliance on expensive imports. By bridging the gap between advanced lab science and small-scale rural farming, these innovations are providing a sustainable roadmap for increasing milk yields, enhancing disease resistance, and securing the economic future of over 8 crore Indian dairy farmers.

Introduction

The livestock and dairy sector occupy a central position in India's agricultural economy, and supporting the livelihoods of millions of rural households, particularly small and marginal farmers. This sector has gained further prominence with India emerging as the world's largest producer of milk. The livestock sector plays a multifaceted role in sustaining rural livelihoods. It contributes to nutritional security through the provision of milk, meat, and eggs; generates organic manure that supports sustainable agriculture; provides draft power and creates extensive employment opportunities, especially for women and landless agricultural labourers. The livestock sector has demonstrated robust growth in has recent years, recording a Compound Annual Growth Rate (CAGR) of 12.99% from 2014-15 to 2022-23. Its contribution to the total agriculture and allied sector GVA has increased from 24.38% in 2014-15 to 30.23% in 2022-23 (at current prices), while accounting for 5.50% of the total GVA in 2022-23. India's leadership in the global dairy sector is particularly noteworthy. The country ranks first in milk production, contributing 24.76% of global milk output. Milk production has recent years, recording a Compound Annual Growth Rate (CAGR) of 12.99% from 2014-15 to 2022-23. Its contribution to the total agriculture and allied sector GVA has increased from 24.38% in 2014-15 to 30.23% in 2022-23 (at current prices), while accounting for 5.50% of the total GVA in 2022-23.India's leadership in the global dairy sector is particularly grown grown at a CAGR of 5.62% over the past decade, increasing from 146.31 million

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tonnes in 2014-15 to 239.30 million tonnes in 2023-24. In comparison, world milk production grew by 1.50% during 2023 (est.) over 2022 (Food Outlook November, 2024). Furthermore, per capita availability of milk in India stands at 471 grams per day in 2023-24, significantly higher than the world average of 329 grams per day in 2023 (est.) (Food Outlook November, 2024).

Advanced breeding technologies such as:

Sex-sorted semen

- ✓ The adoption of sex-sorted semen technology can ensure up to 90% birth of female calves.
- ✓ It will directly strengthening dairy productivity
- ✓ Gir, Sahiwal and Rathi grow into milk-producing cows, thereby increasing herd efficiency and reducing the economic burden associated with non-productive male cattle.
- ✓ A1 and A2 milk produced by these cows sell at a premium cost

IVF-based embryo transfer

- ✓ It enables the multiplication of high-yielding indigenous and crossbred cattle.
- ✓ By implanting embryos from genetically superior cows, farmers can rapidly upgrade their livestock quality, resulting in higher milk yield, improved diseasese resistance and better overall product-ivity,"

Integrating these technologies with proper veterinary care, nutrition, and scientific animal husbandry practices can help farmers to move towards the goal of doubling their income. Livestock-based income provides stability against uncertainties such as climate change, erratic rainfall, and crop losses. Therefore, it can work as transformative tools to boost milk production and enhance farmers' incomes. Adoption of modern breeding techniques, will not only enhance milk production but also contributete to rural prosperity and employment generation.

The Department of Animal Husbandry and Dairying is promoting the following technologies under Rashtriya Gokul Mission

- ✓ Sex sorted Semen Production Technology
- ✓ Genomic Selection
- ✓ Indigenously developed bovine IVF media

Sex sorted semen production technology

- ✓ The Prime Minister's vision of 'Make in India' and 'Atmanirbhar Bharat', the Department of Animal Husbandry and Dairying (DAHD), developed an indigenous, affordable sex sorted semen production technology through the National Dairy Development Board (NDDB) and it was launched on 5.10.2024.
- ✓ The technology has made cost of sex sorted semen affordable to farmers and playing important role in producing female calves with 85-90% accuracy thereby enhancing farmers

income.

- ✓ The benefit of sex sorted semen technology will accrue to more than 8 crore small and marginal farmers engaged in dairying across the country.

Genomic selection

- ✓ The Department of Animal Husbandry and Dairying, through National Dairy Development Board (NDDB) and ICAR-National Bureau of Animal Genetic Resources (ICAR-NBAGR) developed the unified genomic chip: GAUCHIP for indigenous cattle and MAHISHCHIP for buffaloes to enable identification of elite animals across the country.
- ✓ The unified genomic chip has been launched by Hon'ble PM on 5.10.2024. Implementing genomic selection will allow for early identification of young bulls**,** enhancing milk production and overall productivity.
- ✓ Farmers will no longer need to wait 3-4 years to assess the potential of heifers; instead, they can make informed decisions regarding the sale and purchase of animals at an earlier age.
- ✓ The availability of genomic selection services has empowered farmers to make timely decisions, thereby expediting the genetic progress of their herds.

Indigenously developed bovine IVF media

- ✓ For the first time in the country, bovine IVF technology is initiated. The IVF technology is crucial for enhancing productivity of bovines as work which requires 7 generations can be done in single generation through IVF technology.
- ✓ The Department of Animal Husbandry and Dairying through National Dairy Development Board has launched indigenous bovine IVF media on 23rd September 2024.

The indigenous media, offers a cost-effective alternative to expensive imported media, this will make cost of bovine IVF technology reasonable to our farmers engaged in dairying.

"Shashthi" the nation's first homegrown Bovine IVF Media Suite ushering in an era of affordable, high-tech cattle breeding. Launched at the Monsoon Meet in Bhubaneswar by Odisha CM Shri Mohan Charan Majhi and Union Minister Shri Rajiv Ranjan Singh.

Shashthi, that farmer can affordably access IVF technology to breed high-yielding, disease-resistant cows a privilege once reserved for large farms. Here's how "Shashthi" rewrites the rules:

Cost Slashed by 33%: From ₹1,000 to just ₹650 per embryo, making IVF pregnancies accessible to small farmers.

Tailored for Indian Breeds: Optimized for Gir, Sahiwal, and Murrah cattle to maximize embryo survival.

No More Import Reliance: Replaces pricey foreign media with a Made-in- India alternative, saving ₹100+ crore annually.

Conclusion

The adoption of advanced reproductive technologies such as sex-sorted semen, IVF- based embryo transfer, and genomic selection represents a significant advancement in India's dairy sector. These innovations facilitate rapid genetic improvement, enhance milk productivity, and improve disease resistance, thereby strengthening the economic viability of dairy farming. Importantly, government initiatives like the Rashtriya Gokul Mission and indigenous developments such as bovine IVF media have made these technologies increasingly accessible and cost-effective for small and marginal farmers. Furthermore, the integration of scientific breeding practices with improved animal husbandry can ensure long-term sustainability and resilience against climatic and market uncertainties. However, achieving widespread impact will require continued policy support, farmer awareness, and institutional capacity building. Overall, these technologies hold immense potential to transform the dairy sector into a more productive, equitable, and sustainable component of India's agricultural economy.

Benefits of Silicon in Plant Health

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Abstract

For decades, silicon quietly sat on the sidelines of plant nutrition science abundant almost everywhere in the Earth's crust, yet largely dismissed as non-essential. That story has changed dramatically. A growing body of research now shows that silicon acts as a powerful, multi-purpose mineral that helps plants grow stronger, withstand drought, fight off infections, and survive in contaminated soils. This review brings together the latest evidence on how plants absorb and use silicon, how it reinforces cell walls and boosts photosynthesis, and how it defends crops against an impressive range of threats from heat waves and salty soils to fungal attacks and hungry insects. We also look at exciting developments in silicon nanoparticles as precision delivery tools, and explore silicon's broader role in soil health and climate-resilient farming. Despite all this promise, routine silicon fertilisation remains rare in commercial agriculture, and there's still much to learn.

Introduction: The Element That Was Hiding in Plain Sight

Silicon makes up about 28% of the Earth's crust by mass only oxygen is more abundant. Yet for most of the twentieth century, plant scientists largely ignored it. The reasoning was straightforward enough: if you grow a plant without any silicon, it doesn't immediately wilt or show classic deficiency symptoms the way it would without nitrogen or phosphorus. So silicon was written off as optional, a mineral curiosity rather than a critical nutrient. That view has been decisively overturned. Over the past two decades, research has accumulated to the point where the scientific community now broadly accepts silicon as a “quasi-essential” element and for certain plant species, genuinely essential. Plants take it up from soil water in a dissolved form called mono-silicic acid, ferry it through the plant via specialised transport proteins, and deposit it in leaves, stems, and roots as tiny glass-like structures called phytoliths. Far from being inert decoration, these deposits turn out to be doing extraordinary things. The transport machinery itself has been a revelation. In rice the plant where silicon research is most advanced two proteins called Lsi1 and Lsi2 act as molecular gatekeepers, pulling silicon into root cells and then pushing it up toward the shoots. Closely related proteins have since been found in barley, maize, pumpkin, and wheat, suggesting this is an ancient, conserved system that plants evolved for a reason. Even more intriguing, recent studies show that plants can dial up silicon uptake under stress conditions like drought or salinity almost as if they sense trouble coming and reach for this protective tool.

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Why does this matter right now? Because agriculture is under pressure like never before. Droughts, salt-damaged soils, rising temperatures, novel pathogens, and heavy metal contamination are projected to slash global crop yields by over half if nothing changes. Silicon has emerged as a surprisingly affordable, environmentally gentle tool for tackling these overlapping crises and this review brings together the strongest current evidence for what it can do.

What Silicon does to Plant Structure?

Building Stronger Cell Walls: Think of a plant cell wall as a woven fabric flexible enough to allow growth, rigid enough to hold the plant upright. Silicon weaves itself into that fabric and stiffens it. Under a microscope, Si-enriched cell walls show tighter packing of cellulose fibres and better cross-linking between the long-chain molecules that hold the wall together. The result is a structure that resists mechanical stress, bends less under wind, and is significantly harder for pathogens to punch through. In sugarcane, silicon has been shown to increase structural proteins called extensins essentially the scaffolding proteins of the cell wall while also boosting the enzymes that remodel wall architecture during growth. The plant ends up with a cell wall that is both stronger and appropriately flexible: the structural equivalent of reinforced concrete that still allows the building to move a little in an earthquake.

Boosting Photosynthesis: Silicon doesn't just make plants tougher it makes them more productive. Plants treated with silicon consistently show higher chlorophyll levels, better activity across both of the main photosystem complexes (Photosystem I and II), and more stable thylakoid membranes. These are the tiny internal structures inside chloroplasts where sunlight is captured and converted to chemical energy. When they're well-maintained, the plant fixes more carbon dioxide, produces more energy, and grows faster (Etesami, 2025). Silicon also improves how efficiently plants use nutrients. It stimulates the expression of aquaporin genes proteins that act as channels allowing water and dissolved nutrients to cross cell membranes and promotes root elongation, giving roots more surface area to mine the soil. The end result is that silicon-treated plants absorb more nitrogen, phosphorus, potassium, and calcium, even when the supply in the soil stays the same. For sustainable farming systems trying to reduce fertiliser inputs, this is genuinely significant.

The Cuticle and the Roots: Silicon also thickens the waxy cuticle layer on leaf surfaces, making it harder for pathogen spores to germinate and penetrate, and reducing water loss from leaf surfaces directly separate from the regulated opening and closing of stomata. In barley under salt stress, silicon-treated plants showed cuticle layers 40 to 60% thicker than untreated controls, with correspondingly less chloride ion reaching the leaf interior (Martos-García *et al.* (2024). Below ground, silicon promotes longer, more branched roots with more root hairs a bigger foraging network for water and nutrients. In black gram grown under drought conditions, silicon increased root length by nearly 54% compared to

stressed plants without it. Similar patterns have been seen in wheat, maize, and tomato, making silicon relevant not just to what happens in the leaf, but to how well the plant anchors and feeds itself from the start.

Silicon against Abiotic Stresses

Drought: Drought accounts for more than 40% of annual crop yield losses globally, making it the single biggest abiotic stress in agriculture. Silicon's effects here are real but nuanced. Under moderate drought, silicon typically keeps stomata more open, maintaining gas exchange and carbon assimilation. Under severe drought, some studies find the opposite silicon helps stomata close more effectively, conserving water and protecting turgor. This apparent contradiction reflects the context-dependent nature of silicon's action: the right response depends on the crop variety (Thakral *et al*., 2024). At the biochemical level, silicon works on multiple fronts simultaneously. It increases levels of compatible solutes small molecules like proline and trehalose that act as internal shock absorbers, keeping cells functional at low water potential. It boosts signaling through the stress hormone abscisic acid. And it ramps up a whole battery of antioxidant enzymes that mop up the damaging reactive oxygen molecules that drought stress generates in large quantities. Add nano-scale silicon particles to the mix which can be sprayed on leaves at lower doses than conventional silicon fertilizers and drought protection improves further still (Eghlima *et al.*, 2024).

Salt Stress: Around 20% of irrigated agricultural land worldwide is already affected by salinity, and that proportion could reach 50% by mid-century. Salt damages plants in two main ways: it disrupts the water balance (too much sodium outside cells pulls water out), and sodium ions directly interfere with enzyme function inside cells. Silicon addresses both problems. Its primary ion-management strategy involves reducing sodium uptake and helping retain potassium a balance that's critical for cells to function. It does this partly by dialling down the expression of sodium transport proteins in root cells, and partly by physically tightening the cell wall pathways through which sodium ions might otherwise sneak in. It also activates the same antioxidant enzyme systems that handle drought stress, and protects the photosynthetic machinery from the disruption that high chloride levels would otherwise cause. Across multiple analyses of rice, wheat, and barley trials, silicon supplementation under salt stress increases shoot biomass by 15 to 35% and grain yield by 10 to 25% (Ma *et al.*, (2006).

Heavy Metal Contamination: Heavy metals like cadmium, lead, arsenic, and chromium in agricultural soils pose serious risks to food safety. Silicon has emerged as an effective, low-cost way to manage metal contamination, and the mechanisms are impressively varied. In the soil, silicon can form chemical complexes with metal ions that make them less soluble and less available for uptake. Once inside the plant, it promotes the packaging of metals into vacuoles cellular compart-ments that act as safe storage, keeping toxic ions away from the machinery

of the cell. In cadmium-stressed rice, silicon application has reduced grain cadmium content by up to 60% a massive improvement in food safety terms. In willow trees exposed to lead contamination, silicon altered where lead ended up in cells, locking more of it into the cell wall and reducing its movement to leaves and stems. Silicon also curbs the oxidative damage that metal stress triggers in chloroplasts, protecting photo-synthesis in the process.

Heat Stress: As global temperatures rise, heat stress during flowering and grain filling is becoming a more frequent and damaging problem. Silicon-treated plants show better heat tolerance at the molecular level: they accumulate more of the "chaperone" proteins that prevent other proteins from unfolding and clumping together at high temperatures. Their metabolism also adapts better they maintain more efficient energy production and sustain the antioxidant systems that prevent cellular damage. Critically, silicon protects the photo-synthetic membranes from heat-induced disorgan-isation, keeping carbon fixation running when other plants are faltering.

Silicon against Biological Threats

Fungal Pathogens: Silicon's protective effects against fungal disease have been documented for over four decades, and the evidence keeps getting stronger. The first line of defence is physical: silicon-reinforced cell walls and thickened cuticles slow down fungal hyphae trying to penetrate plant tissue. Against obligate biotrophs like powdery mildew pathogens that can only grow inside living plant cells this mechanical delay can be the difference between infection and resistance. But silicon doesn't stop at physical barriers. It activates a cascade of defence genes, including those producing "pathogenesis-related" proteins molecular weapons the plant deploys to attack fungal cell walls. It boosts the production of lignin, making plant tissues even tougher. And it primes the plant's immune system in a way that's reminiscent of vaccination: silicon-treated plants exposed to a pathogen mount a faster, stronger defence response than untreated ones, even before they've actually encountered the disease.

Insect Pests: Insects don't like silicon-enriched plants, and for good reason. The phytoliths deposited in leaves make the tissue physically abrasive they wear down insect mouthparts, slow feeding rates, and increase the energy cost of eating. This reduces pest fitness and reproduction even without any chemical insecticide being involved. Silicon also triggers the production of chemical defences. It stimulates the jasmonic acid signalling pathway the plant's main insect-response system leading to higher levels of proteinase inhibitors that disrupt insect digestion, as well as volatile compounds that both deter pests and attract the natural enemies of those pests. In citrus, silicon application was shown to reduce populations of the Asian citrus psyllid, a devastating pest that transmits citrus greening disease, by making leaves less hospitable for the insect to settle on.

Nematodes: Root-knot nematodes cause more than

$157 billion in crop losses globally every year, and chemical nematicides are increasingly restricted due to their environmental toxicity. Silicon offers a promising alternative. In tomato, silicon-treated roots showed significantly less nematode-induced galling and lower egg production by the parasites, linked to thicker root cell walls, elevated defence enzyme activity, and changes in the plant volatiles that nematodes use to navigate toward roots. The prospect of reducing reliance on synthetic nematicides through silicon application represents a meaningful sustainability gain.

Nano-Silicon: A More Precise Delivery System

Silicon nanoparticles (SiNPs) are an exciting frontier that's moved quickly from lab curiosity to genuine agronomic tool. The basic principle is straightforward: by engineering silicon into particles at the nanoscale, you dramatically increase the surface area available for interaction with plant tissues, improve solubility, and enhance uptake efficiency. The practical payoff is that you can achieve the same protective effects using lower doses which matters for cost, for logistics, and for minimising any environmental loading (Mukarram *et al.* 2024). In rice under simultaneous drought and salt stress a combination that's increasingly common in real farming conditions SiNPs triggered a suite of metabolic changes that preserved cell membrane integrity, maintained energy production, and boosted antioxidant defences. Perhaps most intriguingly, SiNPs appear to induce epigenetic changes: modifications to the way genes are packaged and expressed, which can potentially be passed on to the next generation of plants. If this is confirmed, it suggests that nano-silicon might help breed crops with inheritable stress memory a remarkable prospect. At recommended agronomic doses, SiNPs appear to be safe low phytotoxicity, minimal off-target effects. But the long-term behaviour of nanoparticles in soils is not yet well understood, and robust regulatory frameworks for their use are still being developed. Enthusiasm here should be tempered with the recognition that more research is needed before large-scale deployment.

Silicon Beyond the Plant: Soil Health and the Climate

Silicon's benefits don't stop at the individual plant. Silicon enrichment improves soil physical structure better aggregate stability, better water retention, better resistance to erosion. It shifts soil microbial communities in beneficial directions, supporting microorganisms that promote plant growth and nutrient cycling. The climate angle is particularly interesting. When plants deposit silicon in their tissues, they create phytoliths those microscopic glassy bodies that can persist in soil for thousands of years. Crucially, these structures trap organic carbon inside them in a form that microbes struggle to decompose. This means silicon-accumulating crops contribute to a long-term, stable soil carbon sink a genuine contribution to carbon sequestration that's been largely overlooked in climate discussions. Silicon also helps reduce greenhouse gas emissions from agricultural soils in

other ways: by supporting bacteria that consume methane in flooded rice paddies, and by influencing soil pH in ways that reduce nitrous oxide production a greenhouse gas about 300 times more potent than carbon dioxide. These are small effects per field, but aggregated across the global land area where silicon fertilisation might be applied, they become meaningful.

Silicon in Climate-Smart Agriculture: The pressures converging on agriculture right now more frequent droughts, expanding salinity, new pathogens thriving in warmer conditions, industrial heavy metal contamination require tools that can address multiple problems at once. Silicon is unusually well positioned here. A single silicon amendment can simultaneously improve drought resilience, salt tolerance, heavy metal management, and pathogen resistance. Few other single inputs come close to that range. Practically speaking, silicon fertilisers can be derived from industrial by-products blast furnace slag, fly ash, rice husk ash that are abundant, cheap, and would otherwise require disposal. Integrating these materials into farming systems simultaneously improves soil structure, adjusts pH, and supplies silicon. When combined with other sustainable inputs mycorrhizal inoculants, plant growth-promoting bacteria the effects are often synergistic, greater than the sum of the parts. In agroforestry systems, deep-rooted trees can access subsoil silicon pools that shallow-rooted crops cannot reach, drawing silicon up through root activity and eventually returning it to the surface through leaf litter. This creates a natural recycling loop that progressively enriches the soil. For degraded, intensively farmed soils that have become silicon-depleted, this represents a meaningful restoration pathway.

What we still need to Learn

Despite the impressive body of evidence that has accumulated, there are real and important gaps. Much of the research has been conducted in greenhouse conditions, which don't always translate cleanly to the messiness and variability of real farm environments. Large-scale, multi-site, multi-season field trials remain urgently needed particularly for crops that accumulate less silicon naturally, like soybeans and tomatoes. The molecular biology of silicon transport and action has been worked out in impressive detail in rice and barley grass-family crops that are strong silicon accumulators. But most of the world's calories come from dicotyledonous crops legumes, root vegetables, fruits where the mechanisms are much less understood. Filling this gap is an obvious priority. Questions also remain around soil dynamics: how does repeated silicon fertilisation change the soil's chemistry and microbial ecology over time? How does silicon interact with phosphorus in different soil types? For nano-silicon specifically, what happens to nanoparticles in the soil food web after application, and are there unintended effects on non-target organisms? The epigenetics question is perhaps the most scientifically exciting: early evidence suggests silicon can induce heritable changes in how genes are

expressed, potentially giving offspring plants a head start in dealing with stress. If robust and reproducible, this would have significant implications for breeding programmes. And finally, nobody has yet systematically studied how rising CO_2, higher temperatures, and changing UV radiation levels will affect silicon's uptake and efficacy in future climates a gap that urgently needs system-level modelling to address.

Concluding

Silicon has journeyed from overlooked curiosity to serious contender in the toolkit of sustainable agriculture. The evidence for what it can do structurally, physiologically, and ecologically is now substantial and growing. It won't replace the fundamental inputs of water, nitrogen and phosphorus, but as a complement to them, particularly in an era of escalating environmental stress, its case has never been stronger. The challenge now is translating laboratory and greenhouse findings into practical, farmer-ready guidance across the full diversity of crops, soils, and climatic conditions that define global agriculture.

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Unlocking Fruit Crop Potential: Integrating In-Situ and Ex-Situ Conservation

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Genetic Diversity Overview

Fruit crops encompass thousands of species, varieties, and wild relatives, with tropical regions like India hosting over 100 cultivated types and hundreds of undomesticated kin. Mango, citrus, banana, and jackfruit exemplify rich variation, from landraces adapted to local soils to wild forms offering pest resistance and drought tolerance. Centers of origin, such as Southeast Asia and the Western Ghats, naturally evolve traits like extended shelf life or high nutrient content, supporting resilient breeding. Underutilized fruits like jamun, ber, and phalsa add unique phytochemicals and vitamins, thriving on marginal lands where major crops fail. This diversity fuels hybrid development, ensuring yields under stress from erratic monsoons or pests.

Major Threats: Habitat loss from urbanization and monocropping erodes wild populations rapidly. Climate shifts alter flowering and fruiting cycles, while market biases favor uniform hybrids, sidelining heirloom varieties. Overharvesting for timber or fodder further diminishes gene pools, especially in biodiversity hotspots. Pests and diseases exploit narrowed genetics in commercial orchards, amplifying losses. Long juvenile phases in trees hinder quick recovery, making proactive measures urgent.

In Situ Conservation: Protecting species within native ecosystems preserves natural selection and gene flow. Home gardens and farmer fields maintain landraces through traditional practices. Sacred groves in India shield wild mango and citrus progenitors. Protected areas like national parks and biosphere reserves holistically conserve habitats. Agroforestry blends fruit trees with staples, fostering sustainability and farmer income.

Ex Situ Methods: Off-site storage secures backups via seed banks, field genebanks, and tissue culture. Cryopreservation freezes embryos for vegetatively propagated crops like grapes and sapota. Botanical gardens showcase diversity for education and research. Clonal orchards test traits under controlled conditions, aiding selection. These complement in situ by providing material for breeding programs.

Integrated Approaches

Combining methods optimizes outcomes: in situ for dynamism, ex situ for security. Community involvement links conservation to markets, promoting underutilized fruits through value chains.

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Method	Description	Benefits	Limitations
In Situ	Natural habitat protection	Evolutionary adaptation, low cost	Vulnerable to land use changes
Ex Situ	Controlled storage	Safe duplicates, easy access	Risks genetic drift
On-Farm	Farmer-managed plots	Economic viability, real-world testing	Dependent on markets
Biotech	Genomic tools	Targeted improvements	High tech needs

Biotechnology, including markers and editing tools, mines wild genes for elite varieties. Participatory breeding engages farmers, embedding local knowledge. Policy frameworks prioritize hotspots and incentivize diversity planting.

Nutritional and Economic Value

Diverse fruits combat micronutrient gaps with antioxidants, fibers, and minerals. Wild relatives enhance biofortification, boosting immunity and livelihoods. Smallholders gain from niche markets for organic or heritage produce. Sustainable use cuts chemical inputs via resistant types, aligning with eco-friendly farming.

Regional Examples

India's Northeast and Western Ghats harbor jackfruit kin with superior flavors. Southeast Asia protects durian wilds for flavor genes. Temperate zones conserve apple crabs for scab resistance. Global networks exchange germplasm, accelerating progress.

Future Priorities

Focus on climate-ready varieties from wild pools. Awareness campaigns and funding scale efforts. Tech like remote sensing monitors populations. Holistic strategies ensure fruit biodiversity sustains future generations, blending science, policy, and tradition for enduring impact.

Integrated Pest Management of Sorghum Shoot Fly (*Atherigona soccata*)

Mangal Sukhi Meena, Hemant Swami, Sheenam Bhateja and Amar Singh

Abstract

The sorghum shoot fly (*Atherigona soccata*) is one of the most destructive pests of sorghum (*Sorghum bicolor*), particularly during the early seedling stage. Infestation leads to "dead heart" symptoms, resulting in severe yield losses that may reach up to 80-90% under high pest pressure. Integrated Pest Management (IPM) offers an eco-friendly and sustainable approach by combining cultural, biological, mechanical, and chemical control strategies. This article reviews various IPM components and their integration for effective management of sorghum shoot fly.

Introduction

Sorghum is an important cereal crop widely cultivated in semi-arid regions of Asia and Africa. However, its productivity is significantly affected by insect pests, among which the sorghum shoot fly (*Atherigona soccata*) is a major constraint. The pest attacks seedlings between 7-30 days after emergence, where larvae bore into the central whorl and destroy the growing point, causing a characteristic "dead heart" symptom. Due to its high reproductive capacity and short life cycle (18-25 days), the shoot fly can rapidly build up populations under favourable conditions. Traditional control methods relying solely on chemical insecticides are not sustainable due to environmental hazards and resistance development. Therefore, Integrated Pest Management (IPM) is essential for long-term control.

Concept of Integrated Pest Management (IPM): Integrated Pest Management is a holistic approach that combines multiple control methods to maintain pest populations below economic threshold levels while minimizing environmental impact. IPM strategies for sorghum shoot fly include:

Cultural practices: Host plant resistance, Biological control, Mechanical and physical control, Chemical control (need-based), Monitoring and decision-making tools

Components of IPM for Sorghum Shoot Fly

Cultural Practices

Cultural methods form the backbone of IPM:

Early sowing: Sowing with the onset of monsoon helps escape peak shoot fly incidence

High seed rate and thinning: Ensures optimum plant population after damage

Crop rotation: Avoids pest carryover.

Intercropping (e.g., sorghum + legumes): Reduces pest buildup.

Field sanitation: Removal of infested plants reduces pest sources

Studies have shown that adjusting sowing

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time and plant density significantly reduces shoot fly incidence.

Host Plant Resistance: Use of resistant or tolerant varieties is an effective and economical strategy.

Resistant genotypes exhibit traits such as: Glossy leaves, Trichomes (leaf hairs), Rapid seedling growth. Development of resistant cultivars has been a major focus in sorghum improvement programs.

Mechanical and Physical Control

Rogueing: Removal and destruction of infested plants

Attractant traps: Fish meal traps, ammonia traps, and sticky traps for monitoring adult flies

Light traps: Used for general insect monitoring: Fish meal-baited traps have been found effective in assessing shoot fly populations in field conditions.

Biological Control

Biological control involves the use of natural enemies:

Parasitoids: *Trichogramma* spp. (egg parasitoids), Larval parasitoids: *Neotrichoporoides* spp.

Predators: Spiders, beetles, and other natural enemies. These natural enemies play a significant role in regulating shoot fly populations. Field studies indicate that release of egg parasitoids such as *Trichogramma chilonis* significantly reduces shoot fly incidence when combined with other methods.

Botanical and Biopesticides: Botanical pesticides such as neem-based products are effective alternatives: Neem Seed Kernel Extract (NSKE), Plant extracts (e.g., Vitex negundo). These reduce oviposition and larval survival, contributing to eco-friendly pest control.

Chemical Control

Chemical control should be used judiciously and only when necessary:

Seed treatment: Imidacloprid, thiamethoxam

Soil application: Carbofuran granules at sowing

Foliar spray: Chlorpyrifos (need-based). Proper selection and dosage of insecticides are crucial for effective control and resistance management.

Monitoring and Decision-Making

Monitoring is essential for effective IPM:

- ✓ Use attractant traps to monitor adult populations.
- ✓ Record number of eggs and dead hearts.
- ✓ Apply control measures based on Economic Threshold Level (ETL).
- ✓ Monitoring-based interventions improve timing and effectiveness of control measures.

Integration of IPM Components

Effective management of sorghum shoot fly requires integration of multiple strategies rather than reliance on a single method. A successful IPM module includes:

- ✓ Early sowing + resistant varieties.
- ✓ High seed rate + thinning.
- ✓ Installation of attractant traps.
- ✓ Release of biological control agents.
- ✓ Need-based chemical application

Field studies have demonstrated that integration of cultural practices, biological control, and limited chemical use significantly reduces shoot fly incidence and increases grain yield.

Advantages of IPM Approach

- ✓ Reduces dependency on chemical pesticides.
- ✓ Environmentally safe and sustainable.
- ✓ Cost-effective for farmers.
- ✓ Preserves natural enemies.
- ✓ Delays development of pesticide resistance

Conclusion

The sorghum shoot fly (*Atherigona soccata*) is a serious constraint to sorghum production, especially in semi-arid regions. Integrated Pest Management provides an effective and sustainable solution by combining cultural, biological, mechanical, and chemical methods. Among these, cultural practices and host plant resistance play a central role, while biological and chemical controls support pest suppression. Adoption of IPM strategies can significantly reduce crop losses and promote sustainable agriculture.

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Bioluminescent Fungi: Diversity, Mechanisms and Applications

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Abstract

Bioluminescent fungi are unique organisms capable of emitting visible light through biochemical reactions. Although fungal diversity is vast, only a small number of species exhibit this phenomenon. This article summarizes the diversity, biochemical mechanisms, evolutionary origin, ecological roles, and modern applications of bioluminescent fungi. Special attention is given to the luciferin–luciferase system and its potential in biotechnology and environmental monitoring.

Introduction

Bioluminescence is the emission of light by living organisms through chemical reactions, typically involving luciferin and luciferase. This phenomenon has been observed since ancient times, with early descriptions by Aristotle and Pliny the Elder (Harvey, 1957). Unlike fluorescence, bioluminescence produces light without external excitation and generates minimal heat, making it a form of chemiluminescence (Haddock *et al*., 2010). Fungi are among the least explored organisms, yet they exhibit remarkable diversity. It is estimated that 2-3 million fungal species exist globally, but only a fraction has been described (Naranjo-Ortiz and Gabaldón, 2019). Among these, approximately 100-120 species are known to be bioluminescent, mostly found in tropical and subtropical ecosystems (Desjardin *et al*., 2008).

Diversity and Distribution: Bioluminescent fungi are primarily classified under Basidiomycota, with rare exceptions in Ascomycota (Stevani *et al*., 2020). They are grouped into several evolutionary lineages, including Mycenoid, Armillaria, and Omphalotus. The genus *Mycena* is the most dominant and widely distributed. These fungi grow on decaying wood, forest litter, and tree roots. Their light emission varies depending on the species, occurring in mycelium, fruiting bodies, or both (Desjardin *et al*., 2008). The emitted light is typically green, with wavelengths around 520-530 nm (Airth and Foerster, 1962). Geographically, they are commonly found in Asia, South America, and North America, although some species exhibit region-specific luminescence patterns (Oliveira *et al*., 2015).

Mechanism of Bioluminescence: The mechanism of fungal bioluminescence is based on the oxidation of luciferin catalyzed by luciferase in the presence of oxygen. This reaction releases energy in the form of visible light (Wilson & Hastings, 2013). The process involves two main steps. First, luciferin is reduced by a reductase enzyme using NAD(P)H. In the second step, luciferase catalyzes its oxidation, producing

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oxyluciferin and light (Airth and Foerster, 1962). Recent studies have identified hispidin and 3-hydroxyhispidin as key components of fungal luciferin (Purtov *et al*., 2015). Genetic studies have revealed that bioluminescence is controlled by a cluster of genes, including luciferase (Luz), hispidin synthase (HispS), and hispidin-3-hydroxylase (H3H) (Kotlobay *et al*., 2018). These genes form a metabolic pathway responsible for continuous light production.

Evolution of Bioluminescence: Bioluminescence in fungi is believed to have originated from a common ancestor within the Agaricales order approximately 160 million years ago (Kotlobay *et al*., 2018). However, its uneven distribution suggests gene loss in some lineages or multiple evolutionary events. Genomic analyses support the hypothesis that bioluminescence evolved once and was later lost in various fungal groups (Ke *et al*., 2020). The conservation of gene clusters across species indicates a shared evolutionary pathway.

Ecological Significance: The ecological function of bioluminescence in fungi remains debated. One widely accepted hypothesis is that light attracts insects, which help disperse spores, especially in dark forest environments (Oliveira *et al*., 2015). Another theory suggests that bioluminescence acts as a warning signal to deter predators (Sivinski, 1981). Some researchers argue that light emission may simply be a metabolic by-product without adaptive significance (Weinstein *et al*., 2016). Environmental factors such as humidity and circadian rhythms also influence light production in certain species (Oliveira *et al*., 2015).

Applications: Bioluminescent fungi have important applications in biotechnology and research. The luciferase system is widely used as a reporter gene to study gene expression and cellular processes (Wilson and Hastings, 2013). It is also used in bioluminescence imaging to monitor disease progression and drug effects in living organisms (Contag *et al*., 1997). In environmental science, these fungi serve as bioindicators for detecting pollutants such as heavy metals and toxic chemicals (Stevani *et al*., 2020). Advances in genetic engineering have enabled the creation of self-luminous plants by incorporating fungal bioluminescence pathways, offering potential for sustainable lighting (Mitiouchkina *et al*., 2020).

Conclusion

Bioluminescent fungi are a unique and scientifically valuable group of organisms. Despite advances in understanding their mechanisms and applications, many aspects of their biology remain unexplored. Their conserved biochemical pathways and ecological significance highlight their importance in both natural ecosystems and technological innovation. Continued research will further enhance their applications in biotechnology, medicine, and environmental monitoring.

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Importance of Medicinal Herbs in Fisheries

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Abstract

Medicinal plants have been used for thousands of years as natural immunostimulants and are now widely applied in aquaculture as safe alternatives to antibiotics and synthetic chemicals. Their use is increasing globally due to their low cost, easy availability, simple preparation, and minimal harmful effects on aquatic organisms and the environment. A wide variety of plants, including herbs, spices, seaweeds, and traditional herbal medicines, have been studied for their beneficial effects on fish and shellfish. These plants can be used in different forms such as whole plants, or specific parts like roots, leaves, seeds, and flowers, as well as in extract form using solvents like ethanol or methanol. They can be administered through feed, water, or in combination with other immunostimulants. Medicinal plants are known to enhance growth, improve immunity, and provide antibacterial and antiviral protection. However, their exact mechanisms, optimal dosages, and long-term effects are still not fully understood, requiring further research for effective and standardized use.

Introduction

Microbial diseases in aquaculture cause significant economic losses, and the excessive use of antibiotics can lead to harmful side effects. As a result, alternative approaches such as the use of medicinal plants have gained attention for improving aquaculture sustainability. Many plant-based compounds exhibit growth-promoting, antimicrobial, and immunostimulatory properties in aquatic organisms. These phytochemicals are considered potential substitutes for conventional chemotherapeutics and can be used as feed additives or immunoprophylactic agents. Medicinal plants including herbs, spices, seaweeds, and plant extracts are widely used due to their low cost, ease of preparation, and minimal environmental impact. They contain bioactive compounds such as phenolics, alkaloids, and terpenoids, which enhance immunity, stimulate growth, and improve disease resistance. Although widely applied, their mechanisms of action, especially at the molecular level, are not fully understood. Further research is needed to optimize their application and better understand their species-specific effects in aquaculture.

Source of medicinal herb: Medicinal plants have been used as natural immunostimulants in traditional medicine systems for thousands of years and are now increasingly applied in aquaculture as safe alternatives to antibiotics. Their use helps improve fish health while reducing the risks associated with

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chemical treatments. A wide range of herbs such as aloe vera, garlic, ginger, ginseng, green tea, tulsi, guava, peppermint, and seaweeds are commonly used to enhance growth, boost immunity, and increase resistance against diseases in aquatic organisms. More than 60 different plant species have been studied for their role in fish health management. These plants can be used in various forms, including whole plants or specific parts like leaves, roots, seeds, fruits, and flowers. They are often incorporated into fish diets as powders or extracts, either alone or in combination with other natural additives. Some plant-based products are also commercially available and are known for their effectiveness in strengthening the immune system of fish. The extraction of bioactive compounds from medicinal plants is relatively simple and can be carried out using solvents such as ethanol, methanol, acetone, or even by boiling in water. The type and yield of extract may vary depending on the plant species and method used. Overall, medicinal plants offer a natural, cost-effective, and environmentally friendly approach for disease prevention and health management in aquaculture, although further research is still needed to better understand their mechanisms of action.

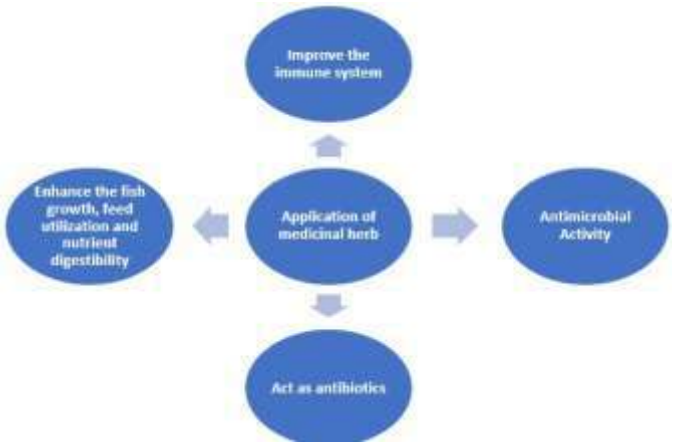
Administration and application methods

Medicinal plants in aquaculture can be administered through injection, immersion (bathing), or orally, with oral delivery via feed being the most practical and commonly used method. Herbal extracts are often added to fish diets either individually or in combination, as mixtures of herbs generally provide stronger immunostimulatory and growth-promoting effects than single herbs. Various herbal combinations have been shown to enhance immune responses, including increased phagocytic activity, respiratory burst, and lysozyme activity in different fish and shrimp species. These mixtures can also improve growth performance, feed efficiency, and resistance to bacterial and viral infections. In some cases, herbal formulations are used as preventive measures to replace antibiotics in disease control. Combining herbs with micronutrients such as boron, selenium, or zinc, or with probiotics like *Bacillus*, can produce synergistic effects, further improving immunity, survival, and growth. Another effective approach is bioencapsulation, where herbal extracts are delivered through live feed such as *Artemia* or rotifers, enhancing nutrient uptake and disease resistance in larvae and juveniles. Although injection and immersion methods are also used, especially for specific treatments, oral administration remains the most efficient and cost-effective. Overall, medicinal plants offer a promising, eco-friendly strategy for disease management and health improvement in aquaculture.

Application of medicinal herb

Improve the immune system: Many medicinal plants show antimicrobial activity and help improve growth, maturation, and immunity in fish, leading to increased interest in their use as immunostimulants in aquaculture. These plant-based compounds mainly enhance the innate (non-specific) immune

system, which plays a key role in protecting fish from infectious diseases. Herbs such as *Astragalus membranaceus*, *Angelica* species, turmeric (*Curcuma longa*), and garlic (*Allium sativum*) have been widely used to strengthen immune responses in various fish species. Medicinal plants contain active compounds like polysaccharides, alkaloids, and flavonoids that stimulate important immune parameters such as lysozyme activity, complement system, phagocytosis, respiratory burst, and antioxidant enzymes. These responses help fish defend against bacterial, viral, fungal, and parasitic infections. For example, plant extracts like green tea and *Prunella vulgaris* have been shown to improve immune activity, stress resistance, and overall health. Phagocytic cells are a major part of the fish immune system, and their activity often increases with herbal supplementation. Many plant extracts enhance phagocytosis and respiratory burst activity, improving the fish's ability to fight pathogens. Overall, medicinal plants act as effective natural immunostimulants, although their exact mechanisms still require further study.



Antimicrobial Activity: Medicinal plants and their active compounds have been widely studied for their strong antimicrobial properties in aquaculture. Herbal extracts show effective antibacterial activity against both Gram-positive and Gram-negative bacteria, and they can also help control viral, fungal, and parasitic diseases. For example, plant extracts such as Indian almond, rosemary, cinnamon, and tulsi have been used to treat infections like *Aeromonas hydrophila* and *Streptococcus* in fish, while also improving immunity and disease resistance. Many herbs also exhibit antiviral properties by reducing viral replication and enhancing the host's non-specific immune response. Extracts from plants like *Clinacanthus nutans*, *Cynodon dactylon*, and mango kernel have shown protection against serious viral diseases such as white spot syndrome virus (WSSV) and yellow head virus (YHV) in shrimp. Similarly, olive leaf extracts have been effective against viral infections in fish. In addition, medicinal plants are useful in controlling parasitic and fungal diseases in aquaculture species. Overall, herbal extracts provide a natural, eco-friendly, and effective alternative to synthetic chemicals for managing a wide range of aquatic diseases while also boosting the immune system.

Act as antibiotics: Several studies show that medicinal plants can act as effective natural alternatives to antibiotics in aquaculture. Fish and shrimp fed with herbal immunostimulants often show higher survival rates after being challenged with pathogens. Many herbal extracts, such as *Withania somnifera*, *Psidium guajava*, tulsi, green tea, cinnamon, and ginseng, have been found to

improve resistance against infections like *Aeromonas hydrophila* and *Vibrio* species. Herbal treatments can control a wide range of pathogens, including bacteria, and are effective in species like tilapia, grouper, and prawns. For example, guava extract has been shown to be even more effective than some antibiotics in reducing bacterial load, while seaweed and garlic extracts have successfully controlled viral and bacterial diseases in shrimp. Overall, dietary supplementation with medicinal plants enhances immune responses, reduces mortality and improves disease resistance in aquatic organisms. This makes them a promising, eco-friendly and cost-effective alternative to conventional antibiotics in aquaculture.

Enhance the fish growth, feed utilization and nutrient digestibility

Medicinal plants have been proven to act as natural growth promoters in aquaculture. They improve digestion by enhancing the activity of enzymes such as protease, amylase, and lipase, which leads to better feed utilization, higher survival, and faster growth of aquatic animals. Herbal supplementation also increases important nutrients like proteins, vitamins, amino acids, and minerals in fish and prawns. Various herbs such as ginseng, green tea, cinnamon, tulsi, and papaya leaf have shown positive effects on growth performance, feed conversion ratio (FCR), and specific growth rate (SGR) in different species. Herbal mixtures and plant extracts can further improve nutrient digestion, fatty acid utilization, and overall health. In addition, their antimicrobial and anti-stress properties help increase survival rates. Overall, the use of medicinal plants in diets enhances growth, improves feed efficiency, and supports better physiological performance, making them an effective and eco-friendly alternative to synthetic growth promoters in aquaculture.

Conclusion

In conclusion, medicinal plants offer a promising and sustainable approach for improving health management in aquaculture. Their natural origin, cost-effectiveness, and eco-friendly nature make them suitable alternatives to antibiotics and synthetic chemicals. The ability of these plants to enhance growth, strengthen immune responses, and provide protection against pathogens highlights their significant potential in aquaculture practices. Moreover, their flexibility in application through feed, water, or combined treatments further supports their practical use. However, despite these advantages, there is still a need for detailed studies to better understand their mechanisms of action, appropriate dosages, and long-term effects. Standardization and scientific validation are essential to ensure consistent results and safe application. Therefore, continued research and development will play a key role in fully utilizing medicinal plants for sustainable and efficient aquaculture production.

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Carbon Credit Opportunities in Indian Agriculture: A New Era of Green Economics

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Introduction

Indian agriculture is facing serious challenges due to climate change, declining soil fertility, water scarcity and increasing production costs. At the same time, agriculture has the potential to become a part of the solution through sustainable farming practices. In recent years, carbon credits and carbon farming have gained attention as new concepts in agricultural economics. Farmers can store carbon in soil and vegetation through eco-friendly practices and may receive financial benefits through carbon markets. This approach connects farm management with environmental sustainability and opens new opportunities for Indian farmers.

Concept of Carbon Credits in Agriculture

Carbon credits are tradable certificates issued for reducing or sequestering one metric ton of carbon dioxide (CO_2) or its equivalent in other greenhouse gases. In agriculture, carbon credits are generated through practices that either reduce emissions or enhance carbon sequestration in soil and biomass.

Key agricultural practices that contribute to carbon credits include:

- ✓ Conservation tillage and no-till farming
- ✓ Agroforestry systems
- ✓ Crop residue management
- ✓ Efficient fertilizer and water use
- ✓ Methane reduction in rice cultivation

Scope of Carbon Credit Opportunities in India

India has immense potential for carbon farming due to its diverse agro-climatic zones, vast agricultural land and large farming community. The adoption of sustainable agricultural practices can significantly contribute to carbon sequestration.

Major opportunities include:

Soil Carbon Sequestration: Enhancing soil organic carbon through sustainable land management

Agroforestry Expansion: Integrating trees with crops to absorb CO_2

Biochar Application: Improving soil health while storing carbon

Climate-Smart Agriculture: Reducing emissions through precision farming techniques

Economic Benefits to Farmers

Carbon credits provide an additional income source for farmers beyond traditional crop production. Benefits include:

- ✓ Financial incentives for sustainable practices
- ✓ Reduced input costs through efficient resource use
- ✓ Improved soil fertility and crop productivity
- ✓ Risk mitigation against climate variability

Carbon Markets and Agricultural Economics

Carbon markets are systems where carbon

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credits are bought and sold. These markets encourage industries and organizations to offset their emissions by investing in carbon reduction projects. There are mainly two types of carbon markets:

Compliance Carbon Markets: These markets operate under government regulations and international climate agreements. Organizations exceeding emission limits must purchase carbon credits to comply with environmental regulations.

Voluntary Carbon Markets: Voluntary carbon markets allow companies, organizations, and individuals to voluntarily purchase carbon credits to achieve sustainability goals and carbon neutrality. Agriculture is becoming an important component of voluntary carbon markets because sustainable agricultural practices can generate measurable environmental benefits. From an agricultural economics perspective, carbon credits represent a new form of ecosystem service payment. Farmers are compensated not only for food production but also for environmental conservation and climate regulation. The emergence of carbon markets may significantly influence farm management decisions, resource allocation, land use patterns and agricultural investment strategies in the future.

Role of Technology and Innovation

Emerging technologies are playing a crucial role in enabling carbon credit systems in agriculture:

- ✓ Remote sensing and GIS for monitoring carbon sequestration
- ✓ Artificial Intelligence (AI) for data analysis and prediction
- ✓ Blockchain for transparent carbon credit trading
- ✓ Internet of Things (IoT) for real-time farm monitoring

Future Prospects of Carbon Farming in India

The future of carbon farming in India appears highly promising due to increasing global focus on climate change mitigation, sustainability and green economic development. Several factors indicate strong future potential:

- ✓ Growing demand for carbon credits worldwide
- ✓ Increasing investment in climate-smart agriculture
- ✓ Expansion of digital agriculture technologies
- ✓ Rising awareness regarding environmental sustainability
- ✓ Government emphasis on natural and regenerative farming
- ✓ Corporate interest in achieving carbon neutrality
- ✓ International climate commitments under the Paris Agreement

Conclusion

Carbon credit opportunities in Indian agriculture mark the beginning of a new era of green economics, where farmers are rewarded not only for food production but also for environmental stewardship. By adopting sustainable agricultural practices, Indian farmers can contribute to climate change mitigation while improving their livelihoods. However, to fully realize this potential, coordinated efforts involving government, private sector, researchers, and farmers are essential. With the right policies, technologies and awareness, carbon farm-

ing can become a cornerstone of sustainable agricultural development in India.

Farmer Income Crisis and Rising Input Costs in India: Challenges and Sustainable Pathways

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Introduction

Agriculture has always been the backbone of the Indian economy. For millions of people living in rural areas, farming is not just an occupation but a way of life. Agriculture provides food for the country, raw materials for industries, employment opportunities and income for a large section of the population. Even today, a major part of India's rural population depends directly or indirectly on agriculture and allied activities for their livelihood.

Despite its importance, Indian agriculture is facing several economic challenges in the present time. Farmers across the country are struggling to earn a stable and satisfactory income from farming. One of the biggest reasons behind this problem is the continuous increase in the cost of cultivation. The prices of fertilizers, diesel, electricity, labour, machinery, seeds and pesticides have increased rapidly over the years. At the same time, the prices farmers receive for their crops often remain uncertain and unstable. Because of this imbalance between rising production costs and low returns, many farmers are facing financial stress and economic insecurity. Today, farmer income crisis has become one of the most serious concerns in the field of Agricultural Economics because it affects not only farmers but also rural development, food security and the overall economy of the country.

Meaning of Farmer Income Crisis

Farmer income crisis refers to a situation in which farmers are unable to earn enough income from agriculture to meet their farming expenses and household needs. Even after investing money, labour and time into cultivation, many farmers are left with very little profit. In simple words, when the cost of farming increases faster than the income earned from crops, farmers experience economic difficulties. This problem is more common among small and marginal farmers because they have limited land, fewer financial resources and less access to modern technology. The crisis not only affects farmers financially but also impacts their living standards, children's education, healthcare and future investments in agriculture.

Rising Input Costs in Agriculture: Agricultural inputs such as seeds, fertilizers, pesticides, labour, irrigation, and machinery have become increasingly expensive. According to the Commission for Agricultural Costs and Prices (CACP), rising inflation, fuel prices and dependence on purchased inputs have increased the cost of cultivation. As a result, farmers' profit margins have declined, and in some cases, they fail to recover even the basic production cost.

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Increase in Fertilizer Prices: Fertilizers like urea, DAP, and potash are essential for crop production but have become costly due to global price increases and higher energy costs. Farmers now spend a significant portion of their budget on fertilizers. Overuse also reduces soil fertility, increasing long-term production costs.

Increase in Diesel and Fuel Costs: Diesel plays a very important role in agriculture. It is used for operating tractors, irrigation pumps, harvesters, and transporting agricultural produce to markets. Continuous increases in diesel prices have raised the operational cost of farming. Farmers who depend on machinery and irrigation systems are spending much more than before. Transportation costs have also increased, reducing the income farmers finally receive after selling their crops.

Rising Labour Charges: Agriculture depends heavily on manual labour. Due to migration to cities, labour availability has declined, leading to higher wages. This has increased the cost of cultivation, especially for labour- intensive crops.

Expensive Seeds and Pesticides: Improved seeds and pesticides are necessary for higher productivity but are expensive. Climate change and increasing pest attacks have further increased the need for crop protection, raising production costs.

Major Causes of Farmer Income Crisis

Small and Fragmented Land Holdings: Small landholdings limit productivity, mechanization, and income. They increase cultivation costs and reduce marketable surplus.

Unstable Market Prices: Frequent price fluctuations and limited access to MSP lead to distress sales and income instability.

Climate Change and Weather Uncertainty: Climate change has become a major challenge for Indian agriculture. Irregular rainfall, droughts, floods, heat waves, and pest attacks are affecting crop productivity across the country. Climate-related problems have made agriculture more uncertain and risky than before.

Increasing Debt Burden: Farmers often take loans to meet rising costs, but low returns make repayment difficult, increasing financial stress.

Impact of Farmer Income Crisis

The crisis reduces farm profitability and increases rural poverty. It forces migration to cities and threatens future food security. Farmers struggle to meet basic needs like education and healthcare, affecting overall rural development

Government Initiatives to Improve Farmer Income

The government has introduced schemes such as MSP, PM-KISAN, PMFBY, and Farmer Producer Organizations (FPOs). These aim to provide price support, financial assistance, risk coverage, and better market access. Sustainable agriculture practices are also being promoted to reduce costs.

Role of ICAR in Improving Farmer Income: The Indian Council of Agricultural Research supports farmers through research and innovation. It develops high-yielding and climate-resilient crop varieties and

promotes modern farming techniques. Training and extension services help farmers improve productivity and reduce costs.

Measures to Overcome Farmer Income Crisis: Farmers should diversify into allied activities like dairy, poultry and horticulture. Improving marketing systems, storage, and digital platforms can ensure better prices. Adoption of modern technologies and efficient water management can reduce costs and improve productivity.

Improvement in Agricultural Marketing: Better storage facilities, cold chains, transportation systems, and digital marketplaces can help farmers receive fair prices for their produce and reduce post-harvest losses.

Adoption of Modern Technology: Modern technologies such as drones, mobile advisory services, artificial intelligence and precision farming can improve farming efficiency and reduce input wastage.

Efficient Water Management: Techniques such as drip irrigation, sprinkler irrigation, rainwater harvesting and micro-irrigation can reduce irrigation expenses and improve water-use efficiency.

Conclusion

Rising input costs and unstable prices have created a serious income crisis in Indian agriculture. Structural challenges and climate change have worsened the situation. Addressing this issue requires policy support, sustainable practices and improved market systems. Strengthening farmer income is essential for rural development, food security and economic growth.

Importance of Composting and Vermicomposting in Organic Crop Production Systems

Amanullah Qumar Rehan

Abstract

Organic farming is growing in global reach as farmers look to sustainable options which are so different from chemical-based farming. In this regard composting and vermicomposting have come forth as key practices for soil health and environmental protection. Composting is the process by which organic waste like that from crop residue, animal manure and kitchen waste is broken down into rich organic material. Also, vermicomposting which uses earth worms to speed up the breakdown process and which produces what is known as vermicast has also become very important. These practices are very important in ameliorating soil structure, encouraging microbial growth and in the increase of available nutrients which plants use. Also, we see that as opposed to synthetic fertilizers, those based on compost have a slow release of nutrients and at the same time minimize the issue of nutrient leaching as well as soil degradation. Also, they help in that they improve water retention in the soil and also decrease the use of chemicals thus which in turn reduces production costs for farmers. With the issues of soil health, climate change, and sustainable food production at large present, we see that composting and vermicomposting are key elements in organic crop production. They do well in transforming farm waste into useful products and at the same time put forth economic and environmental sound agricultural practices which very much in demand today in modern agriculture.

Introduction

The increasing demand for safe, nutritious food and the growing concern over environmental degradation have led to a shift toward organic farming practices. Among these, composting and vermicomposting have gained significant attention as sustainable and eco-friendly methods of managing organic waste and improving soil fertility. Composting involves the natural decomposition of organic materials such as crop residues, farm waste, and animal manure into a stable, nutrient-rich product. Vermicomposting enhances this process by utilizing earthworms to convert organic waste into high-quality vermicast, which is rich in essential plant nutrients and beneficial microorganisms. These practices play a crucial role in maintaining soil health by improving soil structure, aeration, and water-holding capacity. They also promote microbial activity, which is vital for nutrient cycling and plant growth. Unlike chemical fertilizers, compost and vermicompost release nutrients slowly, ensuring long-term soil productivity and reducing environme-

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ntal pollution. In organic crop production systems, where the use of synthetic inputs is restricted, these natural amendments serve as a reliable source of nutrients. Therefore, composting and Vermicomposting are integral to achieving sustainable agriculture and enhancing crop yield while preserving ecological balance.

Concept and Process Vermicomposting

Vermiculture means "worm-farming". Earthworms feed on the organic waste materials and give out excreta in the form of "vermicasts" that are rich in nitrates and minerals such as phosphorus, magnesium, calcium and potassium. These are used as fertilizers and enhance soil quality. Vermicomposting is the scientific method of making compost, by using earthworms. They are commonly found living in soil, feeding on biomass and excreting it in a digested form. "Vermicomposting is a process in which the earthworms convert the organic waste into manure rich in high nutritional content."

Vermicomposting comprises two methods:

Bed Method: Composting is done on the pucca / kachcha floor by making bed (6x2x2 feet size) of organic mixture. This method is easy to maintain and to practice.

Pit Method: Composting is done in the cemented pits of size 5x5x3 feet. The unit is covered with thatch grass or any other locally available materials. This method is not preferred due to poor aeration, water logging at bottom, and more cost of production.

Process of Vermicomposting

This process is mainly required to add nutrients to the soil. Compost is a natural fertilizer that allows an easy flow of water to the growing plants. The earthworms are mainly used in this process as they eat the organic matter and produce castings through their digestive systems.

The nutrients profile of vermicompost's are

- ✓ 1.6 per cent of Nitrogen
- ✓ 0.7 per cent of Phosphorus
- ✓ 0.8 per cent of Potassium
- ✓ 0.5 per cent of Calcium
- ✓ 0.2 per cent of Magnesium
- ✓ 175 ppm of Iron
- ✓ 96.5 ppm of Manganese
- ✓ 24.5 ppm of Zinc

Materials Required

- ✓ Water
- ✓ Cow dung
- ✓ Thatch Roof
- ✓ Soil or Sand
- ✓ Gunny bags
- ✓ Earthworms
- ✓ Weed biomass
- ✓ A large bin (plastic or cemented tank)
- ✓ Dry straw and leaves collected from paddy fields
- ✓ Biodegradable wastes collected from fields and kitchen

Procedure

- ✓ To prepare compost, either a plastic or a concrete tank can be used. The size of the tank depends upon the availability of raw materials.
- ✓ Collect the biomass and place it under the sun for about 8-12 days. Now chop it to the required size using the cutter.
- ✓ Prepare a cow dung slurry and sprinkle it on the heap for quick decomposition.
- ✓ Add a layer (2-3 inch) of soil or sand at the bottom of the tank.
- ✓ Now prepare fine bedding by adding partially decomposed cow dung, dried leaves and other biodegradable wastes collected from fields and kitchen. Distribute them evenly on the sand layer.
- ✓ Continue adding both the chopped bio-waste and partially decomposed cow dung layer-wise into the tank up to a depth of 0.5-1.0 ft.
- ✓ After adding all the bio-wastes, release the earthworm species *Eisenia foetida, Eudrillus eugeniae* over the mixture and cover the compost mixture with dry straw or gunny bags.
- ✓ Sprinkle water on a regular basis to maintain the moisture content of the compost.
- ✓ Cover the tank with a thatch roof to prevent the entry of ants, lizards, mouse, snakes, etc. and protect the compost from rainwater and direct sunshine.
- ✓ Have a frequent check to avoid the compost from overheating. Maintain proper moisture and temperature.

Result

After the 24th day, around 4000 to 5000 new worms are introduced and the entire raw material is turned into the vermicompost. The vermicompost becomes ready for harvesting when it turns dark brown or black, has a fine, granular structure, and gives an earthy smell, usually within 45-60 days of preparation.

Advantages of Vermicomposting

The major benefits of vermicomposting

- ✓ Develops roots of the plants.
- ✓ Improves the physical structure of the soil.
- ✓ Vermicomposting increases the fertility and water-resistance of the soil.
- ✓ Helps in germination, plant growth, and crop yield.
- ✓ Nurtures soil with plant growth hormones such as auxins, gibberellic acid, etc.

Concept and Process Composting

Composting is the natural process of decomposition of organic matter by microorganisms under controlled conditions. Raw organic materials such as crop residues, animal wastes, food garbage, some municipal wastes and suitable industrial wastes, enhance their suitability for application to the soil as a fertilizing resource, after having undergone composting. A mass of rotted organic matter made from waste is called compost. The compost made from farm waste like sugarcane trash, paddy straw, weeds and other plants and other waste is called farm compost. The average nutrient contents of farm compost are 0.5 per cent N, 0.15 per cent P_2O_5 and 0.5 per cent K_2O. The nutrient value of farm compost

can be increased by application of superphosphate or rock phosphate at 10 to 15 kg t^{-1} of raw material at the initial stage of filling the compost pit. The compost made from town refuses like night soil, street sweepings and dustbin refuse is called town compost. It contains 1.4 per cent N, 1.00 per cent P_2O_5 and 1.4 per cent K_2O. Farm compost is made by placing farm wastes in trenches of suitable size, say, 4.5 m to 5.0 m long, 1.5m to 2.0 m wide and 1.0 m to 2.0 m deep. Farm waste is placed in the trenches layer by layer. Each layer is well moistened by sprinkling cow dung slurry or water. Trenches are filled up to a height of 0.5 m above the ground. The compost is ready for application within five to six months. Composting is essentially a microbiological decomposition of organic residues collected from rural area (rural compost) or urban area (urban compost).

Methods of composting

Coimbatore method: In Coimbatore method, composting is done in pits of different sizes depending on the waste material available. A layer of waste materials is first laid in the pit. It is moistened with a suspension of 5-10 kg cow dung in 2.5 to 5.0 l of water and 0.5 to 1.0 kg fine bone meal sprinkled over it uniformly. Similar layers are laid one over the other till the material rises 0.75 m above the ground level. It is finally plastered with wet mud and left undisturbed for 8 to 10 weeks. Plaster is then removed, material moistened with water, given a turning and made into a rectangular heap under a shade. It is left undisturbed till its use.

Indore method: In the Indore method of composting, organic wastes are spread in the cattle shed to serve as bedding. Urine-soaked material along with dung is removed every day and formed into a layer of about 15 cm thick at suitable sites. Urine-soaked earth, scraped from cattle sheds is mixed with water and sprinkled over the layer of wastes twice or thrice a day. Layering process continued for about a fortnight. A thin layer of well decomposed compost is sprinkled over top and the heap given a turning and reformed. Old compost acts as inoculum for decomposing the material. The heap is left undisturbed for about a month. Then it is thoroughly moistened and given a turning. The compost is ready for application in another month.

Bangalore method: In the Bangalore method of composting, dry waste material of 25 cm thick is spread in a pit and a thick suspension of cow dung in water is sprinkled over for moistening. A thin layer of dry waste is laid over the moistened layer. The pit is filled alternately with dry layers of material and cow dung suspension till it rises 0.5 m above ground level. It is left exposed without covering for 15 days. It is given a turning, plastered with wet mud and left undisturbed for about 5 months or till required. In Coimbatore method, there is anaerobic decomposition to start with, following by aerobic fermentation. It is the reverse in Bangalore method. The Bangalore compost is not so thoroughly decomposed as the Indore compost or even as much as the Coimbatore compost, but it is bulkiest. Compost is a rich source of organic matter.

Soil organic matter plays an important role in sustaining soil fertility, and hence in sustainable agricultural production. In addition to being a source of plant nutrient, it improves the physico-chemical and biological properties of the soil. As a result of these improvements, the soil:

- ✓ Becomes more resistant to stresses such as drought, diseases and toxicity
- ✓ Helps the crop in improved uptake of plant nutrients
- ✓ Possesses an active nutrient cycling capacity because of vigorous microbial activity.

These advantages manifest themselves in reduced cropping risks, higher yields and lower outlays on inorganic fertilizers for farmers.

Impact on Soil Health

Composting and vermicomposting have a significant positive impact on soil health by improving its physical, chemical, and biological properties. They increase organic matter content, which enhances soil structure, aeration, and root penetration. These practices also boost beneficial microbial activity, promoting efficient nutrient cycling and availability to plants. Vermicompost, in particular, contains growth-promoting substances and enzymes that support plant development. Additionally, they improve water-holding capacity and reduce soil erosion. Regular application helps maintain soil fertility over the long term, making the soil more resilient, productive, and suitable for sustainable organic crop production systems.

Comparison with Chemical Fertilizers

Composting and vermicomposting play a vital role in organic crop production systems when compared to chemical fertilizers. Organic manures such as compost and vermicompost release nutrients slowly and steadily, ensuring long-term availability and reducing nutrient losses through leaching. In contrast, chemical fertilizers provide immediate nutrients but often lead to nutrient imbalance and rapid depletion of soil health if used excessively. Compost improves soil structure, enhances microbial activity, and increases water-holding capacity, whereas chemical fertilizers do not contribute to these physical and biological properties of soil. Moreover, composting is environmentally friendly and helps recycle organic waste, while chemical fertilizers may cause soil and water pollution. Although chemical fertilizers can boost short-term yields, composting and vermicomposting support sustainable agriculture by maintaining soil fertility, improving crop quality, and ensuring long-term productivity.

Economic Benefits for Farmers

Composting and vermicomposting provide significant economic advantages by reducing the overall cost of cultivation. Farmers can utilize locally available materials such as crop residues, animal dung, and farm waste to produce organic manure, minimizing the need to purchase expensive chemical fertilizers. This leads to substantial savings, especially for small and marginal farmers. Additionally, the use of on-farm inputs reduces dependency on external resources, making farming more self-reliant

and resilient to market price fluctuations. Vermicomposting can also generate additional income, as surplus vermicompost can be sold in local markets. Over time, improved soil health and fertility result in stable yields and reduced input requirements, further lowering production costs and increasing profitability.

Challenges

Composting and vermicomposting involve several practical challenges for farmers. These processes are time-consuming, often taking 45-60 days or more for completion, which may not align with immediate nutrient needs. They require regular labour for activities like turning, watering, and monitoring the compost beds. Maintaining proper moisture levels is critical, especially in vermicomposting, as earthworms are sensitive to dryness and excess water. Temperature control and protection from extreme weather conditions also add to the difficulty. In many areas, farmers lack proper training and awareness, which leads to poor management practices and reduced efficiency of compost production.

Limitations

Despite their benefits, composting and vermicomposting have certain limitations. The nutrient content of compost is relatively lower compared to chemical fertilizers, requiring larger quantities for effective crop nutrition. These methods also need sufficient space for compost pits or beds, which may not be available to all farmers. Initial setup and maintenance costs, though low, can still be a constraint for small farmers. Additionally, the quality of compost may vary depending on raw materials and management practices. Slow nutrient release may not meet the immediate demands of crops, making it less suitable as a sole nutrient source in intensive farming systems.

Emerging Trends in Agriculture: Transforming Farming for the Future

G. Shashidhar, G. Prasanna Laxmi and Karre Anusha

Introduction

Agriculture has always been the backbone of human civilization, but in recent years it has entered a phase of rapid transformation. Increasing population, climate change, limited natural resources and rising demand for food have forced the agricultural sector to adopt innovative approaches. Traditional farming methods alone are no longer sufficient to meet global food requirements. Emerging trends in agriculture focus on integrating modern technology, scientific knowledge and sustainable practices to improve productivity and efficiency. These trends are reshaping agriculture into a more precise, intelligent and environmentally friendly system. The future of farming lies in adopting these advancements to ensure food security and sustainability.

Artificial Intelligence in Agriculture

Artificial Intelligence (AI) is becoming an essential tool in modern agriculture. It involves the use of machine learning algorithms, data analytics and automation to assist farmers in decision-making. AI systems can analyze large amounts of data related to weather conditions, soil properties, crop growth and pest outbreaks. Based on this information, farmers can make better decisions regarding irrigation, fertilization and pest control. One of the major applications of AI is in crop disease detection. Using image recognition technology, AI can identify diseases at an early stage, allowing farmers to take preventive measures. AI is also used in yield prediction, helping farmers estimate production and plan accordingly. In addition, AI-powered machinery such as autonomous tractors and robotic harvesters are reducing labour dependency and increasing efficiency. These technologies not only save time but also improve accuracy in farming operations.

Precision Farming: Precision farming is one of the most important emerging trends in agriculture. It involves managing crops and soil variability using advanced technologies such as GPS, sensors, drones and data analytics. In conventional farming, inputs like water and fertilizers are applied uniformly across the field. However, in reality, soil fertility and crop requirements vary within a field. Precision farming addresses this issue by applying inputs in a site-specific manner. For example, sensors can measure soil moisture levels and irrigation systems can supply water only where needed. Similarly, fertilizers can be applied based on nutrient requirements of specific zones within a field. Precision farming leads to better

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resource utilization, reduced input costs and higher crop yields. It also minimizes environmental pollution caused by excessive use of fertilizers and chemicals.

Climate-Smart Agriculture: Climate change is one of the biggest challenges facing agriculture today. Irregular rainfall, extreme temperatures and natural disasters are affecting crop production worldwide. Climate-smart agriculture (CSA) is an approach designed to address these challenges.

CSA focuses on three main objectives:

- ✓ Increasing agricultural productivity
- ✓ Enhancing resilience to climate change
- ✓ Reducing greenhouse gas emissions

Farmers adopt practices such as drought-resistant crop varieties, efficient water management, and improved soil conservation techniques. These practices help maintain productivity even under adverse climatic conditions. Climate-smart agriculture ensures that farming systems remain sustainable and adaptable in the face of changing environmental conditions.

Internet of Things (IoT) in Agriculture: The Internet of Things (IoT) is revolutionizing agriculture by connecting devices and sensors to collect real-time data from the field. These sensors monitor parameters such as soil moisture, temperature, humidity and nutrient levels. The data collected is transmitted to farmers through mobile applications or computer systems. Based on this information, farmers can take timely actions such as irrigation, fertilization or pest control. For example, smart irrigation systems use soil moisture sensors to automatically supply water only when needed. This not only saves water but also improves crop growth. IoT technology makes farming more efficient, precise and less dependent on manual observation.

Vertical Farming and Soilless Agriculture: With the increasing scarcity of arable land, vertical farming and soilless agriculture are gaining importance. Vertical farming involves growing crops in stacked layers, often in controlled indoor environments. Techniques such as hydroponics (growing plants in nutrient solutions), aeroponics (growing plants in air with mist nutrients) and aquaponics (combining fish farming with plant cultivation) are used in soilless agriculture. These systems require less water, space and pesticides compared to traditional farming. They also allow year-round production, independent of weather conditions. Vertical farming is particularly useful in urban areas where land availability is limited.

Agricultural Robotics and Automation: Automation is playing a significant role in modern agriculture. Robots and automated machines are being used for various farming operations such as planting, weeding, harvesting and spraying. Robotic systems can perform tasks with high precision and efficiency. For example, automated weeders can identify and remove weeds without damaging crops. Similarly, drones are used for spraying fertilizers and pesticides over large areas. Automation reduces labour costs and increases productivity. It also ensures timely completion of farm operations, which

is crucial for crop growth and yield.

Biotechnology and Improved Crop Varieties: Biotechnology is another important emerging trend in agriculture. It involves the use of scientific techniques to develop improved crop varieties with desirable traits. Through genetic engineering and gene editing, crops can be made resistant to pests, diseases, and environmental stresses such as drought and salinity. These improved varieties help increase productivity and reduce dependence on chemical inputs. Biotechnology also plays a role in improving nutritional quality of crops, contributing to better human health.

Blockchain Technology in Agriculture: Blockchain technology is emerging as a tool to improve transparency and efficiency in the agricultural supply chain. It allows tracking of agricultural products from farm to consumer. This ensures food safety, prevents fraud and provides fair prices to farmers. Consumers can also access information about the origin and quality of the food they purchase. Blockchain strengthens trust between farmers, traders and consumers.

Sustainable and Regenerative Agriculture: Sustainability is becoming a central focus in agriculture. Practices such as organic farming, conservation agriculture, and regenerative agriculture aim to protect natural resources and improve soil health. These practices include crop rotation, cover cropping, reduced tillage and use of organic inputs. They help maintain soil fertility, reduce erosion and improve water retention. Sustainable agriculture ensures long-term productivity while minimizing environmental impact.

Challenges in the Adoption of Emerging Technologies

Despite their benefits, emerging agricultural technologies face several challenges:

- ✓ High initial cost of equipment and technology
- ✓ Lack of awareness and technical knowledge among farmers
- ✓ Limited access to digital infrastructure in rural areas
- ✓ Small landholdings in developing countries

To overcome these challenges, government support, training programs and affordable technologies are essential.

Conclusion

Emerging trends in agriculture are transforming the sector into a more efficient, productive, and sustainable system. Technologies such as artificial intelligence, IoT, precision farming and biotechnology are helping farmers improve productivity while conserving resources. The integration of modern innovations with traditional farming practices is essential for ensuring food security and environmental sustainability. By adopting these emerging trends, agriculture can meet future challenges and provide a stable food supply for the growing global population.

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Bioremediation and Phytoremediation for Sustainable Water Pollution Management

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Abstract

Water pollution caused by industrial, agricultural, and domestic activities is a major environmental concern worldwide. Bioremediation and phytoremediation are sustainable, eco-friendly technologies that use microorganisms and plants to remove, degrade, or stabilize pollutants from contaminated water. These methods are cost-effective, energy-efficient, and suitable for treating heavy metals, nutrients, pesticides, dyes, and organic wastes. They also support ecosystem restoration and biodiversity improvement. Although some limitations exist, recent advances such as genetic engineering, nanotechnology, and hybrid systems are enhancing their efficiency. Therefore, these green technologies offer promising solutions for sustainable water pollution management and long-term environmental protection.

Introduction

Water pollution is the contamination of rivers, lakes, groundwater, oceans, and other water bodies by harmful physical, chemical, or biological substances that reduce water quality and threaten human health and aquatic ecosystems. Common pollutants include industrial effluents, domestic sewage, agricultural runoff, heavy metals, pesticides, plastics, and pathogenic microorganisms. Rapid industrialization, urbanization and population growth have greatly increased the discharge of these pollutants, making water pollution a major global environmental challenge. Sustainable water pollution management is essential to ensure the availability of clean water for drinking, agriculture, fisheries, industry, and ecosystem balance. Polluted water can cause serious health problems, biodiversity loss, reduced agricultural productivity, and economic damage. Therefore, effective management strategies must focus on long-term environmental protection, efficient resource use, and reduced ecological impact. Eco-friendly remediation technologies are gaining importance because conventional treatment methods are often expensive, energy-intensive, and may produce secondary waste. Green treatment approaches use natural processes to remove contaminants in a safer and more sustainable manner. Among these, bioremediation and phytoremediation are promising solutions. Bioremediation uses micro-organisms such as bacteria, fungi, and algae to degrade or detoxify pollutants, while phytoremediation uses plants to absorb, stabilize, or remove contaminants from water and sediments. Both methods are cost-effective, environmentally friendly

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and suitable for sustainable water quality improvement. Their increasing adoption can play a significant role in addressing modern water pollution problems.

Water Pollution: Sources and Types

Water pollution arises when harmful substances enter water bodies such as rivers, lakes, ponds, groundwater, and oceans, reducing water quality and making it unsafe for human use and aquatic life. These pollutants originate from various natural and human-made sources, with anthropogenic activities being the major contributors. Industrial wastewater is one of the leading sources of water pollution. Industries such as textile, paper, leather, chemical, mining, and pharmaceutical units discharge wastewater containing dyes, acids, alkalis, oils, suspended solids, and toxic substances. If untreated, these effluents can severely damage aquatic ecosystems and contaminate drinking water sources. Agricultural runoff is another major source of pollution. Excessive use of chemical fertilizers, pesticides, herbicides, and animal manure in farming leads to the washing of nutrients and toxic residues into nearby water bodies during rainfall or irrigation. This often causes eutrophication, algal blooms, and oxygen depletion. Domestic sewage includes wastewater generated from households, kitchens, bathrooms, and sanitation systems. It contains organic matter, detergents, nutrients, plastics, and disease-causing microorganisms. Discharge of untreated sewage into rivers and lakes creates foul odor, lowers dissolved oxygen and spreads water-borne diseases (Viman *et al*., 2010). Heavy metals and toxic chemicals such as lead, mercury, cadmium, chromium, and arsenic are highly dangerous pollutants commonly released from industries, mining, batteries, and electronic waste. These substances are non-biodegradable, accumulate in aquatic organisms, and may enter the food chain, causing serious health risks. Organic pollutants and pathogens include petroleum hydrocarbons, dyes, solvents, pharmaceuticals, bacteria, viruses, and parasites. Organic pollutants increase biological oxygen demand (BOD), while pathogens cause diseases such as cholera, typhoid, and dysentery. Understanding the major sources and types of water pollution is essential for developing effective and sustainable management strategies to protect water resources and public health.

Bioremediation: Bioremediation is a sustainable and environmentally friendly process that uses living microorganisms to remove, degrade, or neutralize pollutants from contaminated water and other environments. It mainly involves bacteria, fungi,

algae, and other microbes that naturally break down harmful substances through their metabolic activities. These microorganisms use pollutants as a source of energy or nutrients and convert them into less toxic or harmless products such as carbon dioxide, water, and biomass. Because of its natural approach, bioremediation is considered an effective alternative to conventional chemical and physical treatment methods, which are often costly and may create secondary pollution. Bioremediation is broadly classified into two main types: in situ bioremediation and ex situ bioremediation. In situ bioremediation refers to the treatment of contaminants directly at the polluted site without removing the contaminated water or sediments. This method is commonly used in rivers, lakes, ponds, groundwater, and soil, and it is cost-effective because it requires less transportation and handling. Ex situ bioremediation, on the other hand, involves removing contaminated materials from the original site and treating them in controlled environments such as tanks, lagoons, or bioreactors. This method allows better control of factors such as temperature, pH, oxygen supply, and nutrient levels, resulting in faster and more efficient treatment (Abatenh *et al*., 2017). The success of bioremediation depends on several important mechanisms. Microbial degradation is the most common mechanism, where microorganisms enzymatically break down complex organic pollutants such as petroleum hydrocarbons, pesticides, and industrial chemicals into simpler and non-toxic compounds.

Biosorption is another mechanism in which contaminants, especially heavy metals, are adsorbed onto the surface of microbial cells through physical or chemical interactions. This process is highly useful for removing metals like lead, cadmium, and chromium from wastewater. Bioaccumulation involves the uptake and storage of pollutants within microbial cells, thereby reducing their concentration in water.

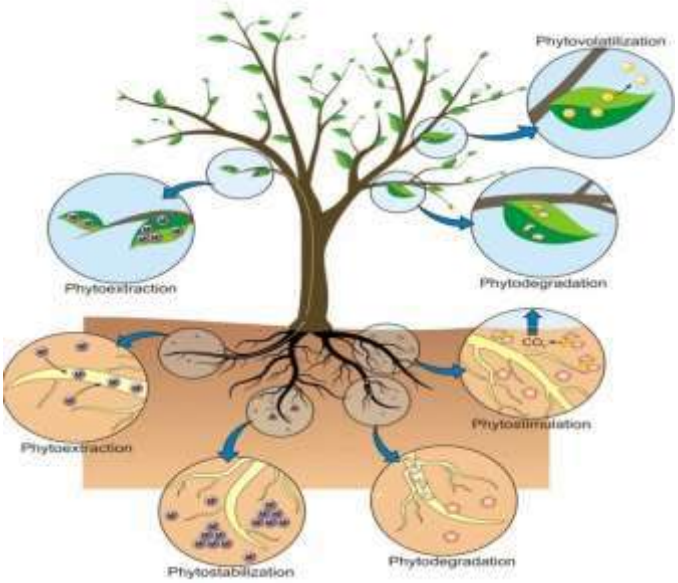
These biological processes work individually or together to detoxify polluted environments effectively. Bioremediation has wide applications in water treatment and pollution management. It is extensively used in oil spill cleanup, where hydrocarbon-degrading bacteria help break down crude oil and petroleum products in marine and freshwater systems. It is also an important part of wastewater treatment, where microbial communities in activated sludge systems and biofilters remove organic matter, nutrients, and suspended solids from domestic and industrial effluents. In addition, bioremediation is highly effective in the removal of

pesticides and dyes, particularly in agricultural runoff and textile wastewater, where specialized microbes degrade toxic chemicals and reduce color pollution. Due to its low cost, eco-friendly nature, and ability to treat a wide range of contaminants, bioremediation has become a valuable tool for sustainable water pollution management.

Phytoremediation

Phytoremediation is an environmentally friendly and cost-effective technology that uses plants to remove, absorb, degrade, stabilize, or contain pollutants from contaminated water, soil, and sediments. It is based on the natural ability of certain plants to take up nutrients and toxic substances through their roots and store or transform them into less harmful forms. This green remediation method has gained significant attention as a sustainable alternative to conventional treatment systems because it is simple, economical, and aesthetically beneficial (Sharma *et al.,* 2023). Phytoremediation includes several important processes. Phyto-extraction involves the uptake of pollutants, especially heavy metals, from water or sediments by plant roots and their accumulation in stems, leaves, or shoots, after which the plants can be harvested safely. Phytodegradation refers to the breakdown of organic contaminants such as pesticides, hydro-carbons and other toxic compounds within plant tissues through metabolic activities.

Phytostabilization is the use of plants to immobilize pollutants in the root zone or sediments, thereby preventing their movement into water bodies or the food chain. Rhizofiltration is a process in which plant roots absorb, adsorb, or precipitate contaminants from polluted water, making it particularly useful for treating wastewater and industrial effluents. A variety of aquatic and terre-strial plants are commonly used in phytoremediation because of their rapid growth, high biomass production, and pollutant tolerance. Water hyacinth (*Eichhornia crassipes*) is widely used for removing nutrients, suspended solids, and heavy metals from wastewater. Duckweed (*Lemna minor*) is a small floating plant effective in absorbing nitrogen, phosphorus, and organic matter from ponds and lagoons. Sunflower (*Helianthus annuus*) is known for its ability to accumulate heavy metals such as lead, cadmium, and uranium, while Vetiver grass (*Vetiveria zizanioides*) is highly valued for stabilizing sediments and absorbing toxic chemicals due to its deep and dense root system. Phytoremediation has several practical applications in water treatment.



It is widely used for heavy metal removal, where plants absorb metals such as chromium, arsenic, mercury, lead, and cadmium from contaminated water. It also plays an important role in nutrient reduction by removing excess nitrogen and phosphorus that cause eutrophication and algal blooms in lakes and ponds. In addition, phytoremediation is commonly used for wastewater polishing, which is the final stage of treatment where plants further improve water quality by reducing suspended solids, odors, pathogens, and residual contaminants after primary or secondary treatment. Constructed wetlands, oxidation ponds, and floating treatment wetlands are common examples of systems using phytoremediation. Due to its low operational cost, minimal energy requirement, eco-friendly nature, and ability to improve habitat quality, phytoremediation has become an important tool for sustainable water pollution management.

Role in Sustainable Water Pollution Management

Bioremediation and phytoremediation play an important role in sustainable water pollution management because they provide effective treatment through natural and low-cost methods. These technologies require less investment, lower operational costs, and minimal energy compared with conventional chemical or mechanical treatment systems, making them suitable for both developing and developed regions. They are considered environment-friendly methods because they use microorganisms and plants to remove pollutants without generating harmful secondary waste.

As renewable and natural processes, they rely on biological activities that can continue over time with proper management and maintenance. Plants used in phytoremediation can regrow naturally, while microorganisms multiply under favorable conditions ensuring long-term treatment potential. These methods also contribute to the improvement of ecosystem health by restoring water quality, increasing dissolved oxygen levels, reducing toxic substances, and supporting biodiversity. Constructed wetlands and vegetated treatment systems can create habitats for fish, birds and beneficial micro-organisms. Therefore, these green technologies are highly valuable for achieving sustainable and eco-friendly water management (Makanda *et al.*, 2022).

Advantages

Bioremediation and phytoremediation provide several valuable advantages for sustainable water pollution management. They are highly cost-effective because they require lower capital investment, reduced energy consumption, and minimal maintenance costs compared with conventional chemical and mechanical treatment systems. Their simple operation makes them easy to implement and manage, as these methods mainly depend on natural processes involving microorganisms and plants rather than complex machinery. Another important benefit is the reduced use of chemicals, which lowers the chances of producing harmful by-products or secondary pollution and makes the treatment process safer for the environment. These technologies are also well suited for developing countries, where

access to expensive treatment infrastructure may be limited. They can be applied in rural and urban areas using locally available resources and natural systems. Overall, bioremediation and phyto-remediation are practical, eco-friendly, and affordable solutions for improving water quality and supporting sustainable environmental management.

Limitations

Bioremediation and phytoremediation also have certain limitations. These methods are often a slow process, requiring weeks or months to achieve significant pollutant removal. Their effectiveness is site-specific, as treatment performance depends on environmental factors such as pH, temperature, oxygen level, and pollutant concentration. In phytoremediation, plant growth and remediation efficiency may show seasonal dependency, especially during winter, drought, or unfavorable weather conditions. Additionally, these technologies are limited for highly toxic pollutants, since excessive contamination can inhibit microbial activity or damage plant growth. Therefore, careful planning and monitoring are necessary for successful application (Doran, 2009).

Future Prospects

The future of bioremediation and phyto-remediation is highly promising due to continuous scientific and technological advancements. Genetic engineering of microbes and plants can significantly improve remediation efficiency by developing organisms with enhanced ability to degrade toxic chemicals, tolerate harsh environmental conditions, and absorb heavy metals more effectively. Such modified species may provide faster and more targeted pollutant removal. The integration of nanotechnology is another important advancement. Nanomaterials can enhance adsorption capacity, improve contaminant breakdown, and support microbial growth, leading to better treatment performance. Combining biological systems with nanoparticles may increase the removal of persistent pollutants from wastewater. Hybrid remediation systems, which combine bioremediation, phytoreme-diation and conventional treatment methods, are expected to become more effective and reliable. Examples include constructed wetlands with microbial inoculation, biofilters with aquatic plants, and combined physical-biological treatment units. These systems can treat multiple pollutants simultaneously and improve overall efficiency. In the future, large-scale implementation of these technologies is likely to expand in urban wastewater treatment, industrial effluent management, agricultural runoff control, and restoration of polluted rivers and lakes. With proper research, policy support, and public awareness, these green technologies can play a major role in sustainable water pollution management worldwide.

Conclusion

Bioremediation and phytoremediation have emerged as effective, eco-friendly, and sustainable approaches for managing water pollution in the modern world. With increasing contamination of water resources from industrial wastewater, agricul-

tural runoff, domestic sewage, heavy metals, and toxic chemicals, the need for affordable and environmentally safe treatment technologies has become more important than ever. These biological methods use the natural potential of microorganisms and plants to remove, degrade, stabilize, or detoxify pollutants without causing significant environmental harm. Both technologies offer several advantages, including low operational cost, reduced chemical usage, simple implementation, and suitability for rural as well as urban areas. They also contribute to ecosystem restoration by improving water quality, supporting biodiversity, and creating healthier aquatic environments. Although certain limitations such as slow treatment rate, seasonal dependency, and reduced efficiency under highly toxic conditions still exist, ongoing research and innovation are continuously improving their performance. Future developments such as genetic engineering, nanotechnology integration, and hybrid treatment systems are expected to enhance their efficiency and expand their practical applications on a larger scale. Therefore, bioremediation and phytoremediation represent valuable green solutions for sustainable water pollution management. Their wider adoption can help conserve water resources, protect public health, and support long-term environmental sustainability for future generations.

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Biochar as a Soil Amendment: Impacts on Nutrient Dynamics and Crop Productivity

Gaytri Soni

Introduction

Biochar has emerged as a promising soil amendment in modern agriculture due to its potential to improve soil health, enhance nutrient availability, and increase crop productivity in a sustainable manner. Produced through the pyrolysis of organic biomass under limited oxygen conditions, biochar is a stable, carbon-rich material that can persist in soils for long periods. Its unique physical and chemical properties such as high porosity, large surface area, and strong adsorption capacity enable it to influence soil processes in ways that conventional amendments often cannot. In agricultural systems, nutrient dynamics play a critical role in determining soil fertility and crop performance. However, challenges such as nutrient leaching, low nutrient use efficiency, and soil degradation continue to limit productivity, particularly in tropical and semi-arid regions. Biochar has been shown to modify these dynamics by retaining essential nutrients, improving cation exchange capacity, and enhancing microbial activity. These changes can lead to more efficient nutrient cycling and reduced losses, ultimately supporting better plant growth. Furthermore, the application of biochar can improve key soil properties, including water retention, pH balance, and soil structure. These improvements create a more favorable environment for root development and microbial interactions, which are essential for nutrient uptake. As a result, biochar not only contributes to immediate increases in crop yield but also supports long-term soil sustainability.

Properties of Biochar Relevant to Soil Systems

Biochar's effectiveness as a soil amendment is largely determined by a set of distinctive physical, chemical, and biological properties that influence soil processes and plant growth. These properties vary depending on the type of feedstock used (e.g., crop residues, wood, manure) and the conditions of pyrolysis, but several key characteristics consistently make biochar relevant to soil systems. One of the most important physical properties of biochar is its high porosity and large surface area. The porous structure improves soil aeration and water retention, which is especially beneficial in sandy or degraded soils. These pores also act as microhabitats for soil microorganisms, supporting microbial colonization and activity. Improved water-holding capacity helps plants withstand short-term drought stress, making biochar particularly useful in semi-arid regions.

Chemically, biochar is known for its high cation exchange capacity (CEC), which allows it to retain and exchange essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), calci-

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um (Ca), and magnesium (Mg). This reduces nutrient leaching and increases nutrient availability to plants over time. Biochar can also influence soil pH; most biochars are alkaline in nature and can help neutralize acidic soils, improving nutrient solubility and uptake. Another important chemical feature is its stability. Biochar contains a high proportion of aromatic carbon structures, making it resistant to microbial decomposition. This stability allows biochar to remain in the soil for hundreds to thousands of years, contributing to long-term carbon sequestration and sustained soil improvement. From a biological perspective, biochar interacts with soil microbial communities by providing habitat and influencing microbial processes. It can enhance beneficial microbial populations, including nitrogen-fixing bacteria and mycorrhizal fungi, which play a crucial role in nutrient cycling. Additionally, biochar can adsorb organic compounds and toxins, potentially reducing soil contaminants and improving overall soil health.

Impact on Nutrient Dynamics

The application of biochar to soil significantly alters nutrient dynamics, influencing the availability, retention, transformation, and overall efficiency of nutrients essential for plant growth. These effects arise from biochar's unique physical structure, chemical composition, and its interaction with soil microorganisms. As a result, biochar plays a vital role in improving soil fertility and promoting sustainable agricultural productivity, particularly in nutrient-deficient or degraded soils. One of the most notable impacts of biochar is its ability to enhance nutrient retention and reduce leaching losses. Due to its highly porous structure and large surface area, biochar can adsorb nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). In soils prone to leaching especially sandy soils or those experiencing heavy rainfall nutrients are often lost beyond the root zone. Biochar helps to trap these nutrients within its pores and on its surfaces, making them available to plants over a longer period and improving nutrient use efficiency.

Another key contribution of biochar is its role in increasing the cation exchange capacity (CEC) of soils. CEC is a measure of the soil's ability to hold and exchange positively charged ions (cations). Biochar surfaces, particularly after aging in soil, develop functional groups that enhance their ability to attract and retain cations. This increased CEC ensures a more stable supply of essential nutrients to plants and reduces the need for frequent fertilizer applications. Soils amended with biochar often show improved nutrient buffering capacity, which stabilizes nutrient availability even under fluctuating environmental conditions.

Biochar also has a significant influence on nitrogen cycling within the soil. Nitrogen is one of the most dynamic and essential nutrients, often subject to losses through leaching, volatilization, and denitrification. Biochar can reduce these losses by adsorbing ammonium (NH_4^+) and nitrate (NO_3^-), thereby slowing their movement through the soil.

Additionally, biochar creates a favorable habitat for soil microorganisms involved in nitrogen transformations, such as nitrogen-fixing bacteria and nitrifying organisms. This can enhance biological nitrogen fixation and promote more efficient conversion of nitrogen into forms that plants can absorb. However, in some cases, biochar may temporarily immobilize nitrogen, particularly if it has a high carbon-to-nitrogen ratio, which should be considered in management practices.

Phosphorus availability is another critical aspect of nutrient dynamics influenced by biochar. In many soils, especially acidic or highly weathered tropical soils, phosphorus becomes fixed and unavailable to plants due to interactions with iron and aluminum oxides. Biochar can improve phosphorus availability by increasing soil pH, which reduces phosphorus fixation, and by directly supplying small amounts of phosphorus depending on the feedstock used. Moreover, biochar can enhance microbial activity, including phosphate-solubilizing bacteria, which further contributes to making phosphorus more accessible to plants.

Effects on Soil Biological Activity

Biochar plays a significant role in shaping soil biological activity by influencing the abundance, diversity, and functioning of soil microorganisms. Its highly porous structure provides a protective habitat for microbes, shielding them from environmental stresses such as desiccation and predation. These microhabitats create favorable conditions for the colonization and proliferation of beneficial microorganisms, including bacteria, fungi, and actinomycetes, which are essential for soil health and nutrient cycling. One of the key impacts of biochar is the stimulation of microbial biomass and activity. By improving soil aeration, moisture retention, and nutrient availability, biochar creates an environment that supports microbial growth. Enhanced microbial activity accelerates the decomposition of organic matter and promotes the release of nutrients in plant-available forms. This leads to more efficient nutrient cycling and improved soil fertility over time.

Biochar also influences the composition of microbial communities. It tends to favor beneficial groups such as nitrogen-fixing bacteria and mycorrhizal fungi. These organisms play a crucial role in nutrient acquisition nitrogen-fixing bacteria convert atmospheric nitrogen into usable forms, while mycorrhizal fungi enhance the uptake of phosphorus and other immobile nutrients by extending the root system's effective reach. As a result, plants grown in biochar-amended soils often exhibit improved nutrient uptake and growth. Another important effect of biochar is its ability to adsorb toxic substances and reduce soil contaminants, which can otherwise inhibit microbial activity. By immobilizing heavy metals and organic pollutants, biochar creates a safer environment for microbial processes to occur. This detoxification effect further supports a healthy and active soil biological community.

Impact on Crop Productivity

The application of biochar has been widely

associated with improvements in crop productivity, primarily through its positive effects on soil physical, chemical, and biological properties. By enhancing soil conditions, biochar creates a more favorable environment for plant growth, leading to better crop performance across a range of agricultural systems. One of the most direct ways biochar influences crop productivity is by improving nutrient availability and use efficiency. As discussed earlier, biochar enhances nutrient retention and reduces leaching losses, ensuring that essential elements such as nitrogen, phosphorus, and potassium remain accessible to plants for longer periods. This sustained nutrient supply supports steady plant growth and can reduce dependence on chemical fertilizers, particularly in nutrient-poor soils.

Biochar also improves soil water relations, which is critical for crop productivity, especially in semi-arid and drought-prone regions. Its porous structure increases the soil's water-holding capacity, allowing crops to access moisture over extended periods. This not only reduces water stress during dry spells but also improves germination rates, root development, and overall plant vigor. In sandy soils, where water drains quickly, biochar can significantly enhance moisture retention, leading to better crop establishment and yield. Another important factor is the improvement in soil structure and aeration.

Environmental Benefits of Biochar

- ✓ Enhances long-term carbon sequestration by storing stable carbon in soils, helping mitigate climate change
- ✓ Reduces greenhouse gas emissions such as nitrous oxide (N_2O) and methane (CH_4) from agricultural soils
- ✓ Improves soil health and prevents land degradation, especially in degraded or nutrient-poor areas
- ✓ Minimizes nutrient leaching, thereby reducing water pollution and eutrophication of water bodies
- ✓ Promotes efficient use of fertilizers, lowering the risk of chemical runoff into ecosystems
- ✓ Supports waste management by converting agricultural and organic residues into useful biochar
- ✓ Improves water retention in soil, reducing irrigation demand and conserving water resources
- ✓ Immobilizes heavy metals and toxins, decreasing soil contamination and environmental risks
- ✓ Enhances biodiversity in soil by supporting beneficial microbial communities
- ✓ Contributes to sustainable agriculture and resilience against climate variabilit

Challenges and Limitations of Biochar

Variability in biochar properties: Biochar characteristics differ widely depending on feedstock (crop residues, wood, manure) and pyrolysis conditions. This inconsistency makes it difficult to predict performance across different soils and crops.

High initial cost and limited accessibility: Production, processing, and transportation of biochar can be expensive, especially for smallholder farmers.

Access to efficient pyrolysis units is still limited in many regions.

Uncertain short-term effects: In some cases, biochar does not show immediate yield benefits and may even temporarily reduce nutrient availability (e.g., nitrogen immobilization), particularly just after application.

Lack of standardized guidelines: There is no universal recommendation for application rates, methods, or types of biochar suitable for specific soils and crops, which can lead to inconsistent results.

Potential contamination risks: If produced from unsuitable feedstocks or under improper conditions, biochar may contain harmful substances such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), or toxins.

Limited awareness and technical knowledge

- ✓ Farmers and practitioners may lack knowledge about proper production techniques, application methods, and long-term benefits, hindering adoption.
- ✓ Slow integration into soil systems: Biochar benefits often develop gradually over time, requiring patience and long-term management rather than providing quick results.
- ✓ Possible alteration of soil pH beyond optimal levels
- ✓ While beneficial in acidic soils, excessive application of alkaline biochar can increase soil pH too much, negatively affecting nutrient availability.
- ✓ Scalability challenges: Producing biochar at a large scale while ensuring sustainability, cost-effectiveness, and environmental safety remains a challenge.
- ✓ Limited long-term field data: Although research is growing, there is still a need for more long-term, location-specific studies to fully understand biochar's impacts under diverse agro-ecological conditions.

Conclusion: Biochar has emerged as a promising soil amendment with significant potential to improve soil health, optimize nutrient dynamics, and enhance crop productivity in a sustainable manner. Its unique physical and chemical properties such as high porosity, stability, and nutrient retention capacity enable it to address key challenges in modern agriculture, including nutrient loss, soil degradation, and low input-use efficiency. By improving soil structure, increasing water-holding capacity, and supporting beneficial microbial activity, biochar creates a more favorable environment for plant growth. In terms of nutrient dynamics, biochar plays a critical role in reducing leaching losses, enhancing cation exchange capacity, regulating nitrogen transformations and improving phosphorus availability. These effects contribute to more efficient nutrient cycling and sustained soil fertility over time. Additionally, its ability to sequester carbon and reduce greenhouse gas emissions highlights its importance not only for agriculture but also for environmental management and climate change mitigation.

Role of Vertical Farming in Food Security

Kathirvel L., Akshaya Lakshmi M. P., Deepa Sindhuja S., Dhatchana S. J., Elakkiyaa M. K., Maragathalakshmi M. and Miruthu Bhashini T.

Abstract

Food security is a big global issue. It stems from population growth, climate change, and limited natural resources. Vertical farming has come forward as a new solution. It allows for growing crops in controlled indoor spaces using stacked layers. This article looks at how vertical farming helps food security by improving availability, accessibility, quality, and stability. It emphasizes the benefits of soilless growing methods like hydroponics and aeroponics. These methods support year-round production while using less water and land. Furthermore, vertical farming promotes sustainable agriculture by reducing environmental harm and providing safe, high-quality food. Despite challenges such as high initial costs and energy use, technology improvements are making this approach more practical. Overall, vertical farming can significantly help with sustainable food production and address future food needs.

Introduction

Food security is one of the most pressing global issues today. The demand for food keeps rising due to rapid population growth, urbanization, and changing dietary habits. According to global estimates, the world population is expected to surpass 9 billion by 2050. This growth will require a significant increase in food production. However, traditional agriculture faces serious challenges like shrinking farmland, deteriorating soil quality, water scarcity, and the negative impacts of climate change. Extreme weather events such as droughts, floods, and heatwaves have made agricultural production more unpredictable and vulnerable (FAO, 2008).

Urban expansion has transformed agricultural land into housing and industrial sites, further reducing available space for farming. Labor shortages in rural areas and rising input costs have also weakened traditional farming. Meanwhile, concerns about food safety and environmental sustainability have increased due to the heavy use of chemical fertilizers and pesticides. In this difficult situation, we need innovative and sustainable farming practices to ensure a stable and reliable food supply. (FAO, 2008) Vertical farming has emerged as a groundbreaking solution that can tackle many of these problems by allowing crop production in controlled indoor environments. By growing crops in vertically stack-

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ed layers using modern technologies, vertical farming makes the most of limited space, reduces resource use, and guarantees year-round production. It represents a move away from traditional farming to technology-driven agriculture and offers significant potential for improving global food security, especially in urban areas (Despommier, 2010).

Factor	Traditional Farming	Vertical Farming
Land use	Large land required	Very low land (multi-layer)
Water usage	High	Up to 98%less water
Yield per area	Normal	10-20 times higher
Climate dependency	High	very low (controlled environment)
Crop production	Seasonal	Year-round production
Transportation	Long distance	Local/short distance

Food Security

Food security is a broad concept that includes not just the availability of food but also access to it, its nutritional quality, and the stability of supply over time. It exists when everyone, at all times, has physical, economic, and social access to enough safe and nutritious food that meets their dietary needs and preferences for a healthy life. The first pillar, availability, relates to producing and supplying enough food through agriculture, imports, and reserves. The second pillar, accessibility, concerns individuals' ability to obtain food, which relies on income levels, market prices, and distribution systems. The third pillar, utilization, focuses on proper nutrition, food safety, and the body's ability to absorb nutrients. The fourth pillar, stability, ensures that food supplies remain steady over time and are not disrupted by events like natural disasters, economic crises, or political instability. In recent years, these pillars have faced increasing threats from global challenges such as climate change, population growth, pandemics, and supply chain disruptions. For instance, extreme weather can lower crop yields, and transportation challenges can hinder food distribution. Vertical farming offers a contemporary solution to these issues by enabling localized, controlled and efficient food production that supports all four pillars of food security. (FAO, 2008).

Vertical Farming

Vertical farming is a modern agricultural method where crops are grown in vertically stacked layers within controlled indoor

environments. Unlike traditional farming, which relies heavily on soil and natural weather conditions, vertical farming uses soilless methods like hydroponics, aeroponics, and aquaponics. These systems supply nutrients directly to plant roots through water or mist, leading to efficient absorption and faster growth. Using advanced technologies is a key aspect of vertical farming. Artificial LED lighting provides the right light spectrum for photosynthesis, while climate control systems manage temperature, humidity, and carbon dioxide levels. Sensors and automation technologies track plant health and environmental conditions in real time, ensuring optimal growth. In some advanced setups, artificial intelligence is used to analyse data

and adjust growing conditions automatically. Vertical farming systems often operate in urban settings, such as warehouses, high-rise buildings, and shipping containers. This makes them well-suited for cities where land is limited and demand for fresh produce is high. The ability to grow crops year-round without relying on seasonal changes makes vertical farming a reliable and efficient food production method. (Kozai *et al.*, 2016).

Role of Vertical Farming in Food Security

Enhancing Food Availability: Vertical farming significantly boosts food availability by maximizing production in limited space. By using vertical stacking, multiple layers of crops can be grown at once, leading to higher yields than traditional farming. Additionally, controlled environments allow crops to be grown year-round without seasonal breaks. This continuous production ensures a steady food supply, lowering the risk of shortages. Protection from pests, diseases, and severe weather also enhances productivity and reduces crop losses. (Touliatos *et al*., 2016)

Improving Accessibility: Vertical farming enhances food accessibility by shortening the distance between production and consumption. In traditional agriculture, food often travels long distances from rural farms to urban markets, increasing costs and reducing freshness. Vertical farms in cities can provide fresh produce directly to consumers, grocery stores, and restaurants. This cuts down on transportation costs and helps consumers access fresh, nutritious food. Over time, increased local production can stabilize food prices and make healthier options more affordable (Specht *et al*., 2014).

Improving Food Quality and Nutritional Value: Vertical farming ensures the production of high-quality, nutritious food by maintaining controlled growing conditions. Since crops grow in clean indoor settings, the use of chemical pesticides and fertilizers is minimized or eliminated. This results in safer food with fewer contaminants. Furthermore, precise nutrient control allows plants to grow with optimal nutritional content. Freshly harvested produce retains more vitamins and minerals compared to food that is transported long distances. This leads to better health outcomes for consumers. (Kozai *et al.*, 2016)

Ensuring Stability in Food Supply: One of the key contributions of vertical farming is its ability to provide stability in food production. Traditional agriculture heavily relies on weather conditions and is vulnerable to climate change. In contrast, vertical farming utilizes controlled environments unaffected by external factors like droughts, floods, and storms. This ensures consistent production throughout the year, even in tough situations. Therefore, vertical farming can serve as a dependable food source during emergencies and disruptions in the supply chain. (Kalantari *et al*., 2017)

Economic and Social Importance: Vertical farming offers substantial economic and social benefits that contribute to food security. It creates jobs in areas like agricultural technology, farm

management, and research. Urban farming initiatives can generate income for entrepreneurs and small businesses. Additionally, vertical farming supports local food systems, reducing reliance on imports and strengthening regional economies. Socially, it raises awareness about sustainable agriculture and encourages communities to adopt healthier eating habits by increasing access to fresh produce (Specht *et al.*, 2014)

Resource Efficiency: Vertical farming uses natural resources very efficiently, making it a sustainable alternative to conventional agriculture. It requires significantly less water thanks to closed-loop systems that recycle water, reducing waste. This is especially helpful in areas facing water shortages. Land use is minimized as crops grow vertically rather than horizontally. Nutrient delivery systems ensure that plants receive what they need, cutting back on excess use and environmental impact. This efficient resource use makes vertical farming a friendlier option for the environment (Benke and Tomkins, 2017).

Environmental Benefits: Vertical farming promotes environmental sustainability in several ways. It reduces the need for deforestation by lessening dependence on extensive agricultural land. The controlled environment eliminates the need for chemical pesticides, which lowers soil and water pollution. Moreover, the proximity of vertical farms to urban markets cuts down on transportation needs, leading to lower greenhouse gas emissions. By incorporating renewable energy sources, vertical farming can further lessen its environmental impact and aid in climate change mitigation. (Kalantari *et al.*, 2017)

Indian Perspective

In India, vertical farming is slowly gaining traction due to increasing urbanization and a growing demand for safe, organic food. Cities like Bengaluru, Mumbai, and Chennai are seeing the rise of vertical farming startups that employ hydroponic and indoor farming techniques. These farms provide fresh vegetables and greens directly to urban consumers, restaurants, and supermarkets. Despite its potential, vertical farming in India faces challenges such as high start-up costs, limited awareness, and a lack of technical know-how. However, with more government support, advancements in technology, and private sector investment, vertical farming is expected to grow.

Challenges

Despite its benefits, vertical farming faces several challenges that limit its widespread use. The initial setup cost is high because it requires complex infrastructure, lighting systems, and climate control technologies. Energy consumption is another issue, as artificial lighting and temperature regulation need electricity. Moreover, only certain crops are currently suitable for vertical farming, and skilled workers are necessary to manage these systems effectively (Kalantari *et al.*, 2017)

Future Prospects

The future of vertical farming looks bright, with ongoing technology advancements and growing

global interest. Using renewable energy sources like solar power can lower operational costs and reduce environmental impact. Artificial intelligence and automation can also improve efficiency and lessen labour needs. As research continues, more crop varieties may become suitable for vertical farming, broadening its potential. With the right support and investment, vertical farming could play a significant role in sustainable agriculture (Benke and Tomkins, 2017)

Conclusion

Vertical farming is a sustainable and new way to tackle food security issues. It boosts food availability, accessibility, quality, and stability by allowing year-round production in controlled settings. It also uses less water and land while lowering environmental damage. Even though there are challenges like high costs and energy consumption, ongoing technological progress can help address these issues. Overall, vertical farming has great potential to be a key player in future food production.

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Empowering Agriculture: Women's Role in Preserving Indigenous Knowledge in Arunachal Pradesh

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Introduction

Women in Arunachal Pradesh, particularly among the Adi, Galo, Monpa, Tagin, Apatani and other tribal communities, play a vital role in preserving indigenous agricultural and food-related knowledge. This knowledge forms the foundation of food security, biodiversity conservation, and climate-resilient farming systems that are closely connected to local culture and traditions. Agriculture in the region is not just an economic activity but a way of life shaped by a deep relationship with nature. Over generations, communities have developed practices that help manage land, crops, and natural resources in a balanced and sustainable manner, and women remain at the centre of this system and pass on traditional practices to the next generation. Women are actively involved in selecting and preserving seeds, maintaining crop diversity, preparing food, and passing on traditional practices to younger generations. Through their daily work, they ensure that farming methods remain suited to the local environment. They also play an important role in using forest resources carefully, collecting food, fuel, and medicinal plants without disturbing ecological balance. These practices help protect biodiversity and sustain livelihoods over time.

At the same time, this knowledge system is facing serious challenges. Rapid modernization, changing lifestyles, and migration have reduced the interest of younger generations in traditional practices. As a result, valuable knowledge that has been preserved for centuries is at risk of being lost. In this situation, it becomes important to recognize the role of women and support their efforts. Strengthening their position in agriculture and encouraging the continuation of traditional knowledge can help ensure sustainable development and protect the cultural and ecological heritage of the region.

Meaning of Indigenous Knowledge (IK)

Indigenous knowledge refers to the traditional skills, practices, and understanding developed by local tribal communities over generations. It includes a wide range of knowledge related to agriculture, the environment, culture, food systems, healthcare, and daily survival. This knowledge forms an important part of traditional ecological systems and is mainly passed orally from elders to younger generations, ensuring the continuity of cultural and practical wisdom. In Arunachal Pradesh, indigenous knowledge plays a strong role in sustaining agriculture, where it supports practices such as seed selection, crop diversity, soil management, and the

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use of organic methods like composting and mixed cropping. It also includes valuable understanding of medicinal plants and traditional food preservation techniques such as drying and fermentation, which contribute to nutrition and health. This knowledge is not formally taught in institutions but is learned through daily life and close interaction with nature, making it an essential part of community-based sustainable living.

Importance of Indigenous Knowledge

Indigenous Knowledge is the foundation of life for tribal communities in Arunachal Pradesh and plays a crucial role in shaping their livelihood, culture, and environment. It supports sustainable agriculture by promoting traditional farming methods that maintain soil fertility, conserve water, and protect crop diversity. It also helps in the effective management of natural resources, ensuring that forests, land, and water are used responsibly without causing ecological damage. Beyond its environmental role, Indigenous Knowledge is deeply linked with cultural identity and traditions. It preserves local customs, beliefs, rituals and practices that strengthen community bonds and maintain social harmony. This knowledge also contributes to biodiversity conservation by encouraging the protection of plants, animals, and forest ecosystems that are essential for long-term ecological balance. Forests hold special importance in the lives of tribal communities, as they are the main source of livelihood. People depend on forests for food, medicinal plants, fuelwood and shelter, making them essential for daily survival. Indigenous Knowledge helps communities adapt to changing environmental conditions and supports climate resilience through time-tested practices. This deep relationship between indigenous knowledge and forest resources reflects a sustainable lifestyle that has evolved over generations and continues to guide community survival and well-being.

Community-Based Forest Management

Forest conservation in many indigenous regions is driven by active community participation rather than external enforcement. Elders play an important guiding role by passing down rules on sustainable use of resources, teaching younger generations when to harvest, what areas to protect, and how to maintain ecological balance. These customary laws, supported by social norms and traditions, help regulate human activity and prevent overuse of forest resources.

Indigenous Agricultural Practices

Traditional farming systems are closely aligned with local ecology and terrain. Farmers commonly practice methods such as mixed cropping, shifting cultivation (jhum), and the use of natural fertilizers and locally saved seeds. These approaches are well adapted to hilly landscapes and changing climatic conditions. They also help maintain soil fertility, reduce dependency on chemicals, and support long-term agricultural sustainability.

Role of Apatani and Adi Women in Natural Resource Management

Women play a key role in agriculture and

natural resource management, contributing throughout the farming cycle from seed selection and cultivation to harvesting and storage. They also gather forest resources like food, fuel, and medicinal plants, supporting both household needs and environmental sustainability. Their traditional knowledge of crops, seasons, and soil helps maintain productivity and biodiversity. A notable example is the Apatani tribe's paddy-cum-fish cultivation system, which is highly efficient, supports rich biodiversity, conserves soil and water, and yields higher productivity than the state average. Women are also crucial in preserving seed diversity. By selecting, storing, and passing on quality indigenous seeds, they help maintain locally adapted crop varieties, ensuring food security and resilience against climate change and environmental uncertainty.

Traditional Food Systems and Cultural Knowledge

Food practices are deeply embedded in cultural traditions. Among communities such as the Adi, women's recipes and food-related rituals connect local plants and animals with social and cultural life. Knowledge is transmitted informally through families, festivals, and women's networks, ensuring continuity across generations. Women's community groups also strengthen this knowledge system by maintaining exchange networks and preserving important plant species used for food and cultural purposes.

Women-Led Conservation Practices

Women's involvement in resource management extends beyond farming into broader ecological conservation. Their sustainable harvesting practices, guided by customary beliefs and community norms, help protect forest biodiversity. They also contribute to the maintenance of community knowledge gardens and clan forests, where a wide variety of food and medicinal plants are conserved. These spaces encourage shared knowledge, equitable resource use, and long-term environmental stewardship, reflecting a strong integration of culture, livelihood, and conservation.

Challenges Facing Indigenous Knowledge

Indigenous knowledge systems face several challenges today. Modernization and western influence are leading to the decline of traditional practices, while younger generations are becoming less connected to their cultural heritage. Most indigenous knowledge is orally transmitted, so the lack of documentation further increases the risk of its loss. In addition, limited government and institutional support weakens efforts to preserve and sustain these systems.

Need for Preservation and Integration

To address these issues, it is important to document indigenous knowledge and integrate it into school curricula. Awareness programs can help communities value traditional practices, while policy support and training can strengthen their continuation. Linking indigenous knowledge with modern systems can make agriculture more sustainable and inclusive.

Conclusion

Women in Arunachal Pradesh are central to indigenous agricultural and ecological systems. They conserve seeds, manage forests and home gardens, and maintain food and medicinal plant diversity while passing this knowledge to future generations. However, their contributions often go unrecognized, and are threatened by modernization, migration, and reduced access to resources and decision-making. Empowering women through education, training, and institutional support is essential for protecting this knowledge. Recognizing their role not only strengthens rural livelihoods but also promotes food security, biodiversity conservation, and sustainable agriculture for the future.

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Integrated Soil Fertility, Nutrient Dynamics and Sustainable Agricultural Management: A Multidisciplinary Approach to Enhancing Crop Productivity and Environmental Quality

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Abstract

Soil fertility and plant nutrition constitute the foundation of agricultural productivity and ecological sustainability. Essential plant nutrients are indispensable for plant growth, development, and reproduction, and their availability in soil determines both yield and quality of crops. This research article presents a comprehensive and multidisciplinary analysis of essential plant nutrients, including the criteria of essentiality, classification, physiological functions, mechanisms of ion uptake, and forms of nutrients in soils. It also discusses deficiency symptoms, luxury consumption, nutrient interactions, and the role of chelated micronutrients in improving nutrient use efficiency. The study further examines soil fertility evaluation and management practices, emphasizing soil testing, fertilizer recommendations, and integrated nutrient management approaches. Soil classification systems, diagnostic horizons, and land capability classification are analyzed to highlight their importance in sustainable land-use planning. The application of modern technologies such as remote sensing, Geographic Information Systems (GIS), Global Positioning Systems (GPS), and Soil Information Systems (SIS) in agriculture is critically reviewed. In addition, the role of soil microorganisms in nutrient cycling, organic matter decomposition, carbon-nitrogen (C:N) ratios, mineralization, immobilization, and humus formation is explored. The significance of soil organic matter in maintaining soil structure, fertility, and environmental quality is emphasized. The paper also evaluates soil erosion processes, types, and control measures, along with classifications of fertilizers and manures, composting techniques, and recycling of organic wastes. Environmental concerns such as soil and water pollution are discussed with respect to their sources, impacts, and management strategies. The integration of sustainable nutrient management practices with advanced technological tools is essential for enhancing agricultural productivity while preserving environmental integrity. This study provides a scientific framework for improving soil health, optimizing nutrient use efficiency, and ensuring long-term sustainability in agriculture.

Introduction

Agriculture remains the backbone of food security and economic development, particularly in developing countries such as India. The productivity of agricultural systems largely depends on soil fertility and nutrient availability. Soil is a dynamic

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natural resource that supports plant growth by providing essential nutrients, water, and anchorage. However, increasing population pressure, intensive farming practices, and environmental degradation have led to declining soil fertility and productivity. The concept of sustainable agriculture emphasizes maintaining soil health while ensuring optimum crop yields. This requires a comprehensive understanding of nutrient dynamics, soil classification, microbial activity, and modern technological interventions. The integration of traditional knowledge with scientific advancements such as remote sensing and GIS has transformed agricultural practices into more precise and efficient systems. This paper aims to provide an integrated understanding of soil fertility, plant nutrition, and sustainable agricultural management by examining key concepts and practices that influence crop productivity and environmental sustainability.

Essential Plant Nutrients and Criteria of Essentiality: Essential plant nutrients are chemical elements required for the normal growth and development of plants. The criteria of essentiality were established by Arnon and Stout (1939), which state that an element is essential if its absence prevents completion of the plant life cycle, its deficiency is specific, and it is directly involved in plant metabolism. Plants require 17 essential nutrients, which are classified into macronutrients and micronutrients. Macronutrients such as nitrogen, phosphorus, and potassium are required in large quantities, while micronutrients such as iron, zinc, and boron are needed in smaller amounts. Each nutrient has specific roles in plant metabolism. Nitrogen is a major component of proteins and nucleic acids, phosphorus is involved in energy transfer, and potassium regulates enzyme activity and osmotic balance. Micronutrients act as cofactors in enzymatic reactions and play crucial roles in physiological processes.

Functions of Nutrients in Plant Growth: Plant nutrients perform diverse functions that are essential for growth and development. Nitrogen promotes vegetative growth and chlorophyll formation, leading to increased photosynthesis. Phosphorus enhances root development, flowering, and seed formation. Potassium improves water regulation, disease resistance, and enzyme activation. Secondary nutrients such as calcium, magnesium, and sulfur also play important roles. Calcium strengthens cell walls, magnesium is a central component of chlorophyll, and sulfur is involved in protein synthesis. Micronutrients, although required in small quantities, are vital for plant metabolism. Iron is essential for chlorophyll synthesis, zinc regulates hormone production, and boron is important for cell division and reproductive growth.

Mechanisms of Ion Uptake and Movement in Plants: Plants absorb nutrients from the soil solution through their root systems. Ion uptake occurs through both passive and active mechanisms. Passive uptake involves diffusion and mass flow, while active uptake requires energy in the form of ATP. Nutrient movement within plants occurs through

apoplastic and symplastic pathways. The apoplastic pathway involves movement through cell walls, while the symplastic pathway involves movement through cytoplasm via plasmodesmata. Root hairs increase the surface area for absorption, and mycorrhizal associations enhance nutrient uptake, particularly phosphorus. The selective uptake of ions is regulated by membrane transport proteins and ion channels.

Forms of Nutrients in Soils: Nutrients in soils exist in multiple chemical and physical forms, which directly influence their availability to plants. These forms include soluble, exchangeable, fixed, and organically bound nutrients. The soluble fraction, present in soil solution, is immediately available for plant uptake, while exchangeable nutrients are held on soil colloids and can be readily released. Fixed nutrients, particularly phosphorus and potassium, are trapped within mineral structures and are not easily accessible. Organic forms are bound within plant and microbial residues and require mineralization before becoming available. Nitrogen is unique in that it occurs in both organic and inorganic forms, including ammonium (NH_4^+) and nitrate (NO_3^-), which are the primary forms absorbed by plants. Phosphorus exists mainly as orthophosphate ions but is often fixed in soil through reactions with calcium, iron, or aluminum, depending on soil pH. Potassium is present in mineral, exchangeable, and solution forms, with only a small fraction immediately available. Soil pH is a critical determinant of nutrient availability, influencing solubility and chemical reactions. In acidic soils, nutrients such as phosphorus and molybdenum become less available, while toxic levels of aluminum may increase. In alkaline soils, micronutrients like iron and zinc become less soluble, leading to deficiencies. Soil texture and organic matter content also affect nutrient retention and release. Understanding these forms is essential for effective nutrient management. Farmers and agronomists must adopt practices such as pH correction, organic matter addition, and balanced fertilization to enhance nutrient availability and optimize crop productivity.

Deficiency Symptoms and Luxury Consumption: Nutrient deficiencies in plants manifest through distinct physiological and morphological symptoms that can significantly reduce crop yield and quality. Common symptoms include chlorosis (yellowing of leaves), necrosis (death of tissue), stunted growth, delayed maturity, and poor root development. The pattern of deficiency symptoms often depends on nutrient mobility within the plant. Mobile nutrients such as nitrogen, phosphorus, and potassium are translocated from older to younger tissues, resulting in deficiency symptoms appearing first in older leaves. In contrast, immobile nutrients like calcium, boron, and iron exhibit deficiency symptoms in younger leaves and growing points. Diagnosis of nutrient deficiencies is essential for timely corrective measures. Visual observation, plant tissue analysis, and soil testing are commonly used methods. However, symptoms can sometimes be misleading due to overlapping deficiencies or environmental

stress factors. Luxury consumption refers to the uptake of nutrients by plants in quantities exceeding their physiological requirements without a corresponding increase in yield. This phenomenon is particularly common with potassium and nitrogen. While it does not directly harm the plant, luxury consumption can lead to nutrient imbalances, increased production costs, and environmental concerns such as nutrient leaching and pollution. Efficient nutrient management aims to avoid both deficiencies and excesses by ensuring balanced fertilization. Understanding deficiency symptoms and luxury consumption helps optimize nutrient use efficiency, reduce input costs, and promote sustainable agricultural practices.

Nutrient Interactions and Chelated Micro-nutrients: Nutrient interactions play a crucial role in determining the availability and uptake of nutrients in plants. These interactions can be synergistic, where the presence of one nutrient enhances the uptake of another, or antagonistic, where one nutrient inhibits the availability of another. For example, nitrogen and sulfur exhibit a synergistic relationship in protein synthesis, whereas excessive phosphorus can reduce the availability of zinc, leading to deficiency symptoms. Such interactions are influenced by soil properties, nutrient concentrations, and plant species. Imbalanced fertilization can disrupt nutrient equilibrium, resulting in reduced crop productivity and nutrient use efficiency. Therefore, understanding nutrient interactions is essential for developing balanced fertilization strategies. Chelated micronutrients have emerged as an effective solution to overcome micronutrient deficiencies. Chelation involves binding micronutrients with organic molecules, forming stable complexes that protect nutrients from precipitation and fixation in soil. Common chelating agents include EDTA, DTPA, and EDDHA. Chelated forms of micronutrients such as iron, zinc, and manganese are more readily available to plants, especially in alkaline soils where nutrient solubility is limited. These compounds enhance nutrient mobility, improve uptake efficiency, and reduce losses. The use of chelated micronutrients is particularly important in intensive agriculture, where micronutrient deficiencies are increasingly common. Their application ensures balanced nutrition, improved crop yield, and better quality produce, making them an integral component of modern nutrient management practices.

Soil Fertility Evaluation and Management: Soil fertility evaluation is a scientific approach to determining the nutrient status of soil and its capacity to support plant growth. It involves soil testing, which analyzes physical, chemical, and biological properties, including pH, organic matter content, and nutrient levels. Soil testing provides essential information for making fertilizer recommendations tailored to specific crops and soil conditions. Effective soil fertility management aims to maintain a balance between nutrient supply and crop demand. Integrated Nutrient Management (INM) is a sustainable approach that combines chemical fertilizers, organic manures, crop residues and biofertil-

izers. This strategy enhances soil health, improves nutrient use efficiency, and reduces environmental impacts. Organic manures such as farmyard manure and compost improve soil structure, water retention, and microbial activity. Biofertilizers, including nitrogen-fixing and phosphate-solubilizing micro-organisms, contribute to nutrient availability and sustainability. Precision agriculture techniques, supported by soil testing and modern technologies, allow site-specific nutrient management, optimizing fertilizer use and minimizing waste. Proper soil fertility management not only increases crop productivity but also ensures long-term sustainability of agricultural systems.

Soil Classification and Land Capability Classification

Soil classification is a systematic process of grouping soils based on their physical, chemical, and biological characteristics. It provides a framework for understanding soil properties and their suitability for different uses. Diagnostic horizons, such as epipedons (surface horizons) and endopedons (subsurface horizons), are key criteria used in soil classification systems. Modern soil classification systems, such as the USDA Soil Taxonomy, categorize soils into orders, suborders, and series based on properties like texture, structure, and mineral composition. This classification helps in identifying soil behavior and management requirements. Land capability classification evaluates the suitability of land for agricultural use based on soil characteristics, topography, climate, and erosion risk. Land is classified into eight classes, ranging from Class I (highly suitable for cultivation) to Class VIII (unsuitable for agriculture). This classification system aids in land-use planning, ensuring that land is used according to its capability. It helps prevent soil degradation, optimize resource use, and promote sustainable agriculture. By matching land use with soil capability, farmers can enhance productivity while conserving natural resources.

Soil Survey: Types, Objectives, and Uses

Soil surveys involve the systematic study, classification, and mapping of soils within a specific area. They provide detailed information on soil properties, distribution, and potential uses. Soil surveys are conducted at various levels, including reconnaissance, semi-detailed, and detailed surveys, depending on the purpose and scale. The primary objective of soil surveys is to assess soil suitability for different agricultural and non-agricultural uses. They help identify soil limitations such as poor drainage, salinity, or low fertility and provide recommendations for improvement. Soil surveys are essential for land-use planning, irrigation development, and crop selection. They support decision-making in agriculture, forestry, and environmental management. For example, farmers can use soil survey data to select appropriate crops, determine fertilizer requirements and implement soil conservation practices. Advancements in technology, including remote sensing and GIS, have enhanced the accuracy and efficiency of soil surveys. These tools enable the integration of spatial data, improving

soil mapping and analysis. Overall, soil surveys are a vital tool for sustainable land management, ensuring optimal utilization of soil resources and minimizing environmental degradation.

Remote Sensing, GIS, GPS and SIS in Agriculture

Modern geospatial technologies have revolutionized agricultural practices by enabling precise monitoring and management of resources. Remote sensing involves the use of satellite or aerial imagery to collect information about soil, crops, and environmental conditions. It provides valuable data on soil moisture, crop health, and land use patterns. Geographic Information Systems (GIS) integrate spatial and non-spatial data, allowing farmers and researchers to analyze and visualize agricultural information. GIS supports decision-making in areas such as crop planning, irrigation management, and soil fertility assessment. Global Positioning Systems (GPS) enable accurate field mapping and navigation, facilitating precision agriculture practices such as variable rate application of fertilizers and pesticides. Soil Information Systems (SIS) store and manage soil data, providing easy access to information for agricultural planning. These technologies contribute to resource efficiency, reduced input costs, and increased productivity. They also support sustainable agriculture by minimizing environmental impacts. The integration of remote sensing, GIS, GPS, and SIS is essential for modern agricultural management and precision farming.

Radio Isotopes and Their Use in Agriculture

Radioisotopes are valuable tools in agricultural research and management. They are used to study nutrient uptake, soil-water relationships, and fertilizer efficiency. By tracing the movement of nutrients within plants and soils, radioisotopes provide insights into nutrient dynamics and improve fertilizer management practices. Nitrogen-15 (^{15}N) is commonly used to study nitrogen fixation and fertilizer use efficiency. It helps determine the proportion of nitrogen derived from fertilizers versus natural sources. Similarly, phosphorus isotopes are used to study phosphorus availability and movement in soils. Radioisotopes also play a role in plant breeding by inducing mutations to develop improved crop varieties. Additionally, they are used in pest control through techniques such as the sterile insect technique. Despite their benefits, the use of radioisotopes requires strict safety measures to prevent environmental contamination and health risks. Proper handling and regulation are essential. Overall, radioisotopes provide a scientific basis for improving agricultural productivity and sustainability through better understanding of nutrient and soil processes.

Conclusion

Sustainable agricultural development depends on a comprehensive and integrated understanding of soil fertility, plant nutrient dynamics, and environmental management practices. Soil is not merely a medium for plant growth but a living system that supports complex biological, chemical, and physical processes. Maintaining its health is essential for ensuring consistent agricultural produc-

tivity and long-term ecological balance. The proper management of essential nutrients through balanced fertilization, organic amendments, and efficient nutrient cycling plays a critical role in enhancing crop yields while preventing soil degradation. Modern agricultural challenges such as declining soil fertility, climate variability, and environmental pollution require innovative and science-based solutions. The integration of advanced technologies like remote sensing, Geographic Information Systems (GIS), and precision agriculture tools allows for accurate monitoring of soil and crop conditions. These technologies enable site-specific management practices, reducing the overuse of fertilizers and minimizing environmental impacts such as soil and water pollution. Equally important is the role of soil conservation practices in preventing erosion and maintaining soil structure. Techniques such as contour farming, afforestation, and sustainable land-use planning help protect soil resources from degradation. Additionally, the incorporation of organic matter through composting, green manuring, and residue recycling improves soil quality, enhances microbial activity, and supports nutrient availability. Environmental sustainability must remain a central goal in agricultural development. Excessive use of agrochemicals has led to soil and water pollution, threatening both ecosystem health and human well-being. Therefore, adopting integrated nutrient management and eco-friendly farming practices is essential. In conclusion, achieving sustainable agriculture requires a balanced approach that combines traditional knowledge with modern scientific innovations. By promoting efficient nutrient management, conserving soil resources, and minimizing environmental impacts, it is possible to ensure food security while preserving natural resources for future generations.

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Organic Production Technology in Horticultural Crops: Improving Quality, Yield and Market Value

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Abstract

Organic production technology has emerged as a sustainable approach in horticulture, focusing on the use of natural inputs and eco-friendly practices to enhance crop performance. This article highlights the role of organic farming techniques in improving the quality, yield, and market value of horticultural crops. By promoting soil health, biodiversity, and biological nutrient management, organic methods contribute to the production of safe, nutritious, and chemical-free fruits and vegetables. Although challenges such as initial yield reduction and certification barriers exist, the long-term benefits include better soil fertility, premium market prices, and increased consumer demand. The adoption of organic production technology is therefore essential for achieving sustainable agriculture and enhancing farmers' income while protecting environmental health.

Introduction

In recent years, agriculture has been undergoing a major transformation as consumers become more conscious about what they eat. The demand for safe, chemical-free, and nutritious food has increased significantly. This shift has brought organic production technology into the spotlight, especially in horticultural crops like fruits, vegetables, and flowers.Organic farming is not just about avoiding chemicals; it is a complete system that focuses on maintaining soil health, ecological balance, and sustainability. When applied properly, it plays a vital role in improving the quality, yield, and market value of horticultural produce.

What is Organic Production Technology?

Organic production technology is a holistic and nature-based approach to farming that focuses on working with natural systems rather than trying to control them through synthetic chemicals. Instead of depending on artificial fertilizers and pesticides, this method uses naturally available resources and biological processes to support plant growth and protect crops. At the heart of organic production is the idea that healthy soil leads to healthy plants. Farmers enrich the soil using organic manures such as farmyard manure, compost, and vermicompost. These not only provide essential nutrients but also improve soil structure, increase water-holding capacity, and encourage beneficial microorganisms. Over time, the soil becomes more fertile and biologically active, reducing the need for external inputs.

Improving Quality through Organic Practices

One of the most noticeable and valuable ben-

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efits of organic horticulture is the significant improvement in the overall quality of produce. Quality, in this context, is not just about how fruits and vegetables look, but also how they taste, smell, nourish the body, and how long they can be stored without spoilage. Organic farming practices focus on creating a healthy growing environment, and this naturally reflects in the final produce. Organic fruits and vegetables are often richer in taste and aroma because they grow at a natural pace without the forceful stimulation of chemical fertilizers. When plants absorb nutrients gradually from organic sources, they develop better flavor compounds and natural sugars. This is why many consumers feel that organically grown produce tastes fresher, more authentic, and closer to its natural form. Another major advantage is the improved nutritional content. Organic crops are often found to contain higher levels of essential nutrients such as vitamins, minerals, and antioxidants. These antioxidants play an important role in protecting the human body from diseases and strengthening immunity. Since the plants grow in biologically active soil rich in microorganisms, they are able to absorb nutrients more effectively, leading to enhanced nutritional value in the harvested produce. One of the most important concerns for today's consumers is food safety, and organic farming directly addresses this through chemical-free production. In conventional farming, synthetic pesticides and fertilizers can leave harmful residues on fruits and vegetables, which may affect human health over time. Organic methods completely avoid these chemicals and instead rely on natural pest control techniques. As a result, the produce is safer to consume and free from toxic residues, making it especially beneficial for children and health-conscious individuals.

Organic produce is also known for its better shelf life and storage quality. Although it may not always appear as shiny or uniform as conventionally grown produce, it tends to remain fresh for longer periods. This is because organic farming promotes balanced plant growth rather than rapid, water-heavy growth caused by chemical inputs. Stronger cell structure and natural resistance help reduce post-harvest losses and maintain freshness during storage and transportation. The improvement in quality is closely linked to the soil management practices used in organic farming. Techniques such as vermi-composting, application of farmyard manure (FYM), and the use of biofertilizers play a crucial role in maintaining soil fertility. Vermicompost, for example, is rich in nutrients and beneficial microbes that enhance soil health. Similarly, FYM improves soil structure and water retention capacity, while biofertilizers increase nutrient availability in a natural way. Healthy soil acts as the foundation for high-quality crops. When the soil is rich in organic matter and microbial life, plants grow stronger, resist diseases better, and produce superior-quality fruits and vegetables. In this way, organic horticulture creates a direct connection between soil health and produce quality.

Enhancing Yield in Organic Horticulture

There is a common misconception that organic farming always results in low yield. While yields may initially decline during the transition period, they stabilize and improve over time with proper management.

Soil Health Improvement: Organic matter increases soil structure, water retention, and microbial activity.

Balanced Nutrition: Biofertilizers such as Azotobacter and Rhizobium help in nutrient availability.

Integrated Pest Management (IPM): Use of neem-based products and beneficial insects reduces crop losses.

Increasing Market Value of Organic Produce

Organic products generally fetch higher prices in the market due to their perceived health benefits and eco-friendly production methods.

Premium Pricing: Consumers are willing to pay more for certified organic products.

Export Opportunities: Organic fruits and vegetables have high demand in international markets.

Brand Value: Organic labeling and certification increase consumer trust and product reputation. Certification from recognized authorities adds credibility and helps farmers access better markets.

Challenges in Organic Production

Although organic farming offers many long-term benefits, it is not without its difficulties. Farmers who adopt organic production technology often face several practical, economic, and technical challenges, especially during the early stages. Understanding these challenges is important to develop effective solutions and ensure successful adoption. One of the most common challenges is the initial reduction in yield during the conversion period. When farmers shift from conventional to organic farming, the soil takes time to recover from the effects of chemical inputs. During this phase, nutrient availability may be limited, and crop performance may not be optimal. This temporary decline can discourage farmers who depend on stable income. Another major issue is the lack of awareness and technical knowledge. Organic farming requires a good understanding of soil biology, crop rotation, pest management, and composting techniques. Many farmers are not properly trained in these methods, which leads to improper implementation and lower productivity.

The certification process is also a significant barrier. To sell produce as “organic” in the market, farmers must obtain certification from authorized agencies. This process can be expensive, time-consuming and complex, especially for small and marginal farmers. It involves documentation, inspections, and strict compliance with standards. A practical difficulty faced by many farmers is the limited availability of organic inputs such as quality compost, biofertilizers, and biopesticides. In many regions, these inputs are either not easily accessible or are more costly compared to chemical alternatives. In addition to these, organic farmers also deal with higher labor requirements. Practices like manual weeding, compost preparation, and natural pest control methods require more time and effort comp-

ared to conventional farming. This increases the overall cost of production.

Another challenge is pest and disease management. Since synthetic pesticides are not used, controlling severe pest outbreaks can sometimes be difficult. Natural methods are effective but may act more slowly, requiring careful monitoring and timely action. Organic farmers also face market-related challenges. Even though organic products can fetch higher prices, there is often a lack of proper marketing channels, storage facilities, and transportation systems. In some cases, farmers do not receive premium prices due to lack of awareness among consumers or middlemen exploitation.

Climate dependency is another important factor. Organic farming relies heavily on natural processes, making it more sensitive to climatic variations such as irregular rainfall, drought, or extreme temperatures.

Conclusion

Organic production technology in horticultural crops is a sustainable approach that not only protects the environment but also enhances crop quality, yield, and market value. It encourages a balanced ecosystem and ensures long-term agricultural productivity.As awareness continues to grow, organic farming is expected to play a crucial role in the future of horticulture. By adopting these practices, farmers can achieve better income while contributing to a healthier society and environment.

Panchagavya and Jeevamrutham in Organic Agriculture: Revitalizing Soil Through Indigenous Knowledge Systems

Isha Mamgain

Abstract

The increasing environmental and economic ccosts associated with chemical-intensive agriculture have necessitated the exploration of sustainable and ecologically sound alternatives. Traditional Indian bio-formulations such as Panchagavya and Jeevamrutham have re-emerged as viable components of organic farming systems. Rooted in indigenous knowledge, these formulations function as bio-enhancers that improve soil fertility, stimulate plant growth, and promote microbial activity. This article critically examines their composition, preparation methodologies, mechanisms of action, and contributions to soil health and crop productivity. Furthermore, it evaluates their relevance in the context of sustainable and climate-resilient agriculture, while highlighting existing limitations and future research needs.

Introduction

Modern agriculture, characterized by e xtensive reliance on synthetic fertilizers and pest-icides, has led to significant degradation of soil health, reduction in biodiversity, and long-term ecological imbalance. In response, organic agri culture has emerged as a sustainable alternative that emphasizes natural inputs, biological processes and ecological harmony. Within the Indian context, traditional agricultural practices have long incorporated cow-based formulations to enhance soil vitality and crop performance. Among these, Panchagavya and Jeevamrutham occupy a prominent position due to their effectiveness, affordability, and compatibility with low-input farming systems. These formulations represent a convergence of indigenous knowledge and ecological science, offering practical solutionns for sustainable agriculture.

Conceptual Framework: Soil as a Living Ecosy stem

Contemporary soil science recognizes soil as a dynamic and living system composed of complex i nteractions among physical, chemical, and biological components. Soil microorganisms play a critical role in nutrient cycling, organic matter decomposition and maintenance of soil structure. However, the ex cessive use of agrochemicals disrupts these processes by diminishing microbial diversity, altering soil pH, and reducing organic matter content. In contrast, organic inputs such as Panchagavya and Jeevamrutham aim to restore biological equilibrium by enhancing microbial activity and promoting nat ural nutrient cycling. Their application aligns with the principles of agroecology and regenerative

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agriculture.

Panchagavya: Composition, Preparation and Functional Dynamics

Composition and Preparathion: Panchagavya is a fermented bio-formulation derived from five primar y cow-based products: dung, urine, milk, curd, and ghee. Supplementary ingredients such as jaggery, banana, and tender coconut water are often added to accelerate microbial fermentation and enhance nutrient content. The preparation involves an initial fermentation of cow dung and ghee, followed by the incorporation of there maining ingredients. The mixture is allowed to ferment for approximately two to three weeks under controlled conditions, with periodic stirring to ensure uniform microbial activity.

Biochemical and Microbial Characteristics

Panchagavya contains a diverse consortium of beneficial microorganisms, including nitrogen-fixing bacteria, phosphate-solubilizing microbes, lac tic acid bacteria, and yeast populations. In addition, it is rich inplant growth regulators such as auxins, gibberellins, and cytokinins, along with essential nutrients, enzymes, vitamins, and amino acids.

Mechanisms of Action

The efficacy of Panchagavya can be attributed to multiple mechanisms:

Microbial inoculation: Introduction of beneficial microorganisms into the soil and phyllosphere

Growth stimulation: Enhancement of plant physiol ogical processes through natural hormones

Nutrient supplementation: Provision of essential macro- and micronutrients in bioavailable forms

Induced resistance: Activation of plant defense responses against pests and diseases

Agronomic Impacts

Empirical observations and experimental stu dies indicate that Panchagavya application results in improved seed germination, enhanced vegetative growth, increased flowering and fruiting and better crop quality. Its foliar application, in particular, has been shown to improve photosynthetic efficiency and nutrient uptake.

Jeevamrutham: A Catalyst for Soil Microbial Ac -tivity

Composition and Preparathion: Jeevamrutham is a liquid organic formulation composed of fresh cow dung, cow urine, jaggery, pulse flour, a small quantity of local soil, and water. The mixture is fermented for a period of five to seven days, during which microbial populations proliferate rapidly.

Functional Role in Soil Systems: Unlike Panchagavya, Jeevamrutham primarily functions as a microbial stimulant rather than a direct nutrient source. It serves as a culture medium that enhances the growth and activity of beneficial soil micro-organisms.

Mechanisms of Action

The application of Jeevamrutham facilitates:

Microbial proliferation: Rapid multiplication of native and introduced microorganisms

Nutrient cycling: Enhanced mineralization and solubilization of nutrients

Organic matter decomposition: Accelerated break-down of crop residues

Soil conditioning: Improvement in soil structure, aeration, and moisture retention

Agronomic Benefits: Regular application of Jeevamrutham leads to improved soil fertility, increased availability of nutrients, and sustained crop productivity. It is particularly effective in restoring degraded soils and maintaining long-term soil health.

Comparative Analysis: Although both formulations are derived from similar sources, their primary functions differ significantly. Panchagavya acts predominantly as a plant growth promoter with direct nutritional and hormonal effects, whereas Je evamrutham serves as a microbial activator that indirectly enhances nutrient availability through biological processes. Their combined use can create a synergistic effect, strengthening both soil health a nd plant growth.

Role in Sustainable and Climate-Resilient Agriculture

The integration of Panchagavya and Jeevamrutham into farming systems contributes to sustainability in multiple ways:

Reduction in chemical inputs: Minimizes environmental pollution and input costs

Carbon sequestration: Enhances soil organic carbon through increased microbial activity

Improved water retention: Strengthens soil structure and drought resilience

Biodiversity conservation: Supports diverse soil microbial communities

These attributes make them valuable tools in climate-resilient agricultural practices.

Economic and Social Implications

The adoption of these formulations offers si gnificant economic advantages, particularly for small and marginal farmers. Their preparation relies on locally available resources, reducing dependence on external inputs. Furthermore, they promote farmer self-reliance and preserve traditional knowledge systems, contributing to rural sustainabili ty.

Scientific Validation and Limitations

Recent studies have demonstrated positive ef fects of Panchagavya and Jeevamrutham on soil microbial biomass, enzymatic activity and crop yields. However, several challenges remain:

- ✓ Lack of standardized preparation protocols
- ✓ Variability in composition and efficacy
- ✓ Limited large-scale validation studies
- ✓ Dependence on indigenous cow-based inputs

Addressing these limitations is essential for wider adoption and scientific acceptance.

Future Research Directions

Further research is required to:

- ✓ Standardize preparation and application methods
- ✓ Characterize microbial communities using ad vanced techniques
- ✓ Evaluate long-term impacts through field trials
- ✓ Integrate these formulations with modern agricultural technologies

Conclusion

Panchagavya and Jeevamrutham represent a scientifically relevant and ecologically sustainable approach to soil fertility management. By enhancing

microbial activity, nutrient cycling and promoting plant growth, these formulations contribute to a regenerative argiculrural paradigm. Their integration into contemporary farming systems, supported by scientific validation and policy initiatives, holdssign ificant potential for advancing sustainable agricul ture and ensuring long-term food security.

Organic Weed and Pest Management for Sustainable Crop Production

Shreya Pal

Abstract

The increasing dependence on chemical pesticides and herbicides has raised serious concerns regarding environmental health, soil degradation, and food safety. Organic weed and pest management offers a sustainable alternative by relying on natural processes, ecological balance, and non-toxic inputs. This article presents a comprehensive overview of organic approaches, including cultural, mechanical, physical, and biological weed control methods along with eco-friendly pest management strategies such as botanical pesticides and biological agents. These techniques not only reduce environmental pollution but also improve soil fertility, biodiversity, and crop resilience. Although organic farming may demand greater effort and knowledge, it ensures long-term agricultural sustainability and safer food systems.

Introduction

Agriculture is no longer just about maximizing yield; it is also about maintaining the health of soil, water, and ecosystems. Overuse of synthetic chemicals has led to problems like resistant pests, declining soil fertility, and contamination of food products. Organic farming addresses these issues by promoting natural farming practices. Instead of eliminating weeds and pests completely, organic systems aim to manage their population within acceptable limits, ensuring ecological balance and sustainable production. Need of Organic Weed and Pest Management in Sustainable Crop Production.

Need of Organic Weed and Pest Management in Sustainable Crop production

The increasing dependency on synthetic chemicals in agriculture has created multiple challenges, making organic management practices a necessity rather than a choice. Firstly, chemical herbicides and pesticides degrade soil quality by reducing beneficial microorganisms. Organic methods help restore soil health by promoting microbial activity and improving soil structure. Secondly, chemical residues in food pose serious health risks to consumers. Organic pest management minimizes these residues, ensuring safer and healthier food products. Another major concern is environmental pollution. Chemicals contaminate water bodies and harm non-target organisms such as pollinators and beneficial insects. Organic practices protect biodiversity and maintain ecological balance. Furthermore, pests often develop resistance to chemical pesticides over time, making them less effective. Organic strategies, on the other hand, use multiple approaches that reduce the chances of resistance development.

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In addition, organic methods improve the resilience of farming systems by enhancing soil moisture retention and reducing the impact of climate stress. Therefore, organic weed and pest management is essential for achieving sustainable crop production, environmental conservation and long-term agricultural productivity.

Organic Weed Management Strategies

Cultural Methods: Cultural practices focus on prevention by creating conditions that discourage weed growth. Crop rotation is one of the most effective techniques, as it interrupts the life cycle of weeds. Intercropping and cover cropping reduce open space, making it difficult for weeds to establish. Dense planting and proper spacing allow crops to outcompete weeds for sunlight and nutrients. These practices not only control weeds but also improve soil structure and fertility over time.

Mechanical Methods: Mechanical weed control involves the direct removal of weeds using human effort or tools. Hand weeding is precise and widely practiced, especially in small farms. Hoeing helps in uprooting weeds and loosening the soil surface. Tillage operations bury weed seeds and destroy existing weeds. Modern tools like wheel hoes and power weeders make the process faster and more efficient. Although effective, these methods require time, labor, and consistency.

Physical Methods: Physical methods utilize natural forces such as temperature, light, and moisture to control weeds. Mulching is highly effective, as it blocks sunlight and prevents weed germination while conserving soil moisture. Soil solarization involves covering soil with transparent plastic sheets to trap heat, killing weed seeds and pathogens. In flooded conditions like paddy fields, water suppresses weed growth. Controlled burning can also be used carefully to destroy weed seeds. These methods are environmentally safe and improve soil conditions.

Biological Methods: Biological weed control uses living organisms to suppress unwanted plants. Certain insects feed specifically on weeds, while microorganisms can inhibit their growth. Grazing animals such as goats and sheep are also used in some farming systems to manage weed populations naturally. This method is sustainable and maintains ecological harmony.

Organic Pest Management Strategies

Biological Control: Biological pest control depends on natural predators and parasites. Ladybird beetles, spiders, and birds help reduce insect populations. Parasitic wasps lay eggs inside pests, eventually killing them. Microbial agents like bacteria and fungi can also control harmful insects. This method reduces reliance on chemicals and preserves beneficial organisms.

Botanical Pesticides: Botanical pesticides are derived from plants and are widely used in organic

farming. Neem oil is one of the most effective natural pesticides, controlling a variety of insects and diseases. Garlic and chili-based sprays act as repellents. These substances break down quickly in nature and are safe for humans and animals when used properly. They provide a balanced approach to pest control without harming the ecosystem.

Cultural Practices: Cultural techniques play a major role in pest prevention. Timely sowing and harvesting help crops avoid peak pest periods. Crop rotation prevents pest buildup in soil. Maintaining field hygiene by removing infected plant material reduces the chances of pest spread. Healthy crops naturally resist pest attacks more effectively.

Traps and Barriers: Traps and physical barriers are simple yet effective pest management tools. Sticky traps capture flying insects, while pheromone traps attract specific pests and disrupt their breeding cycles. Nets and row covers act as protective barriers against insects. These methods are affordable and environmentally friendly.

Advantages of Organic Weed and Pest Management

- ✓ Environment-friendly and pollution-free
- ✓ Improves soil fertility and structure
- ✓ Promotes biodiversity
- ✓ Produces safe and chemical-free food
- ✓ Ensures long-term sustainability

Limitations of Organic Weed and Pest Management

Labor Intensive: Requires more manual work such as hand weeding and monitoring

Time-Consuming: Results are slower compared to chemical methods

Knowledge Requirement: Farmers need proper training and understanding of ecological practices

Initial Yield Reduction: Crop yield may decrease during the transition period from conventional to organic farming

Limited Availability of Inputs: Organic inputs like bio-pesticides may not always be easily available

Weather Dependency: Effectiveness of some methods (like biological control) depends on environmental conditions.

Conclusion

Organic weed and pest management is a key component of sustainable agriculture. By reducing reliance on synthetic chemicals and promoting natural processes, these strategies help protect the environment, improve soil health, and ensure long-term crop productivity. Although there are some challenges, the long-term benefits make organic farming a necessary approach for future food security and environmental conservation.

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Breaking the Barriers: Strategic Solutions to Sociology-Economic and Technical Challenges in Organic Transition

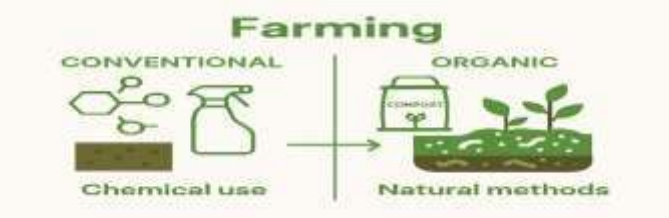
Pallavi Kumari

Abstract

The transition from conventional to organic agriculture is increasingly recognized as a pathway toward sustainable food systems. However, this shift is accompanied by multiple socio-economic and technical challenges, particularly for small and marginal farmers. These challenges include financial risks, lack of awareness, limited market access, and technical knowledge gaps. This article examines the key barriers to organic transition and proposes strategic, inclusive solutions to facilitate adoption. Emphasis is placed on capacity building, institutional support, market development, and integration of traditional knowledge with modern practices. A holistic approach is essential to ensure a smooth and equitable transition toward organic farming.

Introduction

Organic agriculture has emerged as a viable alternative to conventional farming systems that rely heavily on synthetic fertilizers and pesticides. It emphasizes ecological balance, biodiversity conservation and long-term soil health. In the context of growing environmental concerns and increasing consumer demand for safe and chemical-free food, organic farming presents significant opportunities. Despite its advantages, the transition to organic farming is a complex process. Farmers must adapt to new production techniques, endure a temporary decline in yields, and navigate uncertain markets. These challenges are particularly pronounced in developing regions, where access to resources, information, and institutional support is limited. This article explores the socio-economic and technical constraints associated with organic transition and outlines strategic interventions required to overcome them.



Socio-Economic Challenges in Organic Transition

Financial Constraints and Income Instability: One of the primary barriers to organic adoption is the economic risk during the transition period. Farmers often experience reduced yields when shifting away from chemical inputs, while their produce cannot yet be certified as organic. This leads to temporary income instability, discouraging adoption.

Lack of Awareness and Knowledge Dissemination : Limited awareness regarding organic farming practices and benefits remains a critical issue.

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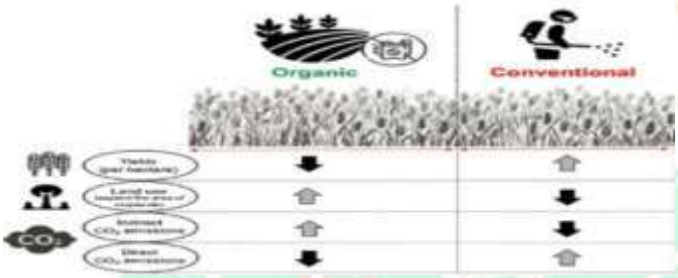
Inadequate extension services and insufficient training programs result in knowledge gaps, making farmers hesitant to adopt new systems.

Market Access and Price Realization: Organic produce often fails to reach premium markets due to weak supply chains and the dominance of intermediaries. Farmers frequently receive prices comparable to conventional produce, reducing the economic incentive for transition.

Certification Barriers: Organic certification is essential for market recognition; however, the process is often costly and complex. Small-scale farmers face difficulties in meeting documentation requirements and bearing certification expenses.



Technical Challenges in Organic Farming

Soil Fertility Management: Maintaining soil fertility without synthetic fertilizers requires the use of organic inputs such as compost, green manure, and crop rotation. These practices demand additional labor, time, and technical understanding.

Pest and Disease Management: Organic pest control relies on biological and cultural methods rather than chemical pesticides. Farmers often lack the expertise to effectively implement these techniques, leading to potential crop losses.

Limited Availability of Organic Inputs: Access to quality organic inputs, including biofertilizers and organic seeds, remains inadequate in many regions. Where available, these inputs may be costly or inconsistent in quality.

Documentation and Compliance Requirements: Organic certification necessitates systematic record-keeping and adherence to strict standards. Many farmers, particularly those with limited literacy or training, find these requirements challenging.

Strategic Solutions for Overcoming Barriers

Capacity Building and Extension Services: Strengthening farmer education through training programs, demonstration plots, and peer learning initiatives is essential. Extension services should focus on practical, location-specific guidance to build farmer confidence.

Financial Support Mechanisms: Governments and financial institutions should provide targeted support, including subsidies for organic inputs, transition assistance payments, access to low-interest credit, and crop insurance tailored to organic systems. These measures can mitigate financial risks during the transition phase.

Simplification of Certification Systems: Promoting cost-effective certification models such as Participatory Guarantee Systems can enhance accessibility. Simplified procedures and group certification approaches can further reduce the burden on small farmers.

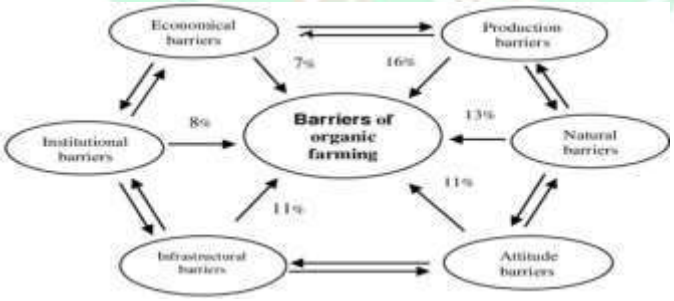
Strengthening Market Linkages: Developing efficient marketing channels is crucial. This can be achieved through farmer producer organizations, direct marketing platforms, digital marketplaces, and

public-private partnerships. Ensuring fair price realization will significantly improve adoption rates.

Enhancing Technical Support Infrastructure: Establishing dedicated organic resource centers and providing real-time advisory services can address technical challenges. Collaboration between research institutions and farmers is necessary to develop region-specific solutions.

Community-Based Approaches: Cluster-based organic farming can reduce costs and improve efficiency. Collective action enables farmers to share resources, knowledge, and market access, thereby strengthening the overall system.

Integration of Traditional and Scientific Knowledge: Combining indigenous farming practices with modern scientific innovations can enhance the effectiveness of organic systems. Documenting and promoting traditional knowledge will make organic farming more adaptable and sustainable.



Conclusion

Organic agriculture offers a sustainable pathway for addressing environmental degradation and ensuring food security. However, the transition process is hindered by significant socio-economic and technical barriers. To overcome these challenges, a multi-dimensional approach is required one that integrates financial assistance, capacity building, market development, and institutional support. Special attention must be given to small and marginal farmers to ensure inclusivity. With appropriate strategies and sustained efforts, organic farming can evolve from a niche practice to a mainstream agricultural system, contributing to a more resilient and sustainable future.

Role of Organic Amendments and Green Manuring in Sustainable Crop Production Systems

Ritika Mitra

Abstract

In recent years, agriculture has faced serious challenges such as declining soil fertility, excessive use of chemical fertilizers, and environmental degradation. These problems have raised concerns about the long-term sustainability of crop production systems. Organic amendments and green manuring have emerged as important practices that can improve soil health and reduce dependence on chemical inputs. These methods use natural materials and biological processes to maintain soil fertility, enhance productivity, and protect the environment. This article explains the role of organic amendments and green manuring in sustainable crop production in simple and practical terms.

Introduction

Agriculture is the backbone of food production, but modern farming practices have created many challenges. The heavy use of chemical fertilizers has increased crop yields in the short term, but it has also led to soil degradation, reduced soil organic matter, and environmental pollution. To overcome these problems, farmers are now looking for sustainable alternatives. Organic amendments and green manuring are two such practices that help restore soil health and ensure long-term productivity. These methods are simple, cost-effective, and environmentally friendly, making them suitable for sustainable farming systems.

Organic Amendments: Concept and Types

Organic amendments are natural materials added to the soil to improve its fertility and structure. These materials come from plant or animal sources and decompose over time, releasing nutrients for crops.

Types of Organic Amendments

Farmyard Manure (FYM): A mixture of animal dung, urine, and bedding materials.

Compost: Decomposed organic waste such as crop residues and kitchen waste.

Vermicompost: Compost produced with the help of earthworms.

Green Leaf Manure: Leaves and plant parts added to the soil.

Crop Residues: Leftover plant materials after harvesting.

Benefits of Organic Amendments

Improvement of Soil Structure: Organic matter helps bind soil particles, making the soil loose and well-aerated. This improves root growth and water infiltration.

Increase in Soil Fertility: Organic amendments release essential nutrients like nitrogen, phosphorus,

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and potassium slowly, ensuring a steady supply to crops.

Enhancement of Microbial Activity: Soil micro-organisms play a key role in nutrient cycling. Organic matter provides food for these microbes, increasing their activity.

Better Water Retention: Soils rich in organic matter can hold more water, which helps crops during dry periods.

Reduction in Chemical Use: By improving natural fertility, organic amendments reduce the need for chemical fertilizers.

Green Manuring: Concept and Importance

Green manuring is the practice of growing specific crops and then incorporating them into the soil while they are still green. These crops are usually fast-growing and rich in nutrients.

Common Green Manure Crops

- ✓ Leguminous crops like sunhemp, dhaincha, and cowpea
- ✓ Non-leguminous crops like mustard and buckwheat
- ✓ Leguminous plants are especially important because they fix nitrogen from the atmosphere into the soil.

Benefits of Green Manuring

Addition of Organic Matter: Green manure crops add a large amount of biomass to the soil, improving its organic content.

Nitrogen Fixation: Leguminous green manure crops increase soil nitrogen levels naturally, reducing the need for synthetic fertilizers.

Improvement in Soil Structure: The roots of green manure crops help loosen the soil and improve aeration.

Weed and Pest Control: Green manure crops suppress weeds and can reduce pest and disease problems.

Role in Sustainable Crop Production Systems

Organic amendments and green manuring together play a vital role in sustainable agriculture:

Integrated Nutrient Management: They provide a balanced supply of nutrients, reducing dependency on chemical fertilizers.

Long-term Soil Health: Regular use of organic inputs maintains soil fertility over time, ensuring consistent crop yields.

Environmental Protection: These practices reduce pollution, improve biodiversity, and help maintain ecological balance.

Challenges and Limitations

Despite their advantages, these practices face some challenges:

- ✓ Availability of sufficient organic materials
- ✓ Labour-intensive processes
- ✓ Slow nutrient release compared to chemical fertilizers
- ✓ Lack of awareness and training among farmers
- ✓ Proper planning and support can help overcome these limitations.

Future Scope

The importance of organic amendments and green manuring is increasing due to the need for sustainable farming. With growing awareness, gove-

rnment support, and research advancements, these practices can be widely adopted. They are essential for maintaining soil health, improving productivity, and ensuring food security for future generations.

Conclusion

Organic amendments and green manuring are key components of sustainable crop production systems. They improve soil fertility, enhance crop productivity, and reduce dependence on chemical inputs. These practices not only benefit farmers economically but also protect the environment. Adopting these eco-friendly methods is crucial for achieving long-term sustainability in agriculture.

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Adoption of Organic Production Technology for Safe Food, Healthy Soil and Sustainable Livelihood

Faiz Mohammad

Introduction: Reconnecting with the Roots

In the last few decades, agriculture has undergone a tremendous transformation. The wide-spread use of chemical fertilizers, pesticides and high-yield varieties of crops has greatly increased food production, helping to feed a growing population on Earth. But this progress has come at hidden costs: degraded soil health, environmental pollution, reduced biodiversity, and growing concerns about food safety. As awareness of these challenges grows, the technology of organic production has become a promising pathway to a more balanced and sustainable agricultural system. Organic farming is not a return to the old ways, but a scientifically based, ecologically oriented approach which stresses harmony between man, crops, soil and the environment. The adoption of organic production technologies offers an attractive way to achieve three inter-related objectives: producing safe and nutritious food, maintaining and improving soil health, and providing sustainable livelihoods for farmers. From the human-centered perspective on the impact of the application of organic production technology, this article discusses its significance, principles, benefits, challenges, and future potential.

Understanding Organic Production Technology

Organic production technology is a farming system that relies on natural inputs and ecological processes, as opposed to synthetic chemicals. It combines ancient knowledge with modern scientific advances to create a sustainable and resilient agricultural system.

Organic farming is essentially based on a few basic principles

Health: Keeping the health of soil, plants, animals and humans as one integrated system.

Ecology: Working with natural cycles and ecosystems, not against them.

Fairness: Fair relationships between farmers, workers, consumers and the environment.

Care: Taking precautionary action to protect present and future generations.

Organic production technologies include composting, crop rotation, biological pest control, green manuring, vermicomposting, use of biofertilizers and integrated farming systems.

Safe Food: A Growing Necessity

One of the most interesting motives for organic farming is the increasing demand for safe and healthy food. Today's consumers are more mindful of what they eat and wonder if conventional food has chemical residues.

Health Problems: The increasing use of pesticides and chemical fertilizers has raised some concerns on

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their long-term impacts on human health. Pesticide exposure has been associated with a host of health problems, including hormonal disruption, neurological diseases and certain cancers, in studies. There are regulatory limits, but there is concern about the cumulative effect of low-level exposure over time. Organic food, on the other hand, is produced without synthetic pesticides, genetically modified organisms (GMOs) or artificial additives. This greatly reduces the risk of chemical contamination of the food.

Nutritional Benefits: More research is proving that there could be more amounts of specific nutrients like antioxidants, vitamins, and minerals in organic produce. There may be variations depending on the type of plant being grown and other factors, but consumers still consider organics more nourishing compared to conventional produce.

Establishing Trust: Organic certifications play a role in building trust for consumers. When consumers buy organic products, they are putting their trust into something bigger than food itself.

Healthy Soil: The Foundation of Agriculture

"Soil can be considered living skin of earth." The condition of soil is extremely important for successful agriculture. Conventional agriculture, however, has caused several problems with soil.

Problems Related to Soil Degradation

- ✓ Decrease in the content of organic matter
- ✓ Weakening of the microbial activity of soil
- ✓ Increase in soil erosion
- ✓ Decreasing capacity of soil to retain moisture
- ✓ Compaction and salination of soil

These issues decrease productivity and increase the need for external resources for the agricultural activity.

Organic Farming and Soil

Organic agricultural technology considers soil as the main resource. Organic agriculture aims to feed the soil rather than crops with fertilizers.

Some important practices are:

Composting: Organic wastes are converted into rich compost, which is used for improving soil fertility.

Green Manuring: Certain plants are grown and plowed back into the soil for increasing its nitrogen content.

Crop Rotation: Crops are changed from time to time to prevent the loss of nutrients and pests.

Mulching: The soil is covered with mulch to conserve moisture and prevent erosion.

Biofertilizers: Microbes that fix atmospheric nitrogen are added to the soil.

Soils enriched with organic matter become more resilient and promote microbial diversity.

Long-Term Effects

Healthy soils have higher productivity, lower input requirements, and higher resistance to various environmental challenges such as drought and flooding. Soil plays an essential part in carbon sequestration.

Sustainable Livelihood: Empowering Farmers

Farming is not merely an exercise in production but is also an effort toward sustaining livelihoods for countless farmers, particularly in developing nations.

Economic Issues in Traditional Farming

Current farmers have to contend with increasing costs in terms of seed, fertilizer, and pesticide procurement. Simultaneously, the prices of their products are often volatile. This disparity may result in indebtedness, economic hardship, and, in worst-case scenarios, even farmer distress.

Opportunities for Organic Farming in Economics

There are various economic opportunities offered by the organic production technologies. They include the following:

Reduced Input Costs: By using locally available inputs such as biofertilizers, the farmer will minimize input costs.

High Returns: Products produced organically have higher prices compared to those produced through conventional production.

Diversification: Organic production technologies usually foster diversification.

Market Opportunities: The increasing demand for organic products is offering more market opportunities.

Social Advantages

Furthermore, organic agriculture encourages social interaction and the spread of information. Farmers frequently collaborate to learn from one another and help each other convert their operations into organic ones. In addition, minimal chemical exposure ensures that the well-being of the farmers and laborers is not compromised.

Environmental Sustainability: Technology used in organic production is a great contributor to environmental sustainability.

Conservation of Biodiversity: Organic farming promotes biodiversity since there are no synthetic chemicals to harm other organisms. Organic farming promotes a healthy ecosystem.

Conservation of Water Resources: High organic content of organic soils helps retain more moisture in soils, meaning there would be less need for watering and therefore water conservation.

Mitigation of Climate Change: Composting, reduction of tillage, and agroforestry are some of the methods practiced in organic farming that help in sequestration of carbon in soils, thereby mitigating climate change.

Problems Faced During Adoption: Although adoption has many benefits, the uptake of the technology used in organic production has its own problems too.

Period of Transition: Farmers who convert their farms from conventional into organic farms normally have to contend with a reduction in yield during the conversion period.

Certification Requirements: For many small-scale farmers, acquiring an organic certificate is a complicated and expensive task, not forgetting the problem of ignorance about the certification process.

Constraints in Market Access: Even though there is growing demand for organic produce, accessing reliable markets is not always easy for many producers of these commodities.

Ecological Knowledge: Adoption of organic technology requires that the farmer has adequate

knowledge of ecological concepts.

Strategies to Promote Adoption: In order to address the above challenges, several strategies should be considered.

Policy Support: First, the government should take an active part in promoting organic farming by:

- ✓ Offering financial support and incentives
- ✓ Funding research and development
- ✓ Easing and simplifying the certification process
- ✓ Conducting public campaigns on promotion of organic products

Capacity Building: Effective training initiatives can help increase farmers' knowledge on organic techniques.

Market Development: Farmers should have access to efficient supply chain, producer organizations and direct marketing systems.

Technology Integration: Farmers can benefit greatly from incorporating modern technologies, including mobile applications and precision farming techniques.

Human Stories behind Organic Farming

Organic farming technology does not only involve certain practices and policies it can change farmers' lives forever. Consider a farmer who suffered from decreased harvest rates and incurred huge expenses related to traditional methods of cultivation based on extensive use of chemicals. With the transition to organics, he sees significant changes not just in soil quality, but also in overall life. He is no longer worried about using toxic substances. His land gets healthier, diverse and closer to nature. For consumers, buying organic food implies a deeper meaning. In addition to enjoying the natural taste of fruits

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Future Prospects of Organic Production Technology in Sustainable Agriculture and Global Food Systems

Navjeet Anand, Shivani Rai and Abhishek Kumar

Abstract

The integration of advanced production technologies with organic farming principles represents a transformative approach to achieving sustainable intensification in global food systems. This comprehensive analysis examines the convergence of organic agriculture with precision technologies, biotechnology innovations, and digital transformation to address critical challenges of food security, climate resilience, and environmental sustainability. The global organic market reached €145 billion in retail sales by 2024, with farmland expanding to approximately 99 million hectares worldwide. India leads globally with approximately 2.5 million organic producers positioning the country as a critical player in the organic agriculture revolution. The synthesis reveals that while organic systems demonstrate significant environmental benefits including 95% higher species richness, 7% higher soil organic matter content, and emissions reductions of 1,082 kg CO_2 equivalents per hectare annually the persistent yield gap of approximately 19.2% necessitates technological intervention . The article explores emerging technologies such as AI-powered soil monitoring, blockchain traceability, biochar applications, and precision organic farming that are narrowing this gap while enhancing sustainability outcomes. Future prospects emphasize the convergence of organic principles with regenerative practices, precision agriculture, and supportive policy frameworks as essential pathways toward achieving the United Nations Sustainable Development Goals while ensuring food security for a growing global population.

Introduction

The global agricultural landscape faces unprecedented challenges: declining soil fertility, accelerating climate change, increasing biodiversity loss, and growing food demand from a population projected to reach 9.7 billion by 2050. Organic agriculture, with its emphasis on ecological harmony and biodiversity conservation, offers a promising alternative to conventional farming systems. However, the transition to sustainable organic production requires significant technological advancement to bridge the productivity gap while maintaining environmental integrity. The concept of "new-age organic farming" represents a paradigm shift from traditional organic practices, integrating cutting-edge technologies with ecological principles. This evolution addresses the critical need for scalable, efficient and economically viable organic production systems that can compete in modern food markets while delivering environmental and social benefits.

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The convergence of organic agriculture with digital transformation, biotechnology and precision farming technologies is creating unprecedented opportunities for sustainable intensification.

Technological Innovations Transforming Organic Production

Precision Organic Farming Technologies: The integration of precision agriculture technologies into organic farming systems is revolutionizing resource management and productivity. Key innovations include:

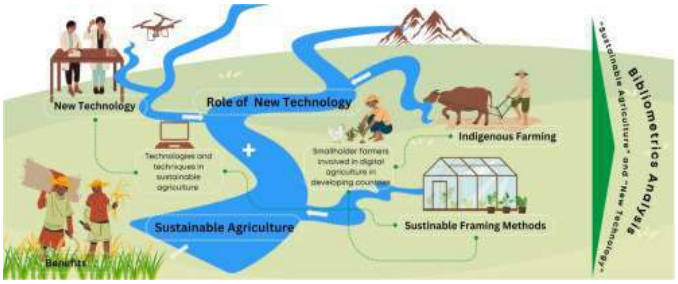
Global Navigation Satellite Systems (GNSS): Enable machinery efficiency and precise field operations without synthetic inputs. Variable Rate Application (VRA) systems allow for optimized input distribution based on field variability, though adapted for organic amendments such as compost and biochar. Advanced sensor networks measure environmental parameters including soil quality, humidity, temperature, and pest infestations in real-time.

Soil Health and Microbiome Management: Advanced soil management technologies are enhancing the fundamental foundation of organic agriculture: Biochar applications represent a significant advancement in soil amendment technology. This carbon-rich material improves soil fertility, water retention, and microbial activity while sequestering atmospheric carbon. Advanced formulations like EBC+ technology enhance nutrient availability and reduce greenhouse gas emissions. AI-powered soil monitoring systems provide real-time tracking of soil conditions using embedded sensors, enabling early detection of nutrient deficiencies and natural fertility restoration. These systems help maintain optimal soil pH, organic matter content, and microbial diversity essential for healthy organic production.

Digital Traceability and Certification: Blockchain technology is revolutionizing organic certification and market access: Blockchain-enabled traceability systems create transparent, tamper-proof records of the entire farming process from seed to market. This technology builds consumer trust, enables premium market access, and reduces certification costs through automated compliance verification. Digital certification systems streamline documentation processes while maintaining rigorous organic standards. These platforms integrate with farm management systems to ensure complete compliance with organic regulations and facilitate market access for smallholder farmers.

Biological and Biotechnological Innovations: Advanced biotechnological approaches are expanding the toolkit for organic production: Beneficial microbe technologies enhance plant growth and fitness through symbiotic relationships, reducing the need for external inputs while improving soil health. These technologies include mycorrhizal fungi, nitrogen-fixing bacteria and plant growth-promoting rhizobacteria. Participatory breeding programs develop organic-compatible crop varieties with enhanced nutritional quality and climate resilience. Biofortification initiatives ensure

that organic crops meet growing nutritional demands while maintaining ecological integrity.



Environmental and Economic Impacts

Biodiversity Enhancement: Organic farms show up to 95% higher species richness of arable flora, 35% increase in field birds, and 23% increase in flower-visiting insects compared to conventional systems.

Carbon Sequestration: Organic farms emit an average of 1,082 kg fewer CO_2 equivalents per hectare annually through enhanced carbon storage and reduced nitrous oxide emissions.

Energy Efficiency: Organic systems demonstrate 19% higher energy efficiency and 12% higher nitrogen efficiency compared to conventional agriculture.

Climate Adaptation: During drought conditions, organic maize yields have been documented at 31% higher than conventional counterparts due to improved soil water retention.

Challenges and Limitations

Average Yield Reduction: Organic yields remain approximately 19.2% lower than conventional systems on average.

Transition Period Challenges: After a five-year transition period, organic yields can equal conventional yields, but this initial period presents significant economic challenges.

Regional Variations: Yield gaps vary significantly across agro-climatic zones and crop types, requiring localized technological solutions.

Conclusion: Pathways to Sustainable Food Systems

The future of organic production technology lies in the intelligent integration of ecological principles with cutting-edge innovations. The convergence of organic agriculture with precision technologies, biotechnology and digital transformation offers a realistic pathway toward sustainable intensification while maintaining environmental integrity and economic viability. Key success factors include:

Technology Appropriateness: Solutions must be tailored to local contexts, farm sizes, and resource availability

Knowledge Transfer: Effective extension services and farmer education programs are essential for technology adoption

Policy Support: Supportive regulatory frameworks and investment incentives accelerate technological adoption

Market Development: Consumer awareness and demand for organic products drive market expansion and farmer profitability

As the global community works toward the United Nations Sustainable Development Goals, organic production technology represents an essential component of sustainable food systems transformation. The continued evolution of these technologies, combined with supportive policies and

market development, will be critical for achieving food security, climate resilience, and environmental sustainability in the decades ahead.

Eco-Friendly Farming: The Rise of Biofertilizers in Modern Agriculture

Ajay Yadav, Ravi Kumar, Ravindra Kumar and Shani Gulaiya

Abstract

Eco-friendly farming has emerged as a sustainable solution to address the environmental and productivity challenges associated with conventional agriculture. Among various approaches, the use of biofertilizers is gaining significant attention due to their ability to enhance soil fertility and crop productivity while minimizing ecological harm. Biofertilizers consist of beneficial microorganisms that improve nutrient availability by fixing atmospheric nitrogen, solubilizing phosphorus, and stimulating plant growth through the production of growth-promoting substances. Their application reduces dependence on chemical fertilizers, lowers production costs, and helps maintain soil health and biodiversity. In modern agriculture, the adoption of biofertilizers is steadily increasing as farmers seek sustainable and cost-effective alternatives to synthetic inputs. Additionally, biofertilizers contribute to long-term environmental sustainability by reducing soil degradation and water pollution. This paper highlights the growing importance of biofertilizers in promoting eco-friendly farming practices and emphasizes their role in achieving sustainable agricultural development. This article provides a comprehensive overview of biofertilizers, emphasizing their role in restoring soil health, enhancing microbial diversity, and promoting efficient nutrient cycling. Biofertilizers have emerged as a practical means of boosting pulse output by improving soil fertility and nutrient availability. The types, modes of action, benefits, and drawbacks of biofertilizers in relation to growing pulses are examined in this review paper. Because of their affordability, simplicity of use, Biofertilizers have emerged as a very successful alternative to chemical fertilizers due to their non-toxicity and environmental friendliness. They also allow plants to use nutrients that are naturally abundant in soil or the atmosphere and act as a supplement to agrochemicals. Future directions and recommendations for maximizing the benefits of biofertilizers in pulse production are also discussed. Because they come from naturally occurring sources including bacteria, fungus, and organic waste, biofertilizers offer a competitive alternative to conventional fertilizers. Their use increases plant growth, enhances soil fertility, and improves nutrient uptake while reducing adverse environmental effects.

Introduction

Although agriculture has always been the foundation of human civilization, contemporary farming methods have put tremendous strain on natural resources. Reduced biodiversity, water pollution, and soil deterioration are all results of overuse of chemical pesticides and fertilizers. Eco-friendly farming methods are gaining traction global-

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ly as a solution to these issues. Among these, biofertilizers have shown themselves to be a viable and efficient alternative that promotes environmental health and productivity. Living microorganisms known as biofertilizers increase the availability of vital nutrients in the soil, improving soil fertility and plant growth. They are harmless for the environment, natural, and biodegradable in contrast to synthetic fertilizers. A major change toward sustainable agriculture is indicated by their growing adoption. Due to their cost-effectiveness, ease of application, non-toxicity, and environmental friendliness, bio-fertilizers have become a highly effective substitute for chemical fertilizers. Additionally, they serve as a supplement to agrochemicals and enable plants to utilize nutrients that are naturally abundant in soil or the atmosphere (Gulaiya *et al.*, 2024).

What are Biofertilizers?

Biofertilizers are mixtures that contain helpful microorganisms like algae, fungi and bacteria. These microorganisms live in the rhizosphere (the area around the roots) or inside the plant and help it grow by making it easier for it to take in nutrients. The term "bio-fertilizer" refers to materials that contain live microorganisms, such as fungi, bacteria, or algae, either as symbionts that associate with plants or in their free-living state. By stimulating a variety of microbial processes, including nitrogen fixation, phosphate solubilization, and the synthesis of chemicals that promote plant growth, biofertilizers, whether applied to seeds, soil, or plant surfaces, improves soil fertility and plant nutrient uptake. Biofertilizers aim to reduce the use of chemical fertilizers and promote soil health in order to support ecologically friendly and sustainable agriculture practices. Unlike most land plants, legumes may work with nitrogen fixing bacteria to generate symbiotic root nodules that provide the necessary nitrogen for growth

Some types of biofertilizers are

Nitrogen-fixing bacteria: Nitrogen-fixing bacteria convert inert atmospheric nitrogen (N_2) into ammonia (NH_3), a usable form for plant growth and protein synthesis, replenishing soil nitrogen. They act as crucial biofertilizers, reducing the need for synthetic nitrogen fertilizers. Key types include Rhizobium (symbiotic), Azotobacter (free-living), and Azospirillum (associative).

Phosphate-solubilizing microorganisms (PSM): including bacteria (Pseudomonas, Bacillus) and fungi (Aspergillus, Penicillium) convert insoluble, fixed phosphorus in soil into soluble forms (like HPO_4^{2-} or H_2PO_4-) that plants can readily absorb. They improve agricultural yields by acting as biofertilizers, increasing phosphorus uptake, and promoting growth in infertile soils.

Mycorrhizal fungi: Mycorrhizal fungi establish a mutualistic symbiotic relationship with plant roots, where the fungus penetrates or surrounds root tissues to form a vast, microscopic hyphal network that drastically increases the root system's surface area for absorption. By extending far beyond the depletion zone surrounding roots, these hyphae efficiently forage for water and essential nutrients

particularly phosphorus, nitrogen and micronutrients transporting them back to the plant. In exchange, the host plant provides the fungus with photosynthetic carbohydrates (sugars), enabling both organisms to thrive, improving plant drought tolerance, soil health, and overall growth.

Cyanobacteria (blue-green algae): particularly genera like Anabaena and Nostoc, are highly beneficial in paddy fields because they act as natural biofertilizers, fixing atmospheric nitrogen (N_2) into ammonia (NH_3) through specialized cells called heterocysts. Thriving in submerged, sunny conditions, these organisms create thick mats that provide a sustainable, eco-friendly source of nitrogen, effectively supplementing chemical fertilizers and boosting rice yields by up to 25 kg N ha^{-1} in a season. Beyond nitrogen fixation, they enhance soil structure, improve water-holding capacity, and release plant growth regulators like phytohormones.

Rhizobium Biofertilizers: Rhizobium is a symbiotic, nitrogen-fixing bacterium applied as a biofertilizers primarily for leguminous crops (pulses, soybeans, groundnuts) to enhance growth and soil health. Upon application, it infects host root hairs, forming root nodules where it lives in a mutually beneficial relationship. Inside these nodules, Rhizobium converts atmospheric nitrogen into usable ammonia, providing the plant with essential nitrogen, while receiving carbohydrates in return. This natural process enhances plant nutrient uptake, increases crop yield, and reduces reliance on chemical fertilizers.

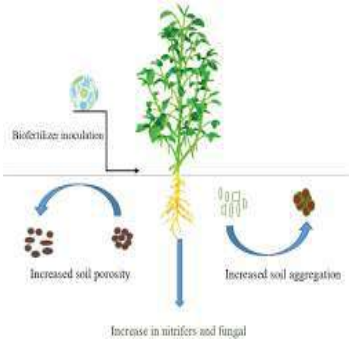
Azotobacter: Azotobacter is a highly effective, free-living, aerobic nitrogen-fixing bacterium that acts as a potent biofertilizer, making it ideal for non-leguminous crops such as wheat, maize, and various vegetables. Unlike symbiotic bacteria that require specific host nodules, Azotobacter colonizes the rhizosphere the root surface and surrounding soil to turn atmospheric nitrogen into ammonium, providing a steady supply of nitrogen directly to crops that cannot fix it themselves. Its application in agriculture is associated with saving 60 to 80 kg of urea per hectare, increasing crop yields by 10%-25%, and enhancing nutrient availability, such as phosphorus. Beyond nitrogen fixation, this bacterium improves plant health by producing phytohormones like indole acetic acid (IAA), gibberellins, and cytokinins, which significantly enhance seed germination, root proliferation, and overall crop vigor. Azotobacter also acts as a biocontrol agent against soil-borne diseases by producing antifungal substances, while its exopolysaccharides (EPS) enhance soil aggregation and structure.

Azospirillum: Azospirillum is a genus of free-living, nitrogen-fixing bacteria commonly used as a biofertilizer for cereals (such as maize, wheat, and rice) and grasses. It colonizes the rhizosphere the area surrounding plant roots and establishes a mutually beneficial relationship by providing nitrogen, producing plant growth-promoting hormones like auxin (IAA), and increasing nutrient uptake. Azospirillum helps improve root hair development, allowing plants to access water and nutrients more

efficiently, which often results in 10-15% higher yields and better stress tolerance against drought and salinity. Because they work by promoting root architecture, Azospirillum is particularly effective for grasses (Poaceae family) and helps reduce reliance on chemical fertilizers, making it a key component of sustainable agricultural practices.

Phosphate Solubilizing Bacteria (PSB): Phosphate Solubilizing Bacteria (PSB) are beneficial microorganisms used as biofertilizers to enhance phosphorus (P) availability for almost all crops, including cereals, legumes, and vegetables, by converting insoluble, fixed phosphorus in the soil into soluble, plant-available forms. While phosphorus is essential for plant energy transfer, photosynthesis, and root development, most of it in soil is trapped in insoluble inorganic (bound with Calcium, Iron, or Aluminum) or organic compounds. PSB address this deficiency by secreting organic acids (such as gluconic and citric acids) and phosphatase enzymes in the root zone (rhizosphere). These acids and enzymes lower soil pH, chelate the metal ions trapping the phosphorus, and break down complex P compounds, making the nutrients directly absorbable by roots. By improving the efficiency of phosphate uptake, PSB reduce the reliance on chemical fertilizers by 25-30%, improve soil health, stimulate root growth, and enhance crop resistance to environmental stress, ultimately leading to higher productivity.

Mycorrhiza (VAM): Vesicular-Arbuscular Mycorrhiza (VAM), a type of endomycorrhizal fungi, is highly effective in horticultural crops and trees by forming a symbiotic, mutually beneficial relationship with plant roots, which significantly enhances nutrient uptake and overall plant resilience. These fungi colonize the root cortex, sending out an extensive network of hyphae that extend far beyond the root system, increasing the effective surface area for absorbing water and nutrients particularly immobile phosphorus, zinc, copper, and nitrogen by up to 1,000-fold. This enhanced uptake is crucial for fruit trees (citrus, apple), vegetable crops (tomato, potato), and ornamentals, leading to stronger root development, healthier plants and 20-40% increased yields in poor or nutrient-fixing soils. Furthermore, VAM improves soil structure by producing glomalin, a “glue” that binds soil particles, improves water retention, and helps plants withstand environmental stressors such as drought, salinity, and soil-borne diseases.



Blue-Green Algae (BGA): Blue-Green Algae (BGA), or cyanobacteria, are widely recognized as a critical, eco-friendly biofertilizer in rice cultivation, particularly within tropical and sub-tropical regions. They are popular because they flourish in the submerged, warm, and sunny conditions of paddy fields. These microorganisms naturally enhance soil fertility without harming the ecosystem. They also promote sustainable agricultural practices by reducing the need for chemical fertilizers, which can

lead to soil degradation and pollution. Utilizing biofertilizers not only supports healthy plant growth but also contributes to a more balanced and resilient agricultural system.

Importance of Biofertilizers in Modern Farming

There are a lot of problems in farming that make the need for biofertilizers urgent:

Effect on Soil health: Continuous, exclusive use of chemical fertilizers often leads to severe soil degradation by reducing essential organic matter and killing beneficial microbes, resulting in decreased natural fertility, soil acidification, and soil compaction. When chemical fertilizers are used constantly, they provide immediate nutrients directly to the plant but fail to feed the microbial community, leading to a decline in soil enzymes and beneficial fungi (such as Trichoderma) that are sensitive to synthetic inputs. Conversely, biofertilizers restore soil fertility by reintroducing, activating, and multiplying beneficial microorganisms, such as Azotobacter and Rhizobium, which enhance the soil's biological activity and improve its structure by increasing aggregation, aeration, and water-holding capacity. By converting unavailable nutrients into plant-usable forms and breaking down organic matter, biofertilizers revive the natural nutrient cycle, creating a sustainable environment that boosts soil health and increases crop resilience, acting as a "probiotic" to bring life back to exhausted soils

Environmental concern: The extensive use of chemical fertilizers in modern agriculture presents a significant environmental threat, primarily due to nutrient leaching and runoff that degrades water quality and soil health. Because these synthetic products are highly soluble, excess nitrogen and phosphorus often applied beyond crop requirements readily leach through the soil, contaminating groundwater aquifers with high nitrate levels that are dangerous for human health. Furthermore, this runoff into rivers and lakes causes eutrophication, which induces harmful algal blooms that deplete oxygen and kill aquatic life, leading to the creation of aquatic "dead zones". Over time, chemical fertilizers can also cause soil acidification, destroy soil microbial diversity, and lower natural soil fertility, creating a vicious cycle of increasing chemical dependence. In contrast, biofertilizers, which consist of living microorganisms like bacteria and fungi, act as eco-friendly alternatives that enhance soil texture, improve aeration, and increase nutrient uptake by plants naturally. Because they work with nature to boost fertility rather than forcing immediate growth, they minimize the risks of water pollution and soil depletion. By improving soil structure and fostering beneficial microbes, biofertilizers promote long-term soil health and sustainable agricultural production.

Increasing Costs of Inputs: As global chemical fertilizer prices continue to rise due to supply chain disruptions and energy cost spikes, farmers are facing significantly higher input costs that squeeze profit margins, forcing many to seek more economical alternatives. Biofertilizers offer a cost-effective, sustainable alternative, often costing up to

40-50% less per acre than synthetic options. Beyond immediate financial savings, biofertilizers provide long-term benefits by restoring soil health, increasing organic matter, and enhancing water retention, whereas continuous chemical use tends to degrade soil structure. By promoting beneficial microorganisms like nitrogen-fixing bacteria and phosphate solubilizers, these products increase natural nutrient availability, allowing farmers to reduce chemical dependence by up to 30% over time. While chemical fertilizers offer quick growth, biofertilizers deliver enduring, sustainable agricultural productivity and better crop quality, representing a crucial shift toward both economic stability and environmental sustainability

Sustainable Crop Production: Biofertilizers promote sustainable crop production by restoring natural soil fertility and maintaining long-term productivity through environmentally friendly biological processes. Unlike chemical fertilizers that can degrade soil health over time, biofertilizers utilize beneficial microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi to convert atmospheric nitrogen and insoluble soil nutrients into accessible forms, encouraging a self-sustaining nutrient cycle. By increasing the population of these microbes in the rhizosphere, they enhance soil structure, improving water retention, aeration, and root penetration, which makes the soil more resilient to drought and erosion. Furthermore, these microbial agents promote healthier crops by producing growth-stimulating plant hormones (like auxins and cytokinins) and reducing reliance on synthetic, polluting chemicals, thereby securing environmental safety and protecting soil biodiversity for future generations.

Conclusion

Biofertilizers represent a transformative shift in modern agriculture by acting as a sustainable bridge between achieving high crop productivity and ensuring long-term environmental health. By utilizing beneficial microorganisms to fix atmospheric nitrogen and solubilize nutrients, they offer a dual benefit: directly increasing crop yields (often by 15-25%) while simultaneously restoring soil fertility, enhancing microbial diversity, and reducing reliance on chemical inputs. Although challenges regarding adoption such as limited shelf life, sensitivity to field conditions, and the need for greater farmer awareness persist, continued research is accelerating their integration into mainstream farming. Ultimately, embracing biofertilizers is essential for shifting toward sustainable, eco-friendly practices that enhance ecosystem resilience and secure global food production for future generations.

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Climate-Smart Vegetable Farming: Strategies for Resilience and Sustainable Production

S. Teja, V. Boomika and J. Devika

Abstract

Climate change is making it harder for vegetable farmers to do their jobs. Heat waves, unpredictable rainfall, water shortages and pest outbreaks all threaten both the amount and quality of the crops. Vegetable crops are very sensitive to climate and when they are stressed, they can lose up to 30-50% of their productivity. To protect crops, scientists and farmers are using climate-smart methods that mix modern breeding, smart use of resources, and environmentally friendly methods. Advanced breeding and genomic tools are making new kinds of tomatoes, peppers, and leafy greens that can handle heat and drought. Smart irrigation systems, mulching and rainwater harvesting all help plants get less water stress. Protected cultivation (polyhouses, shade nets) keeps crops safe from bad weather. Farmers can deal with the growing pressure of diseases without relying too much on pesticides by integrated pest management and bio controls. Together, these approaches form a climate-smart package that strengthens resilience, stabilizes yields and secures farmer livelihoods. By blending scientific advances with practical field strategies, climate-smart vegetable farming offers a pathway to sustainable production and food security in an era of uncertainty.

Introduction

Vegetable farming is one of the most vulnerable sector when it comes to climate change. It's no longer uncommon for temperatures to rise, rain to fall at random times, droughts to last a long time and floods to happen out of the blue. These things are becoming the new normal. This means that farmers are more likely to lose crops, have pest problems and lose money after the harvest. In these uncertain times, using traditional methods alone won't guarantee stable yields. This is where climate-smart vegetable farming comes in. It is a complete system that includes growing crops that can handle stress, using water wisely, using methods that are good for the soil, managing pests in a way that is good for the environment and protecting plants while they grow. Studies and reviews show that using these strategies not only lowers climate risks but also boosts productivity, market value, and long-term sustainability.

Climate smart

Climate smart agriculture is defined as any

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agriculture practice that sustainably increase food production, build resilience to climate change (adaptation), reduces/removes greenhouse gases (mitigation) and enhance the achievement of national food security and development goals (FAO, 2010). This definition integrates the three dimensions of sustainable development (economic, social and environmental) by jointly addressing the food security, ecosystems management and climate change challenges

Influence of extreme climatic conditions on vegetables

Vegetables are highly vulnerable to environmental extremes. Fluctuating temperatures and poor soil moisture reduce photosynthesis, pollination and fruit set, leading to lower yields and quality. Climate change intensifies these stresses, making farming unprofitable through crop failures, pest outbreaks and declining market value. Studies show clear impacts for example, potato yields in India may decline by 3-14% between 2020 and 2050 due to global warming. Beyond heat and drought, floods, salinity, storms and hail also damage vegetable crops, threatening food security and farmer livelihoods.

Carbon Dioxide (CO_2): Rising CO_2 levels can enhance carbohydrate formation and boost vegetable yields. Yet these gains are often offset by weeds, diseases, insect pests and abiotic stresses. Forecasts remain uncertain because elevated CO_2 also interacts with temperature and water availability.

Elevated Temperature: Temperatures beyond the normal growth range reduce germination, photosynthesis, and biomass accumulation. High heat causes flower abortion, poor fruit and seed set and lowers post-harvest quality through disorders like blotchy ripening and sunburn. Crop adaptation strategies and breeding of heat-tolerant varieties are essential to sustain production.

Waterlogging: Excess rainfall or poor drainage reduces soil oxygen, limiting root respiration and damaging shallow-rooted vegetables. Sensitivity varies with species, genotype and plant age, but most vegetables show sharp yield declines under prolonged waterlogging.

Drought Stress: Insufficient rainfall and irrigation lead to reduced germination, nutrient uptake and photosynthesis. High temperatures intensify drought effects through increased evapotranspiration. Succulent vegetables, with edible parts containing over 85% water, are especially vulnerable during bulb, tuber, curd and flowering stages.

Salinity: In arid and coastal regions, soil salinity rises due to groundwater evaporation and seawater intrusion. Vegetables are highly sensitive to salinity, particularly during developmental stages, resulting in reduced yields.

Biotic Stresses: Climate change alters pest, disease and weed dynamics, accelerating their growth and expanding their ranges. New ecological niches emerge, leading to more frequent outbreaks, aggressive strains and weakened plant defence mechanisms (Tabasum *et al*., 2025).

Climate smart practices

Water Management: Climate-smart horticulture begins with efficient water use. Rainwater harvesting allows farmers to store runoff in barrels or cisterns for later use during dry spells. Drip and Micro-irrigation systems minimize evaporation losses and deliver water directly to plant roots. Choosing drought-tolerant varieties with deeper root systems further reduces vulnerability, while mulch-ing and cover crops improve soil structure and water retention.

Heat Stress Management: High temperatures can severely affect crop growth, so heat-tolerant cultivars are essential. Shade nets and misting systems help reduce sunburn and create cooler microclimates around plants. Adjusting planting schedules to avoid peak heat periods, or rotating with cover crops, ensures that crops are less exposed to extreme stress.

Altered Rainfall Patterns: Changing rainfall patterns demand adaptive strategies. Well-designed drainage systems prevent waterlogging and root rot while raised beds improve aeration and drainage in flood-prone areas. Flood-tolerant crop varieties provide resilience against excess water conditions, ensuring production continues even during heavy rains.

Integrated Pest Management (IPM): Pest pressures intensify under climate change, making IPM vital. Biological control encourages natural predators and bio-agents to reduce pest populations. Resistant crop varieties and careful, need-based pesticide use minimize chemical reliance. Climate-based monitoring systems forecast pest outbreaks using weather data, allowing farmers to act proactively.

Greenhouse and Protected Cultivation: In Algeria, adaptive greenhouse systems (SmaSH concept) were introduced to optimize designs for arid climates, improving yields while reducing water and soil-borne disease pressures. This represents a climate-smart innovation tailored to harsh environments.

Crop-Livestock Integration: Integrated crop-livestock systems (ICLS) combine conservation agriculture principles with crop rotation and residue use. This reduces vulnerability, diversifies farm outputs and stabilizes farmer incomes under climate stress.

Forest and Cropland Regeneration: Large-scale projects like Algeria's "Green Dam" restored rangelands and diversified species, helping mitigate erosion and desertification while improving food security.

Biodiversity and Local Livestock Breeds: Maintaining and promoting rustic local cattle breeds (e.g., Brown Atlas ecotypes) supports resilience in semi-arid zones, while also linking to niche markets for traditional dairy products.

Subsurface Fertigation: Demonstration farms in Algeria showed that underground drip fertigation saved over 50% water and increased potato yields compared to center-pivot irrigation.

Urban CSA Practices: In Addis Ababa, urban farmers adapted through early planting, mixed farming, agroforestry, and crop diversification.

Table 1: Various Climate Smart Village (CSVs) Model practices in Farmers Level in Kavre, Nepal (Rijal *et al*., 2019)

CSV Model	Introduced Practices	Results
Nutrient Smart	Use of bio-fertilizer and bio-pesticide Jholmol	Enabling sustainable growth; effective nutrient management; mitigates negative impact of chemical management
Water Smart	Plastic ponds for wastewater and rainwater collection	Increase in vegetable production
Crop Smart	Using different crop varieties in multiple locations	Improved soil fertility; moisture retention through crop rotation; mixed cropping; nitrogen fixation by intercropping
Future Smart	Provided information on insurance and supports	Mitigation of loss and damage
ICT Smart	SMS notification on weather and market	Improvement in pest management, land preparation, weeding, irrigation, and harvesting
Energy Smart	Installation of biogas plants	Environmentally sustainable energy use

Off-farm strategies included shifting occupations or engaging in non-farm activities to buffer climate shocks.

ICT-Based Agro-Advisories: Use of mobile and digital climate information services was highlighted as crucial for urban farmers to anticipate risks and make timely decisions.

Agroforestry and Conservation Tillage: Agro-forestry, mulching and conservation tillage as underutilized but highly effective CSA practices for leafy vegetables in semi-arid regions. These improve soil fertility, conserve water and enhance resilience.

Organic Fertilization and Bio-fertilizers: Organic inputs and bio-fertilizers reduce reliance on chemicals, improve soil health and lower greenhouse gas emissions, making them key CSA strategies for vegetable agri preneurs.

Additional Practices: Modern horticulture also benefits from precision agriculture, where sensors and data guide targeted application of water and fertilizers. Post-harvest care through proper storage reduces food waste and protects farmer income. Climate-informed variety choices, such as shorter-season or drought-resistant crops, ensure adaptability to unpredictable weather (Ariom *et al.*, 2022, Ali *et al.*, 2024, Degefu *et al*., 2024, Erick *et al*., 2025).

Conclusion

Climate-smart vegetable farming is a resilient, resource-efficient system that integrates adaptive crop varieties, soil and water conservation, eco-friendly pest control and modern technologies. Practices such as adaptive greenhouses, crop–livestock integration, agroforestry, organic fertiliza-tion, subsurface fertigation and ICT-based advisories strengthen productivity while reducing vulnerability to droughts, floods and heat stress. By combining ecological restoration with farmer-led innovations and digital tools, vegetable farming becomes more sustainable, ensuring stable yields, improved nutrition and climate resilience**.** In short, it transforms climate risks into opportunities for secure livelihoods and long-term food security.

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Adoption of Organic Production Practices for Sustainable Rural Development and Farmer Welfare

Abhishek Gupta and Radhe Shyam Kumar

Abstract

Organic agriculture is a holistic production management system which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles, and soil biological activity. This article details the systemic adoption of organic practices as a primary vehicle for rural development. By eliminating synthetic fertilizers and pesticides, organic farming reduces the chemical footprint on rural ecosystems while simultaneously offering farmers a pathway out of indebtedness and health crises.

The Global Context of Sustainable Agriculture

Modern agriculture is currently facing a 'trilemma': the need to increase food production, the necessity of protecting biodiversity, and the urgency of mitigating climate change. Conventional farming systems, while productive in the short term, have resulted in soil acidification, water contamination, and a loss of genetic diversity. Organic production provides a viable alternative that addresses these issues while supporting the United Nations Sustainable Development Goals (SDGs).

Core Components of Organic Production Systems

Crop Rotation and Diversity: Maintaining a diverse range of crops prevents the depletion of specific soil nutrients and breaks the life cycles of pests and diseases.

Green Manures and Cover Crops: Leguminous crops are grown specifically to be plowed back into the soil, acting as a natural nitrogen source.

Biological Pest Management: Encouraging natural predators such as ladybugs, spiders, and birds to manage pest populations naturally.

Livestock Integration: The symbiotic relationship where animal manure fertilizes crops and crop residues serve as animal feed.

Non-Chemical Weed Management: Utilizing mulching, thermal weeding and mechanical cultivation to manage unwanted plants without herbicides.

Environmental Benefits and Climate Resilience

Organic farming acts as a carbon sink. Through the increase of soil organic matter, organic farms sequester more atmospheric carbon than conventional farms. This section discusses the mitigation and adaptation potential.

Enhanced Water Retention: Organic soils hold up to 20% more water, providing drought resistance.

Reduction in Nitrate Leaching: The absence of synthetic nitrogen prevents the pollution of groundwater and local streams.

Pollinator Protection: Avoiding neonics and other

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pesticides ensures the health of bees and butterflies essential for global food security.

Economic Impact and Farmer Welfare

Farmer welfare is often measured by income stability, health, and social standing. Organic farming addresses all three.

Reduced Input Expenditure: Farmers save significantly by producing their own bio-fertilizers and seeds.

Price Premiums: Certification opens doors to export markets and premium domestic grocery chains.

Social Equity and Gender Empowerment

In many rural societies, women are the traditional keepers of seeds and livestock. Organic farming elevates these traditional roles into key economic drivers. Furthermore, organic certification often requires compliance with fair labor standards, ensuring better wages and working conditions for landless laborers.

Challenges in the Transition to Organic Systems

The Conversion Period: The initial 2-3 years of transition often see lower yields as the soil recovers.

Certification Logistics: High costs and complex paperwork are barriers for smallholder farmers.

Lack of Organic Extension Services: Most government advisors are trained in conventional methods and lack expertise in biological systems.

Institutional and Policy Frameworks

For organic farming to thrive, it requires government backing. This includes subsidies for organic certification, public procurement of organic food for schools and hospitals, and investment in rural infrastructure like cold storage.

Technological Innovations in Organic Agriculture

Precision Composting: Using sensors to optimize nutrient levels in organic fertilizers.

Drone Monitoring: For identifying pest outbreaks early without chemical broad-casting.

Blockchain Traceability: Allowing consumers to verify the organic origin of their food directly from the farmer.

Global Case Studies and Best Practices

Case Study: Sikkim, India - The first 100% organic state in the world. Sikkim demonstrated that political will combined with farmer education can transform an entire regional economy. By banning synthetic inputs, the state saw a surge in tourism and a revitalization of traditional crop varieties.

Future Directions and Recommendations

- ✓ Develop Regional Bio-Resource Centers to provide low-cost organic inputs.
- ✓ Integrate organic farming into national school curricula.
- ✓ Incentivize 'Carbon Farming' payments for organic producers.

Conclusion

The adoption of organic production practices is not merely a return to the past; it is a sophisticated, science-based approach to the future. It offers a resilient framework for rural development that prioritizes the welfare of the producer and the health of the planet. Through collaborative policy and

technological innovation, organic farming can become the global standard for 21st-century agriculture.

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Structure and Activity Relationship of Neonicotinoids

Karthiga A. R.

Abstract

Neonicotinoids are synthetic compounds similar to nicotine in action and structure (partially) used for systemic control of sucking pests. They eventually replaced organophosphate and carbamate insecticides. This is mainly attributable to the specificity of insect and mammalian nicotinic receptors. These compounds are remarked safe to mammals unlike nicotine due to the difference in their binding site. The first-generation chloropyridinyl- containing neonicotinoids include imidacloprid (IMI), nitenpyram (NIT), acetamiprid (ACE) and thiacloprid (THI) commercialized in 1995, 1996 and 2000.

Introduction

Shell Development Company scientists, Soloway and his colleagues in 1970 developed a compound, namely Nithiazine (Nitromethylene heterocyclic compound) through structural optimization of a lead compound called 2-(dibromonitromethyl)-3-methylpyridine. This compound was claimed to have insecticidal property, hence referred to as I prototype of neonicotinoids. However, it was highly photo labile in nature and therefore it was commercially used as in poultry and animal husbandry pest care. Kagabu and colleagues of Nihon Bayer Agrochemicals continued their research on nithiazine which resulted in the development of II prototype with photostability, namely 1-(6-chloropyridin-3-ylmethyl)-2-nitromethylene-imidazolidine in 1984. This compound was commercially designated as Imidacloprid (IMI) and released into the market in 1991. It successfully replaced OP compounds and Carbamates. Further, intensive research in the area of neonicotinoids led to the development of many classes of compounds. Structures in the second prototype were modified through strenuous research and many other commercially, significant compounds were discovered. The first-generation chloropyridinyl- containing neonicotinoids include imidacloprid (IMI), nitenpyram (NIT), acetamiprid (ACE) and thiacloprid (THI) commercialized in 1995, 1996 and 2000.

Structure and Activity Relationship of Neonicotinoids

Effect of Pyridyl Ring: (3-pyridyl compound) gave higher binding affinity than 2- pyridyl and 4-pyridyl isomers, although the superiority of 3-isomer was not clear from the insecticidal activity.3-pyridyl compounds gave the highest binding affinity and insecticidal activity.

Effect of the Number of Methylene Units between 3-Pyridyl and Imidazolidine

Compound 5 (n=1) gave the highest binding affinity and insecticidal activity. Compound 10 (n=2) showed a certain level of binding affinity, but the

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binding affinity of compound 9 (n=0) was much lower

Effect of Partial Structures: Both 2-nitromethylene-imidazolidine and 3- methylpyridine gave no binding affinity.

Effect of replacing the imidazolidine ring: The heterocyclic groups containing nitrogen on 1-position are concerned, the nitrogen atom on 3-position could be replaced by a sulfur or oxygen atom, or a methylene group without drastic decrease in the binding affinity.

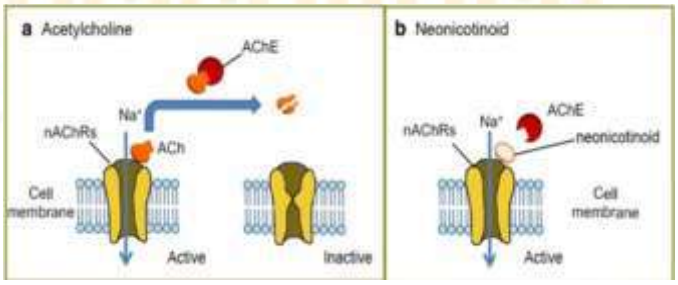
Number of carbon atom present in the ring: Compounds with a five-carbon ring are more potent than those with less than five carbons. For example, the five-carbon ring compound imidacloprid has more insecticide activity than four carbon ring compound thiamethoxam.

Non-carbon atoms present in the ring: The presence of non-carbon atoms also confers the toxicity. Potency of toxicity order: nitrogen> carbon > sulfur > oxygen) in the rings.

The presence of nitramide group: The presence of nitramide group (=N-NO_2) substituent at the 2-position of the imidazolidine ring makes little difference to insecticidal activity compared with compounds that contain a nitromethylene (=CH-NO^2) group at this position, but the presence of the nitramide group (=N-NO_2) in nithiazine significantly reduces affinity for the receptors. This suggests that the reduction in binding resulting from the presence of the nitrogen atom at the 2-position is compensated for by the increase in hydrophobicity, which enhances transport to the target sites.

Mode of action

The insecticides nicotine, neonicotinoids (imidacloprid, acetamiprid, thiamethoxam, nitenpyram and clothianidin) mimics acetylcholine by acting as agonists to activate the nAChR. This activation causes an influx of sodium ions and the generation of action potentials. Under normal physiological conditions, the synaptic action of acetylcholine is terminated by the enzyme AChE, which rapidly hydrolyzes the neurotransmitter. Because these insecticides are not hydrolyzed or destroyed by AChE, the persistent activation leads to an overstimulation of cholinergic synapses, resulting in hyperexcitation, desensitization, convulsion, paralysis, and, finally, death of the insect.



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Organic Production Technology in Modern Agriculture: Integrating Traditional Knowledge with Scientific Innovation

Shivani Rai, Arti and Navjeet Anand

Abstract

Organic agriculture represents a paradigm shift in food production systems, emphasizing ecological balance, biodiversity, and sustainability. This comprehensive analysis examines the integration of traditional knowledge (TK) with modern scientific innovations in organic farming technologies. The study reveals that by 2026, Indian organic farming has evolved into a dynamic synergy where centuries-old agricultural wisdom is enhanced through cutting-edge scientific technologies. Key findings indicate that validated traditional practices, when combined with biological fertilizers, AI-driven advisory systems, and precision agriculture tools, can achieve productivity levels comparable to conventional farming while maintaining ecological integrity. The integration framework demonstrates that traditional water conservation techniques when enhanced with IoT sensors and satellite monitoring, improve water use efficiency by 30-40%. Similarly, traditional pest management methods, when supplemented with biocontrol agents and molecular diagnostics, reduce crop losses by 60-70%. The research validates that this hybrid approach not only preserves cultural heritage but also addresses contemporary challenges of climate resilience, food security and sustainable intensification. The paper concludes that successful integration requires systematic validation of traditional practices, adaptive technology deployment and farmer-centric innovation ecosystems.

Introduction

The global agricultural landscape is undergoing a profound transformation as the world confronts the dual challenges of feeding an expanding population while addressing climate change, biodiversity loss, and environmental degradation. Organic agriculture has emerged as a promising alternative, offering a holistic approach that works with natural systems rather than against them. India, with its rich agricultural heritage spanning thousands of years, stands at the forefront of this revolution, where traditional wisdom meets modern science. The integration of traditional knowledge with scientific innovation in organic production technology represents more than mere nostalgia for past practices; it embodies a sophisticated approach to sustainable agriculture that draws upon generations of empirical knowledge while leveraging contemporary scientific advancements. This convergence is particularly relevant in the Indian context, where smallholder farmers cultivate over 85% of agricultural land and tradition-

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al farming systems have sustained communities for millennia. The concept of Indigenous Technical Knowledge (ITK) in agriculture, as recognized by the Indian Council of Agricultural Research (ICAR), encompasses the wisdom, practices, and innovations developed by farming communities through generations of observation, experimentation, and adaptation. These practices, ranging from rainwater management techniques to pest control methods, are inherently sustainable and context-specific. However, the challenge lies in validating, documenting, and integrating these traditional practices with modern scientific tools to enhance their efficacy, scalability, and adoption. This integration is not merely additive but synergistic. Traditional practices provide the ecological foundation and sustainability principles, while scientific innovations offer precision, efficiency, and scalability. The result is an organic production system that is both ecologically sound and economically viable, capable of meeting contemporary food security demands while preserving environmental integrity.

Traditional Knowledge Systems in Agriculture: Traditional agricultural knowledge in India represents a sophisticated repository of ecological wisdom developed over millennia of continuous observation, experimentation and adaptation. This Indigenous Technical Knowledge (ITK), as documented and validated by the Indian Council of Agricultural Research (ICAR) encompasses a wide spectrum of practices that demonstrate remarkable scientific understanding and ecological sensitivity.

Rainwater Management and Conservation: Traditional Indian agriculture developed intricate water conservation systems long before modern hydrology. Micro-depression techniques around trees like teak, mango, and neem effectively retain soil moisture and recharge groundwater tables. These practices, validated through ICAR experiments, demonstrate soil moisture retention improvements of 25-35% compared to conventional methods. The traditional understanding of watershed management, evident in systems like the Johads of Rajasthan and Eris of Tamil Nadu, showcases sophisticated hydrological engineering that contemporary science is only beginning to appreciate. The scientific validation of these practices has revealed their underlying mechanisms. For instance, micro-depressions create localized zones of high organic matter accumulation and microbial activity, enhancing infiltration rates and reducing runoff. Traditional contour bunding and terracing, when studied through modern soil science, demonstrate erosion reduction rates of 60-80% compared to uncontrolled slopes.

Soil Health Management: Traditional Indian farmers maintained soil fertility through diverse practices that modern science now recognizes as fundamentally sound. The use of green manures like dhaincha and sunhemp for nitrogen fixation, the incorporation of animal waste through compost and vermicompost, and the practice of crop rotation and intercropping all contributed to maintaining soil organic matter levels above 2-3%.The scientific

validation of these practices has revealed their biochemical foundations. Green manuring, for example, involves symbiotic nitrogen fixation through Rhizobium bacteria, while compost enhances soil microbial diversity and organic matter decomposition. Traditional mulching practices using crop residues, pine needles, or other organic materials were found to reduce evaporation losses by 30-40% while suppressing weed growth.

Pest and Disease Management: Traditional pest management in India was remarkably sophisticated, utilizing ecological principles that modern science continues to validate. The use of *Cleistanthus collinus* (parasi) leaves to control rice pests like yellow stem borer and gall fly demonstrated 70-80% efficacy in ICAR trials. Similarly, traditional companion planting practices, such as marigold with tomatoes, utilize allelopathic effects and natural predator attraction to manage pest populations. The scientific investigation of these practices has identified their active compounds and mechanisms. Plant extracts contain secondary metabolites that act as repellents, antifeedants, or growth inhibitors for pests. Traditional biological control methods, like the use of Trichogramma wasps for bollworm control in cotton, have been validated and enhanced through modern rearing and application techniques.

Seed Conservation and Selection: Traditional Indian agriculture maintained remarkable genetic diversity through sophisticated seed selection and conservation practices. Farmers developed and maintained landraces adapted to specific agro-ecological conditions, ensuring resilience against pests, diseases, and climate variations. These practices, now recognized as crucial for climate adaptation, involved selection for traits like drought tolerance, pest resistance, and nutritional quality. Modern genetic studies have revealed that traditional landraces possess unique alleles and genetic combinations that have been lost in modern hybrid varieties. The conservation and utilization of these genetic resources through traditional seed banks and community exchange systems provides a valuable resource for future breeding programs.

Livestock Integration: Traditional Indian farming systems integrated crops and livestock in a synergistic relationship that enhanced overall farm productivity and sustainability. Cattle provided draft power, manure for fertilizer, and milk, while crop residues served as animal feed. This integration maintained nutrient cycling within the farm ecosystem and reduced dependence on external inputs. Scientific studies have quantified the benefits of this integration, showing that farms with integrated crop-livestock systems maintain soil nitrogen levels 20-30% higher than specialized crop farms. The traditional understanding of animal nutrition, health management and manure processing continues to inform modern organic livestock production systems.

Modern Scientific Innovations in Organic Farming

The integration of traditional knowledge with modern scientific innovations has catalyzed the

evolution of organic farming into a sophisticated, technology-driven agricultural system. Contemporary organic farming leverages cutting-edge technologies to enhance efficiency, scalability, and productivity while maintaining ecological principles.

Biological Fertilizers and Biostimulants: The biological products market represents one of the fastest-growing segments in agricultural technology, with annual growth rates of 10-14%. Modern biological fertilizers, biostimulants, and biocontrols are no longer experimental but are being integrated into digital agronomy platforms and nutrient management programs. These products utilize specific microbial inoculants like Rhizobium for legumes, Azospirillum and Azotobacter for cereals, and phosphate-solubilizing bacteria (PSB) for various crops. The scientific validation of these products has demonstrated their efficacy in reducing chemical fertilizer dependency by 30-50% while maintaining or improving yields. Modern formulations enhance microbial survival during storage and application, improving field performance. The integration of these products with precision agriculture tools allows for site-specific application, optimizing nutrient use efficiency.

AI-Driven Advisory Systems

Artificial Intelligence has emerged as the "invisible hand" of modern organic farming, analyzing vast amounts of data to provide real-time, field-specific recommendations. AI systems process satellite imagery, soil sensor data, weather forecasts, and crop health indicators to optimize nutrient management, irrigation scheduling, and pest control decisions. In 2026, AI has evolved into an ecosystem that connects all agricultural technologies across the production cycle. Machine learning algorithms analyze microclimatic variations within fields, enabling variable rate applications of organic inputs. Computer vision systems detect pest infestations and nutrient deficiencies earlier than human observation, enabling timely intervention. These AI systems work in synergy with human experience, amplifying rather than replacing farmer knowledge.

Precision Agriculture Technologies: The integration of IoT technologies has revolutionized precision organic farming. Soil moisture sensors, nutrient meters, and environmental monitoring stations provide real-time data on field conditions. Drones equipped with multispectral sensors assess crop health through NDVI (Normalized Difference Vegetation Index) analysis, enabling precise identification of problem areas. These technologies enable organic farmers to apply inputs at the right rate, right time, and right place, maximizing efficiency and minimizing environmental impact. The combination of GPS-guided equipment, IoT sensors, and AI analytics allows for the creation of prescription maps that guide variable rate applications of compost, biofertilizers, and water.

Biotechnology and Genetic Improvement: Modern biotechnology applications in organic farming focus on enhancing the efficacy of biological products and developing crop varieties adapted to organic production systems.

Tissue culture techniques enable the rapid multiplication of disease-free planting material for organic crops. Genetic improvement programs focus on developing varieties with traits suitable for organic production, including pest resistance, drought tolerance, and efficient nutrient use. Molecular biology tools enable the identification and characterization of beneficial microorganisms, leading to more effective biofert-ilizers and biopesticides. Marker-assisted selection accelerates the development of crop varieties with multiple desirable traits, reducing the breeding cycle from 8-10 years to 3-4 years.

Water Management Technologies: Climate volatility has driven innovation in water management technologies for organic agriculture. Soil moisture sensors integrated with automated irrigation systems enable precise water application, reducing waste and maintaining optimal soil moisture conditions. Precision irrigation techno-logies like drip irrigation and micro-sprinklers, when combined with water-saving techniques like drip fertigation of organic inputs, improve water use efficiency by 40-60%.

Blockchain and Traceability Systems: Modern technology addresses organic certification and mar-ket access challenges through blockchain traceability systems. These platforms provide farm-to-market transparency, enabling consumers to verify the organic status of products and trace them back to specific farms. This technology enhances market access and premium prices for organic farmers while building consumer trust.

Automated Machinery and Robotics: Field robotics and autonomy technologies are transitioning from experimentation to commercial adoption in organic farming. Autonomous tractors, robotic weeders, and mechanical harvesters reduce labor dependencies and improve operational efficiency. These technologies are particularly valuable for organic farming systems that often face labor shortages. Specialized machinery for organic farming includes mechanical weed control equipment, precision seeders for cover crops, and automated sorters for post-harvest processing. The integration of these technologies with GPS and guidance systems enables precise operations that maintain soil structure and organic matter.

Integration Framework and Future Prospects: The successful integration of traditional knowledge with modern scientific innovations requires a systematic framework that respects the wisdom of traditional practices while leveraging the precision and scalability of modern technologies. This integration framework must be context-specific, farmer-centric, and continuously evolving.

Future Research Directions

Future research should focus on several key areas to advance the integration of traditional and scientific knowledge in organic farming. Molecular studies should elucidate the mechanisms of traditional practices, enabling their enhancement through biotechnology. Climate-resilient organic production systems should be developed through the

integration of traditional adaptation strategies with modern climate modeling. The development of low-cost, appropriate technologies for smallholder farmers represents a critical research priority. The optimization of digital technologies for resource-constrained environments will expand the reach of precision organic farming. The development of new market mechanisms that reward the preservation of traditional knowledge and sustainable practices will provide economic incentives for integration.

Scaling and Commercialization

Scaling successful integrated organic farming systems requires attention to business models, value chain development, and market access. The development of farmer producer organizations enables collective marketing and value addition. The integration of traditional products with modern processing technologies creates new market opportunities. The commercialization of integrated organic farming systems should follow the principles of fair trade and benefit-sharing. The development of intellectual property protection mechanisms for traditional knowledge while ensuring benefit sharing with farming communities will support sustainable scaling.

Conclusion

The integration of traditional knowledge with scientific innovation represents a transformative approach to organic agriculture that addresses the complex challenges of modern food systems while preserving ecological integrity and cultural heritage. This integration, as demonstrated in Indian organic farming systems, offers a pathway toward sustainable intensification that can feed growing populations while protecting the environment. The evidence presented demonstrates that traditional agricultural practices, when validated and enhanced through modern science, can achieve productivity levels comparable to conventional farming while maintaining ecological sustainability. The integration of AI-driven advisory systems, precision agriculture technologies, and biological products with traditional soil management, water conservation, and pest control practices creates resilient farming systems capable of withstanding climate variability. The future of organic agriculture lies in continued innovation that respects traditional wisdom while embracing scientific advancement. As climate change intensifies and environmental concerns grow, the integration of traditional and scientific knowledge will become increasingly important for creating sustainable, resilient, and productive agricultural systems. This approach not only addresses agricultural productivity but also contributes to broader goals of environmental conservation, cultural preservation, and rural development. As we move toward a more sustainable future, the integration of traditional knowledge with scientific innovation offers a proven pathway to creating agricultural systems that are productive, sustainable, and socially equitable.

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Role of Organic Production Technology in Reducing Chemical Dependency and Promoting Sustainable Farming

Vidyottma Gupta

Abstract

Agriculture has played a vital role in human survival for thousands of years. However, in recent decades, farming has become highly dependent on chemical fertilizers, pesticides, and herbicides to increase production. While these chemicals have helped boost yields, their excessive use has led to serious problems such as soil degradation, water pollution, loss of biodiversity, and health risks to humans and animals. In this context, organic production technology has emerged as an effective and sustainable alternative. It focuses on natural processes, ecological balance, and reduced chemical use. This article discusses the role of organic production technology in reducing chemical dependency and promoting sustainable farming in simple and practical terms.

Introduction

Modern agriculture has achieved remarkable productivity, but it has also created new challenges. The heavy reliance on synthetic chemicals has harmed the environment and reduced soil fertility over time. Farmers are facing declining yields, rising costs of inputs and health concerns. Organic production technology offers a solution by encouraging farming methods that work with nature instead of against it. It reduces dependence on harmful chemicals and promotes long-term sustainability. Organic farming is not just a method but a complete system that maintains soil health, protects the environment, and ensures safe food production.

Concept of Organic Production Technology

Organic production technology refers to farming practices that avoid the use of synthetic fertilizers, pesticides and genetically modified organisms (GMOs). Instead, it uses natural inputs such as compost, farmyard manure, green manure, biofertilizers and biological pest control.

The main principles of organic farming include:

- ✓ Maintaining soil fertility naturally
- ✓ Promoting biodiversity
- ✓ Recycling farm waste
- ✓ Reducing pollution
- ✓ Ensuring ecological balance

This approach helps create a self-sustaining agricultural system.

Reducing Chemical Dependency

Use of Natural Fertilizers: Organic farming replaces chemical fertilizers with natural sources like compost, vermicompost, and animal manure. These materials improve soil structure, increase microbial activity, and slowly release nutrients.

Biological Pest Control: Instead of chemical pest-

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icides, organic farming uses natural predators, neem-based products, and biopesticides to control pests. This reduces harmful residues in food and protects beneficial insects.

Crop Rotation and Diversification: Growing different crops in rotation helps break pest cycles and improves soil fertility. For example, legumes fix nitrogen in the soil, reducing the need for chemical fertilizers.

Use of Biofertilizers: Biofertilizers like Rhizobium, Azotobacter, and phosphate-solubilizing bacteria naturally enhance nutrient availability, reducing the need for synthetic inputs.

Promoting Sustainable Farming

Improving Soil Health: Organic practices increase organic matter in the soil, making it more fertile and capable of holding water. Healthy soil leads to better crop growth and long-term productivity.

Conserving Water: Organic soils retain more moisture, reducing irrigation needs. Mulching techniques also help conserve water.

Protecting Biodiversity: Organic farming supports a wide range of plants, insects, birds, and micro-organisms. This biodiversity helps maintain ecological balance.

Reducing Environmental Pollution: By avoiding harmful chemicals, organic farming prevents contamination of soil, water, and air. It also reduces greenhouse gas emissions.

Ensuring Food Safety: Organic produce is free from harmful chemical residues, making it safer for consumers and improving public health.

Economic and Social Benefits

Organic farming is not only environmentally friendly but also economically beneficial:

- ✓ Reduces cost of chemical inputs
- ✓ Provides premium prices for organic products
- ✓ Creates employment opportunities
- ✓ Improves farmers' health by reducing exposure to toxic chemicals

However, it may require initial investment and training for farmers.

Challenges of Organic Farming

Despite its benefits, organic farming faces some challenges:

- ✓ Lower yields during the transition period
- ✓ Lack of awareness among farmers
- ✓ Certification and marketing difficulties
- ✓ Limited availability of organic inputs

These challenges can be overcome through proper education, government support, and improved infrastructure.

Future Scope

The future of agriculture depends on sustainability. Organic production technology has great potential to:

- ✓ Restore soil fertility
- ✓ Reduce environmental damage
- ✓ Ensure long-term food security

With increasing awareness among consumers and support from policymakers, organic farming is likely to expand rapidly.

Conclusion

Organic production technology plays a cruc-

ial role in reducing chemical dependency and promoting sustainable farming. It provides a balanced approach that protects the environment, improves soil health, and ensures safe food production. Although there are challenges, the long-term benefits make organic farming a promising solution for the future of agriculture. Adopting organic practices is not just an option but a necessity for achieving sustainable development.

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Organic Production Technology and Its Role in Improving Nutritional Quality and Food Safety

Arti, Shivani Rai and Abhishek Kumar

Abstract

Organic production technology is a sustainable agricultural system that emphasizes the use of natural inputs, ecological balance, and biodiversity conservation. It avoids synthetic fertilizers, pesticides, and genetically modified organisms (GMOs), thereby ensuring safer and healthier food production. With increasing concerns over food safety, environmental degradation, and declining nutritional quality, organic farming has emerged as a viable alternative to conventional agriculture. This article explores the principles, practices, and benefits of organic production technology, particularly its role in enhancing nutritional quality and ensuring food safety. It also highlights challenges and future prospects of organic farming in achieving sustainable agriculture and human well-being.

Introduction

Agriculture plays a vital role in ensuring food security for the growing global population. However, modern agricultural practices heavily depend on chemical inputs such as fertilizers, pesticides, and herbicides, which have raised serious concerns regarding food safety, soil health, and environmental sustainability. Continuous use of these chemicals leads to soil degradation, water pollution, and accumulation of harmful residues in food products.In this context, organic production technology has gained importance as an eco-friendly and sustainable approach. It focuses on maintaining soil fertility, conserving natural resources, and producing high-quality, safe, and nutritious food. Organic farming is not just a method of cultivation but a holistic system that integrates environmental, economic, and social sustainability.

Concept and Definition of Organic Production Technology

Organic production technology refers to a system of farming that relies on natural processes and inputs to maintain soil fertility and crop productivity. It avoids the use of synthetic chemicals and instead promotes biological cycles and ecological balance.

Key Features

- ✓ Use of organic manures (FYM, compost, vermicompost)
- ✓ Application of biofertilizers (Rhizobium, Azoto-bacter, PSB)

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- ✓ Use of biopesticides (Neem oil, *Trichoderma, Bacillus spp*.)
- ✓ Crop rotation and intercropping
- ✓ Green manuring and cover cropping
- ✓ Integrated pest and nutrient management

Principles of Organic Farming

Organic farming is based on four major principles:

Principle of Health: Maintain the health of soil, plants, animals, and humans.

Principle of Ecology: Work in harmony with natural ecosystems.

Principle of Fairness: Ensure fairness in production and consumption systems.

Principle of Care: Protect present and future generations and the environment.

Components of Organic Production Technology

Soil Fertility Management

- ✓ Use of compost, FYM and green manure
- ✓ Recycling of farm waste
- ✓ Enhancing soil microbial activity.

Crop Management

- ✓ Crop rotation to break pest cycles
- ✓ Intercropping for better resource utilization
- ✓ Selection of resistant varieties

Pest and Disease Management

- ✓ Biological control agents
- ✓ Botanical pesticides (Neem-based products)
- ✓ Mechanical methods (traps, hand picking)

Weed Management

- ✓ Mulching
- ✓ Manual weeding
- ✓ Crop rotation

Role in Improving Nutritional Quality

Enhanced Nutrient Content: Organic crops generally contain higher levels of vitamins (Vitamin C), minerals (iron, magnesium), and essential nutrients due to improved soil health.

Higher Antioxidant Levels: Organic fruits and vegetables are rich in antioxidants such as flavonoids and phenolic compounds, which help reduce oxidative stress and prevent diseases.

Improved Protein and Dry Matter Content: Studies indicate that organic grains and pulses often have better protein quality and higher dry matter content.

Better Taste and Shelf Life: Organic produce is known for superior taste, texture, and longer shelf life due to natural growth conditions.

Balanced Nutrient Uptake: Healthy soil micro-organisms improve nutrient availability and absorption by plants.

Role in Ensuring Food Safety

Absence of Chemical Residues: Organic farming eliminates synthetic pesticides and fertilizers, reducing harmful residues in food.

Reduced Risk of Toxicity: Lower exposure to toxic chemicals decreases the risk of chronic diseases such as cancer and neurological disorders.

Safe Animal Products: Organic livestock farming avoids antibiotics and growth hormones, ensuring safer milk, meat, and eggs.

Improved Environmental Health: Reduced pollution leads to safer soil, water, and overall food systems.

Environmental Benefits of Organic Production Technology

Soil Health Improvement

- ✓ Enhances soil structure and fertility
- ✓ Increases organic matter content
- ✓ Promotes beneficial microorganisms

Water Conservation and Protection

- ✓ Reduces water pollution from chemical runoff
- ✓ Improves water retention capacity of soil

Biodiversity Conservation

- ✓ Encourages diversity of plants, insects, and microorganisms
- ✓ Supports pollinators like bees

Reduction in Pollution

- ✓ Minimizes air, soil, and water pollution
- ✓ Reduces greenhouse gas emissions

Climate Change Mitigation

- ✓ Enhances carbon sequestration in soil
- ✓ Promotes sustainable farming practices

Challenges in Organic Production

Lower Initial Yield: Organic farming may produce lower yields in the initial years

High Labor Requirement: Requires more manual work for weed and pest management

Certification Issues: Organic certification process is complex and costly

Limited Availability of Inputs: Organic inputs like biofertilizers may not be easily available

Market and Awareness Constraints: Lack of awareness among farmers and consumers. Limited market access and price fluctuations.

Future Scope and Opportunities

Increasing Demand for Organic Food: Rising health awareness is increasing demand for organic products

Government Support: Policies and schemes promoting organic farming

Employment Opportunities: Organic farming creates jobs in production, processing, and marketing

Export Potential: High demand for organic products in international markets

Technological Advancements: Integration of modern tools like IoT, AI, and precision farming

Sustainable Development Goals (SDGs): Organic farming contributes to global sustainability goals

Conclusion

Organic production technology plays a crucial role in improving nutritional quality and ensuring food safety. By promoting natural inputs and sustainable farming practices, it provides a healthier and environmentally friendly alternative to conventional agriculture. Although challenges exist, the long-term benefits of organic farming for human health, environmental sustainability, and economic growth make it an essential component of future agriculture. Additionally, organic farming systems contribute to rural development by creating skilled employment opportunities, supporting local markets, and preserving traditional agricultural knowledge while adapting it to contemporary environmental challenges and consumer preferences.

Sustainable Nutrient and Pest Management through Organic Production Technology in Agriculture

Suruchi Kumari and Shani Gulaiya

Abstract

Organic production technology has emerged as a scientifically validated, ecologically sustainable alternative to conventional chemical-intensive agriculture. Excessive reliance on synthetic fertilizers and pesticides has caused widespread soil degradation, loss of biodiversity, groundwater contamination, and increased climate vulnerability. This article explores the core principle of organic farming "feeding the soil, not just the plant" and presents a detailed analysis of sustainable nutrient management and eco-friendly pest management strategies. It examines key practices such as composting, vermicompost, biofertilizers, green manuring, crop rotation, biological control agents, and botanical pesticides that enhance soil microbial activity, improve nutrient cycling, and strengthen natural plant defense. Real-world success stories from Sikkim (India's first fully organic state), Zero Budget Natural Farming (ZBNF) in Andhra Pradesh and Maharashtra, and organic basmati clusters in Punjab demonstrate improved soil health, 10-20% higher yields, 80-90% cost reduction, premium market prices, and enhanced farmer incomes. Despite challenges like initial yield dips and input availability, government programmes such as PKVY and the National Mission on Natural Farming are accelerating adoption. Organic production technology offers a climate-resilient, profitable, and environmentally sound pathway for the future of Indian agriculture.

Introduction

Organic production technology has emerged as a scientifically validated and sustainable alternative to conventional chemical-intensive agriculture in India and across the globe. Conventional farming systems, which depend heavily on synthetic fertilizers and broad-spectrum pesticides, have led to widespread soil degradation, depletion of soil organic carbon, groundwater contamination, loss of biodiversity and increased vulnerability to climate change. In contrast, organic production technology is grounded in ecological principles that restore and maintain natural balance, enhance soil biological activity, and promote long-term agricultural productivity without compromising environmental integrity or human health. Sustainable agriculture has become a global imperative, seeking to balance food production with environmental conservation and socio-economic well-being (Choudhary *et al.*, 2023). The core philosophy of organic farming is encapsulated in the principle of "feeding the soil, not just the plant." This approach prioritizes the development of healthy, biologically active soil systems that support nutrient cycling and plant resilience over multiple cropping

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seasons. India has established itself as a global leader in organic agriculture, with more than 2.3 million certified organic farmers cultivating approximately 2.5 million hectares of land. The growing domestic and international demand for chemical-residue-free food products has further enhanced the economic viability of organic systems. Projections indicate that the Indian organic food market is expected to expand significantly in the coming decade, driven by consumer awareness and policy support. This article examines the scientific foundations of organic production technology and provides a detailed analysis of sustainable nutrient management and eco-friendly pest management strategies. It also highlights successful field-level applications and discusses key challenges along with potential pathways for wider adoption.

Table 1: Conventional vs Organic Production Technology: A Quick Comparison

Aspect	Conventional Farming	Organic Production Technology
Soil Health	Declining organic carbon, compaction	Increased microbial activity, higher soil organic carbon
Nutrient Source	Synthetic fertilizers (quick release)	Compost, biofertilizers (slow, balanced)
Pest Control	Broad spectrum chemical pesticides	Cultural, biological & botanical methods
Environmental Impact	High (pollution, biodiversity loss)	Low (enhances biodiversity & ecosystem health)
Long-term Yield	Initially high, then declines	Stable & often improving over time
Farmer Economics	High input costs, debt risk	Lower input costs, premium market prices

Science behind Organic Production Technology

Soil in organic systems is recognized as a dynamic living ecosystem rather than a mere inert growing medium. It facilitates billions of micro-organisms, including bacteria, fungi, actinomycetes, and earthworms, which collectively perform critical functions such as nutrient mineralization, organic matter decomposition, nitrogen fixation, phosphorus solubilization, and humus formation. These biological processes maintain soil structure, improve aggregation, and enhance the soil's capacity to retain water and essential nutrients. In conventional agriculture, repeated application of synthetic fertilizers and pesticides often suppresses beneficial microbial populations, reduces soil organic matter content and leads to compaction and nutrient imbalances. Organic production technology addresses these issues by stimulating microbial diversity and activity through the incorporation of organic amendments. As a result, soil organic carbon levels can increase substantially over time, typically by 20-50 per cent within three to five years of consistent organic management. This improvement translates into better water infiltration, reduced erosion, enhanced drought tolerance, and greater overall ecosystem resilience. Crops grown in biologically active organic soils demonstrate improved root architecture, higher nutrient-use efficiency, and elevated levels of secondary metabolites such as phenolics and antioxidants. These attributes not only contribute to better yield stability but also enhance the nutritional quality and shelf life of the produce.

Sustainable Nutrient Management: Feeding the Soil, Not Just the Plant

Sustainable nutrient management forms the

foundation of organic production systems. It replaces reliance on readily soluble chemical fertilizers with a range of natural and biological inputs that release nutrients gradually while continuously improving soil fertility. The primary components of sustainable nutrient management include:

Compost and Vermicompost: These are prepared from farmyard manure, crop residues, kitchen waste, and other biodegradable materials. Vermicompost, produced with the help of earthworms, is particularly rich in plant-available nutrients, growth-promoting substances, and beneficial microbes. It enhances soil porosity and microbial biomass.

Biofertilizers: Microbial inoculants such as *Rhizobium* (for legumes), *Azotobacter* and *Azospirillum* (for cereals and millets), and phosphate-solubilizing bacteria play a vital role in biological nitrogen fixation and mobilization of otherwise unavailable soil nutrients. These organisms colonize the rhizosphere and improve nutrient uptake efficiency. It's cleared from the data highest microbial cells counts like Rhizobium (15.66 x 106 cfu g^{-1} soil), PSB (18.96 x 106 cfu g^{-1} soil) was recorded under the application of enriched Vermicompost @ 2 t ha^{-1} followed by FYM @ 5 t ha^{-1} along with Rhizobium and PSB (14.83 x 106 cfu g^{-1} soil) and (17.05 x 10^6 cfu g^{-1} soil), Rhizobium and PSB respectively and same trends was observed for actinomycetes. Whereas, highest fungi population was observed under FYM @ 5 t ha^{-1} with combined application of bio-inoculants with respect to 39.83 x 10^4 cfu g^{-1} soil followed by control treatments 34.92 x 10^4 cfu g^{-1} soil and lowest fungi population was recorded under enriched vermicompost@ 2 t ha^{-1} along with combined application of bio-fertilizers (28.32 x 10^4 cfu g^{-1} soil) (Gulaiya *et al.*, 2023).

Green Manuring and Cover Cropping: Fast-growing leguminous crops such as dhaincha (*Sesbania aculeata*), sunhemp (*Crotalaria juncea*), and cowpea are grown during the off-season and incorporated into the soil. This practice adds substantial quantities of organic matter and fixed nitrogen while suppressing weeds and preventing nutrient leaching.

Crop Rotation and Intercropping: Systematic rotation of leguminous and non-leguminous crops prevents nutrient mining and breaks pest and disease cycles. Intercropping further optimizes land use and maintains soil cover.

Additional inputs such as biochar (produced from pyrolyzed crop residues), panchagavya, and jeevamrutha (fermented microbial consortia used in Zero Budget Natural Farming) significantly stimulate soil microbial populations.

Collectively, these practices increase the soil's water-holding capacity, reduce runoff and erosion,

minimize environmental pollution from nutrient leaching, and stabilize crop yields under varying climatic conditions. Long-term field studies indicate that organic nutrient management not only sustains productivity but often leads to progressive improvement in soil health indices.

Eco-Friendly Pest Management: Nature's Own Defense System

Eco-friendly pest management in organic agriculture employs an integrated approach that maintains pest populations below economic thres-hold levels without the use of synthetic pesticides. The strategy focuses on prevention, biological regulation, and the use of naturally derived products while preserving beneficial insects and soil microorganisms. Key strategies include:

Cultural Practices: These encompass crop rotation, intercropping with trap crops such as marigold to divert nematodes and sucking pests, timely sowing to escape peak pest periods, mulching to conserve soil moisture and suppress weeds, and regular field sanitation to eliminate pest habitats.

Biological Control: Encouragement of natural enemies such as predatory insects (ladybirds, lacewings, spiders) and parasitoids, along with the application of microbial agents like *Trichoderma spp.* (for soil-borne fungal pathogens) and *Bacillus thuringiensis* (*Bt*) for caterpillar pests. These agents are highly specific and do not harm non-target organisms.

Botanical Pesticides: Plant-derived formulations based on neem (*Azadirachta indica*), garlic, chilli, and other locally available botanicals serve as effective repellents, antifeedants, and insect growth regulators. These products are biodegradable, leave no harmful residues, and are compatible with organic certification standards.

This integrated pest management (IPM) framework reduces the likelihood of pest resistance development, protects pollinators and other beneficial biodiversity, and ensures the production of safe, residue-free food. Furthermore, plants grown under balanced organic nutrition exhibit stronger physiological resistance due to higher levels of defensive compounds, thereby reducing the overall need for external interventions.

From Lab to Field: Real Success Stories

The transition of organic technologies from controlled laboratory conditions to large-scale field adoption has yielded encouraging results across diverse agro-climatic regions of India. Sikkim was declared the world's first fully organic state in 2016 after a systematic conversion process supported by state policy. Farmers in Sikkim have reported consistent premium market prices for high-value crops such as ginger, large cardamom and veget-ables. Soil health parameters have shown marked

improvement, with increased organic carbon and microbial activity contributing to sustained productivity.

In Andhra Pradesh and Maharashtra, Zero Budget Natural Farming (ZBNF) has been adopted by several lakh small and marginal farmers. The system relies on locally prepared inputs such as jeevamrutha, beejamrutha, and mulching. Field evaluations have documented yield increases of 10-20 per cent in paddy and groundnut, coupled with input cost reductions of 80-90 per cent. Farmers have also experienced improved income stability and reduced indebtedness. Punjab's organic basmati rice clusters and similar initiatives in other states have successfully tapped into premium export markets. India's organic exports reached approximately USD 666 million in recent years, reflecting strong international demand for organic spices, millets, and cereals. These case studies demonstrate that organic production technology can deliver both environmental restoration and tangible economic benefits for resource-poor farmers.

Challenges and the Road Ahead

Despite its proven advantages, organic production technology encounters several practical constraints. These include temporary yield reductions during the three-year transition period, limited availability and higher initial cost of quality organic inputs, complex and expensive certification procedures, and knowledge and skill gaps among small and marginal farmers. Addressing these challenges requires a multi-pronged strategy. Government programmes such as the Paramparagat Krishi Vikas Yojana (PKVY) and the National Mission on Natural Farming are providing subsidized inputs, technical training, and financial support. The formation of Farmer Producer Organizations (FPOs) has improved collective bargaining power, input procurement, and market linkages. Digital tools, including soil health cards, mobile advisory services, and traceability platforms, are bridging information gaps. Integration of traditional indigenous knowledge with contemporary scientific advancements, along with continued research on region-specific organic packages, will be critical for scaling up adoption.

Conclusion

Organic production technology represents a scientifically robust, environmentally sustainable, and economically promising model for the future of Indian agriculture. By prioritizing soil biological health, ecological pest regulation, and resource conservation, it addresses the twin challenges of food security and environmental degradation. As climate variability intensifies and consumer preference for safe, nutritious food grows, the systematic adoption of organic production practices is essential. With continued policy support, research investment, and farmer capacity building, organic agriculture can play a pivotal role in achieving climate-resilient, profitable, and socially equitable farming systems in India.

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Digital Twins and Modelling: Virtual Simulation of Crop Growth and Management

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

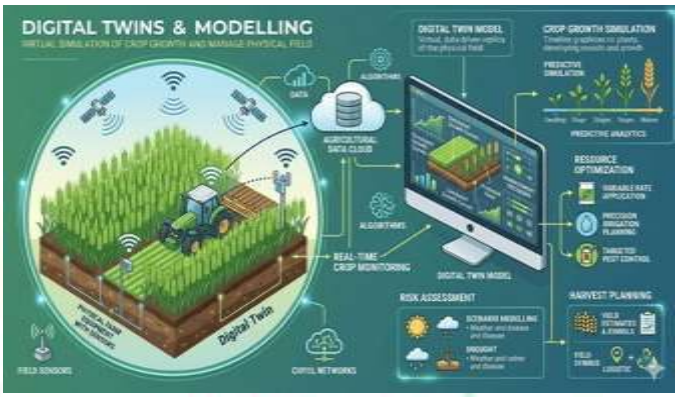
Agriculture is rapidly moving into the digital age. Farmers today are using modern tools such as sensors, drones, and artificial intelligence to monitor and manage crops more effectively. Among these new technologies, Digital Twins are emerging as one of the most revolutionary concepts in smart farming. A Digital Twin is a virtual copy or digital replica of a real-world system. In agriculture, it means creating a computer-based model of a real crop field that behaves and grows just like the real plants in it. With this technology, farmers and scientists can simulate how crops will grow under different weather, soil, and management conditions without actually performing the experiments in the field. This helps in saving time, resources and making better management decisions.

What is a Digital Twin in Agriculture?

A Digital Twin in farming is a virtual version of a real farm, built using data collected from sensors, weather stations, drones, and satellites. It continuously receives real-time data such as:

- ✓ Soil moisture and temperature
- ✓ Weather conditions (rain, sunlight, wind)
- ✓ Crop growth stages
- ✓ Nutrient levels and irrigation data

Using these inputs, the digital model updates itself and shows how the real crop is growing. It can even predict how the crop will respond to future changes like fertilizer application, irrigation, or pest attacks.



In simple terms, a Digital Twin acts like a "virtual mirror" of the farm, helping farmers see the invisible and plan better.

How Does a Digital Twin Work?

A digital twin operates through three major steps:

Data Collection: Sensors in the field measure soil moisture, temperature, pH, light intensity, and plant health indicators. Satellites and drones capture images of crop canopy, leaf color and growth

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patterns.

Data Integration and Modelling: The collected data are fed into computer models that simulate biological processes such as photosynthesis, nutrient uptake and water movement in the soil. Machine learning and AI are used to analyze this information and predict outcomes.

Virtual Simulation and Decision Support: The digital twin allows farmers to run simulations for example:

- ✓ What happens if we irrigate today or wait for rain?
- ✓ How will yield change if we apply more fertilizer?
- ✓ What will be the impact of a week of drought?

The system then suggests the best management practice to achieve higher productivity with fewer resources.

Benefits of Digital Twins in Crop Management

Digital twins offer several practical benefits to farmers, agronomists, and researchers:

Precision and Predictability: They help farmers predict how crops will perform under different scenarios. For example, if rainfall is delayed, the digital twin can estimate how much yield loss might occur and how to reduce it.

Smart Decision-Making: Farmers can make data-driven decisions about irrigation, fertilizer, and pest control. This minimizes waste and saves money.

Early Problem Detection: Digital twins can detect crop stress or disease risk before visible symptoms appear, allowing early intervention.

Cost and Time Saving: Field trials and experiments that take months in real life can be simulated virtually in a few hours.

Climate Adaptation: By simulating future climate conditions, digital twins help design strategies for drought-resistant or heat-tolerant cropping systems.

Sustainable Agriculture: The technology promotes eco-friendly farming by optimizing inputs like water, fertilizers, and pesticides leading to lower environmental impact.

Applications of Digital Twins in Agriculture

Crop Growth Modelling: Digital twins use scientific models to simulate how plants grow under different soil and weather conditions. For example, they can show how rice or wheat responds to changes in irrigation or fertilizer levels.

Irrigation Management: By predicting soil moisture and evapotranspiration, digital twins suggest the right time and quantity for irrigation, preventing both water shortage and overwatering.

Fertilizer Optimization: They track nutrient uptake and guide farmers to apply fertilizers only when needed improving nutrient use efficiency.

Pest and Disease Forecasting: Digital twins can combine weather data and crop growth patterns to predict pest outbreaks, helping in timely control measures.

Farm Planning: Farmers can plan the entire cropping cycle from sowing to harvest virtually, adjusting for weather and market trends before implementing on the ground.

Tools and Technologies behind Digital Twins

Several technologies work together to make digital twins possible:

Internet of Things (IoT): Connects sensors and devices to collect real-time data.

Artificial Intelligence (AI) & Machine Learning (ML): Analyze large amounts of data and make predictions.

Big Data Analytics: Processes and interprets vast datasets from multiple sources.

Geographic Information Systems (GIS): Helps visualize spatial data like soil maps and crop zones.

Cloud Computing: Stores and processes data remotely for easy access.

3D and 4D Modelling: Create dynamic visual representations of fields and plant growth over time. Together, these technologies form the backbone of smart digital agriculture.

Real-Life Examples

Several research institutions and agri-tech companies around the world are testing digital twin technology:

Wheat and Rice Simulation Models: Used to study the effect of heat stress and irrigation timing on yield.

Smart Greenhouses: Digital twins monitor temperature, light, and humidity to adjust conditions automatically.

Digital Vineyards: Used in grape farming to optimize irrigation and predict harvest quality.

Crop Stress Detection: AI-powered twins that simulate pest attacks or nutrient deficiency and recommend solutions.

Though still emerging, these examples show the wide potential of digital twins in transforming crop management.

Challenges and Limitations

While digital twins are promising, a few challenges remain:

- ✓ High cost of sensors and data systems.
- ✓ Need for skilled technicians and data analysts.
- ✓ Limited internet connectivity in rural areas.
- ✓ Integration of multiple data sources can be complex.
- ✓ Farmers' lack of awareness about digital technologies.

Efforts are being made to develop low-cost, farmer-friendly digital twin platforms for developing countries.

The Future of Digital Twins in Farming

The future of farming will be virtual and data-driven. As technology becomes more affordable, even smallholder farmers will be able to use digital twins through smartphones. In the near future, we may see:

- ✓ Cloud-based Digital Twin platforms accessible to all farmers.
- ✓ AI assistants that recommend actions based on real-time data.
- ✓ Integration with drones and robotics for automatic irrigation and spraying.
- ✓ Predictive models that guide long-term farm planning.

Digital twins will help farmers anticipate problems before they occur moving from reactive to proactive farming.

Conclusion

Digital twins and crop modelling represent a major step towards intelligent, sustainable, and resilient agriculture. By creating a virtual version of the farm, this technology allows farmers to experiment safely, manage resources wisely, and optimize yields with less risk. In essence, digital twins make the “invisible processes of plant growth visible”, helping farmers understand their crops better and act faster. As agriculture faces the twin challenges of climate change and food security, digital twins will serve as powerful allies in building a smarter and more sustainable food system.

Influence of Lifestyle Changes on Household Food Consumption in Rural and Urban Areas

Swati and Kavita Dua

Introduction

Lifestyle transformations in recent decades have significantly altered food consumption patterns across rural and urban households. Rapid urbanization, technological advancements, increased workforce participation, and shifting social norms have reshaped how families select, prepare, and consume food. While rural communities traditionally relied on locally sourced and home-cooked meals, exposure to modern influences has gradually modified these practices. Urban households, on the other hand, are experiencing a pronounced shift toward convenience-oriented diets due to time constraints and changing work dynamics. Examining the relationship between lifestyle changes and food consumption offers valuable insight into evolving dietary behaviors and their broader implications.

Lifestyle Transformation and Food Practices: Modern lifestyles are characterized by faster routines, increased mobility, and greater reliance on market-driven systems. In urban areas, long working hours and commuting reduce the time available for meal preparation, leading to increased dependence on ready-to-eat and restaurant foods. The rise of nuclear families has further reduced shared cooking responsibilities, encouraging simplified meal patterns. In rural settings, lifestyle changes are influenced by improved connectivity, access to packaged goods, and diversification of occupations beyond agriculture. Although traditional cooking methods remain prevalent, the incorporation of processed foods is gradually becoming noticeable. The integration of modern elements into daily life has introduced new dietary options that coexist with established food habits.

Time Use and Its Impact on Dietary Choices: Time availability is a crucial determinant of food consumption behavior. Urban households often prioritize convenience due to demanding schedules, resulting in frequent consumption of fast food or semi-prepared items. The reduction in time allocated for cooking has contributed to a decline in elaborate meal preparation. Rural households generally allocate more time to food preparation, allowing for the continuation of traditional cooking practices. However, seasonal workloads and participation in non-farm employment can influence time distribution, occasionally leading to reliance on quicker meal solutions. The balance between time constraints and food preparation remains a defining factor across

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both settings.

Changing Family Structures and Eating Patterns: Family composition plays a significant role in shaping dietary habits. Joint families, more common in rural areas, often maintain collective cooking traditions and regular meal schedules. These arrangements support the consumption of freshly prepared food and reinforce cultural food practices. Urban households are increasingly nuclear, which affects both food preparation and consumption patterns. Individual preferences, irregular schedules, and limited household support contribute to fragmented eating habits. Meals are often consumed separately and the emphasis shifts toward convenience rather than tradition.

Role of Income and Consumer Preferences: Rising income levels and changing aspirations influence food choices by expanding access to diverse food options. Urban consumers, with greater purchasing power, tend to experiment with different cuisines and dining formats. Exposure to global food culture through media and digital platforms further shapes preferences. In rural areas, income growth has improved food accessibility and dietary diversity. Consumers are gradually incorporating new food items into their diets, although affordability remains an important consideration. Preferences are evolving, yet they continue to reflect a balance between tradition and modernity.

Media Exposure and Food Awareness: The expansion of media and digital communication has accelerated the spread of information related to food, nutrition, and lifestyle trends. Advertising campaigns and social media platforms strongly influence consumer perceptions, particularly among younger individuals. Urban populations are more actively engaged with digital content, leading to increased awareness of food choices and emerging dietary trends. Rural communities are also becoming more connected, resulting in greater exposure to processed and branded food products. This growing interaction with media is reshaping consumption behavior in both regions.

Implications for Health and Agriculture: Lifestyle-driven changes in food consumption have implications for both public health and agricultural systems. Increased reliance on processed and convenience foods may affect nutritional quality and long-term well-being. At the same time, shifting demand patterns influence agricultural production, supply chains, and market dynamics. Encouraging balanced diets that incorporate traditional foods alongside modern preferences can support nutritional security while sustaining local agricultural practices. Strengthening awareness about healthy eating is essential for addressing the challenges associated with evolving lifestyles.

Conclusion

Lifestyle changes have emerged as a key factor influencing food consumption patterns in rural and urban households. Urban areas demonstrate a stronger inclination toward convenience-based diets due to time limitations and changing work environments, whereas rural households continue to retain

elements of traditional food practices despite gradual adaptation. Variations in time use, family structure, income, and media exposure collectively shape dietary decisions. Understanding these dynamics is crucial for promoting healthier food choices and ensuring sustainable food systems in a rapidly changing socio-economic landscape.

Role of Railways in Agriculture Improvement

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

Agriculture is the foundation of India's economy, while the railway network is the lifeline that connects the nation's heartland. Together, these two sectors play a vital role in ensuring food security, rural development, and economic growth. The Indian Railways, with its vast and efficient transport network, acts as a bridge between farms and markets carrying crops, fertilizers, seeds, and agricultural machinery across the length and breadth of the country. In recent years, several government initiatives have aimed to integrate railway infrastructure with agricultural development. From modern freight corridors to farmer-friendly schemes like Kisan Rail, the railways have become a key driver of agricultural improvement and rural prosperity.

Railways as the Backbone of Agricultural Transport

India's agricultural output is diverse from grains and fruits to vegetables, milk, and fish. Transporting such large quantities efficiently and safely to markets is a huge challenge. Railways offer a fast, cost-effective, and reliable mode of transportation, especially over long distances.

Key advantages include:

- ✓ Reduced transport cost compared to roadways.
- ✓ Less spoilage of perishable produce due to faster delivery.
- ✓ Bulk movement of commodities such as grains, fertilizers, and sugarcane.
- ✓ Connectivity between rural production zones and urban consumption centers.

Railways thus ensure that farmers get timely access to markets, while consumers receive agricultural produce at stable prices.

Kisan Rail - A Game Changer for Farmers

Launched in 2020, the Kisan Rail scheme is one of the most revolutionary steps by Indian Railways to support the agriculture sector. These are special freight trains designed to transport perishable goods like fruits, vegetables, fish, dairy products, and flowers.

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Key benefits of Kisan Rail include

- ✓ Affordable freight charges with government subsidies.
- ✓ Refrigerated coaches to prevent spoilage and maintain freshness.
- ✓ Regular and timely services ensuring farmers can reach distant markets.
- ✓ Encouragement of interstate trade, helping farmers earns better income.

For example, banana growers in Tamil Nadu, mango farmers in Andhra Pradesh, and vegetable cultivators in Maharashtra have all benefited by sending their produce directly to northern and eastern markets through Kisan Rails. This initiative has not only reduced wastage but also improved farmers' profits by giving them access to wider markets.

Transportation of Agricultural Inputs

Railways not only move farm produce but also play a crucial role in transporting agricultural inputs such as:

- ✓ Fertilizers
- ✓ Pesticides
- ✓ Seeds
- ✓ Agricultural machinery and equipment

By ensuring timely and cost-efficient delivery of these essentials, railways directly support agricultural productivity. During peak seasons like sowing and harvesting, the availability of inputs through rail transport ensures that farming operations are not delayed.

Cold Chain and Warehousing Facilities

The Indian Railways has been expanding its infrastructure for cold storage and warehousing to minimize post-harvest losses. Refrigerated wagons and temperature-controlled storage points have been introduced at major stations.

Some key initiatives include:

- ✓ Dedicated Freight Corridors (DFC) for rapid movement of agricultural goods.
- ✓ Cold storage units at major railway junctions.
- ✓ Integrated logistics parks that combine storage, processing, and transport facilities.

These facilities help maintain the quality of perishable items like milk, fish, meat, fruits, and vegetables, thus improving food availability and farmer incomes.

Boost to Rural Economy and Employment

The expansion of railway connectivity in rural areas has created new employment opportunities and encouraged local entrepreneurship. Small traders, aggregators and farmer producer organizations (FPOs) use railway transport for collective marketing of produce. Moreover, new rural railway stations have become centers of trade and logistics, attracting markets, warehouses, and agri-businesses. This integration of agriculture with railway infrastructure is transforming the rural economy by:

- ✓ Enhancing market access for small farmers.
- ✓ Reducing dependence on middlemen.
- ✓ Promoting inclusive growth in rural communities.

Railways Supporting Government Schemes

The Indian Railways supports several government programs that aim to strengthen agriculture,

such as:

- ✓ PM Kisan Sampada Yojana - for food processing and storage infrastructure.
- ✓ Atmanirbhar Bharat – encouraging self-reliant agriculture and logistics.
- ✓ National Agriculture Market (e-NAM) providing digital market connectivity through improved rail transport.

By integrating with these schemes, railways act as a multiplier that enhances the overall efficiency of agricultural supply chains.

Environmental Benefits of Railway Transport

Compared to road transport, railways are far more environment-friendly. They consume less fuel and emit fewer greenhouse gases per ton of goods transported. This contributes to India's climate goals by promoting sustainable logistics for agriculture. Electric and hybrid freight trains further reduce pollution, helping create a greener and cleaner ecosystem for both agriculture and transportation sectors.

Challenges and Future Prospects

Despite its many advantages, there are challenges that need attention:

- ✓ Limited last-mile connectivity from farms to railway stations.
- ✓ Need for more refrigerated coaches and improved scheduling.
- ✓ Awareness among farmers about the benefits of rail transport.
- ✓ Development of multimodal hubs integrating road, rail, and water transport.

Future strategies should focus on digitization, smart cargo management, and expanding the Kisan Rail network to every major agricultural zone in India. The role of railways in agricultural improvement is both fundamental and transformative. By providing cost-effective, safe, and sustainable transportation, Indian Railways ensures that farmers can access markets, consumers can access food, and the economy can move forward efficiently. With continued investment in infrastructure, cold storage, and digital logistics, railways can become the true "engine of agricultural growth" connecting India's farms to its future.

Revitalizing the Foundation: Organic Production Technologies for Enhancing Soil Structure, Fertility and Biological Activity in North Bihar

Gaurav Sah

Abstract

The alluvial plains of North Bihar, once renowned for their natural fertility, are now facing a crisis of declining soil organic carbon, deteriorating physical structure, and suppressed biological activity. This paper presents on-farm and observational data from five key districts of the region Samastipur, Muzaffarpur, Madhubani, Sitamarhi and Vaishali to examine the effectiveness of low-cost organic production technologies. Baseline soil data reveals that organic carbon content ranges from 0.40% to a concerning 0.21% in calcareous tracts, while nitrogen levels often fall below the recommended threshold. This paper evaluates the impact of four interventions: vermicompost, green manuring with dhaincha (*Sesbania aculeata*), biofertilizer application, and the fermented concoction Jeevamrut. Our results show significant improvements: in Samastipur, vermicompost application led to a 75% improvement in nutrient use efficiency in sugarcane over chemical fertilizers alone. Furthermore, adoption studies indicate that over 60% of trained farmers in the region have adopted vermicompost technology at a moderate level. We conclude that organic production technologies, when implemented using a phased approach, are not only viable but essential for restoring the agricultural foundation of North Bihar. The initial "transition dip" of 10-15% in yield can be effectively managed without significant economic loss, with soil biological activity showing significant recovery within two cropping cycles.

Introduction

The agricultural landscape of North Bihar is a complex mosaic of alluvial soils, shaped by the floodplains of the Gandak, Burhi Gandak, Bagmati, and Kosi rivers. With a cropping intensity among the highest in the nation, this region comprising districts like Samastipur, Muzaffarpur, Vaishali, Darbhanga, and Madhubani is a vital contributor to India's food security. However, the high productivity has come at a steep cost. Decades of intensive rice-wheat monocropping and indiscriminate use of chemical fertilizers have pushed the soil to its limit. The "Newer Alluvium" or *Khadar* soil, traditionally known for its replenishing ability after floods, is now showing signs of exhaustion. As a result, soil organic carbon (SOC) levels in the region are often found to be "low to medium," hanging perilously close to the 0.4% threshold, while the pH has turned alkaline in many pockets. For instance, a comprehensive study in Vaishali found that while mean organic carbon was 0.54%, the range could drop as low as 0.21% in calcareous alluvial soils.

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Table 1: Baseline agro-ecological characteristics of the study districts

District	Agro-climatic Zone	Major Crops (*kharif/rabi*)	Initial SOC (%) Range	Key Soil Challenge
Samastipur	Zone I	Rice-Wheat, Sugarcane	0.40-0.84 (Avg. 0.62)	N, P, K levels low to medium
Muzaffarpur	Zone I	Rice-Wheat, Maize, Litchi	0.38-0.65	Low bioavailability of micronutrients
Madhubani	Zone I	Rice-Wheat	0.50-0.70	High rainfall, flood-prone, low NPK application
Sitamarhi	Zone I	Rice-Wheat, Maize, Sugarcane	0.55-0.75	Imbalanced NPK application, potash deficiency
Vaishali	Zone I (Diara)	Vegetables, Maize, Wheat	0.21-1.21 (Mean 0.54)	Calcareous soil, high pH, poor structure

The problem is further compounded by imbalanced fertilizer use. Surveys in Madhubani and Sitamarhi revealed that farmers applied far less than the recommended doses of NPK (e.g., 76:45:28 kg ha^{-1} in Madhubani compared to the recommendation), leading to diminishing returns and a "hidden hunger" of secondary and micronutrients. This has created a vicious cycle: poor soil structure leads to compaction, low biological activity reduces nutrient cycling, and low fertility forces farmers to rely even more heavily on expensive chemical inputs.

This paper is born from direct observations and interactions with farmers across these districts. It does not aim to preach theoretical organic farming but instead provides a practical, on-ground assessment of what works in the specific ecological and socio-economic context of North Bihar. We explore how simple, accessible technologies can heal the "Foundation" of North Bihar's agriculture.

Materials and Methods

Study Locations and Cropping Systems: This study was conducted across five districts of the North Bihar alluvial plains, focusing on their dominant cropping systems (Table 1).

Organic Production Technologies Implemented

Based on the needs identified from the baseline data, the following interventions were implemented across demonstration plots (0.4-1.0 acre each) in each district.

Vermicomposting: Adopted from training progr-ams conducted by Krishi Vigyan Kendras (KVKs), which have been shown to be effective in the region. Standardized cement tanks (8x4x2 ft) with thatched roofs were used. *Eisenia fetida* were fed a mixture of crop residues and cow dung. The final produce was applied at 4-5 t ha^{-1}.

Green Manuring with Dhaincha: In the rice-wheat systems of Samastipur and Muzaffarpur, *Sesbania aculeata* (Dhaincha) was sown during the summer fallow period (April-May) at 30-40 kg ha^{-1}. It was incorporated into the soil at 45 days (at flowering). This practice is documented to produce up to 20 tonnes of biomass per hectare, enriching the soil with nitrogen and organic matter.

Biofertilizers: Focus was on making Rhizobium, Azotobacter and PSB (Phosphate Solubilizing Bacteria) consortia available through KVKs. Seeds were treated with a jaggery-based slurry mixed with the biofertilizer carrier.

Jeevamrut / Amrit Pani: A fermented microbial

culture (fresh cow dung, cow urine, jaggery, pulse flour, and soil) was prepared and applied as a soil drench every 15 days, known to be a practice well-suited to the moist, warm conditions of the Bihar plains.

Data Collection

Data was collected through three primary methods:

Soil Sampling: Standard composite soil samples (0-15 cm) were analyzed for pH, EC, Organic Carbon (Walkley-Black), and available NPK before the intervention and after two years.

Field Observations: Parameters such as bulk density (by core method), water infiltration rate (by double-ring infiltrometer), and earthworm count (by hand sorting) were recorded.

Farmer Surveys & Secondary Data: Results from published studies, including a survey of 150 farmers across Samastipur, Muzaffarpur, and Madhubani, were used to understand the adoption and impact of organic inputs.

Results and Discussion

Addressing Soil Fertility and Structure: The baseline soil health data from North Bihar reveals that a "one-size-fits-all" approach cannot work. In Vaishali, the significant spatial variability of micronutrients necessitates site-specific management. In Sitamarhi and Madhubani, the core issue is replenishing the specific NPK deficits while improving the soil's cation exchange capacity. The strategic combination of organic inputs proved highly effective:

- ✓ In the calcareous soils of Vaishali, the application of PSB biofertilizer, which solubilizes fixed phosphorus, was critical. This aligns DSTL (District soil test laboratory), which found that the combined use of vermicompost, *Azotobacter*, and PSB resulted in a 75% improvement in nutrient use efficiency for sugarcane compared to using only the recommended fertilizer dose.
- ✓ The impact on soil structure was evident in Muzaffarpur's sugarcane and maize fields. The application of Jeevamrut and green manuring reduced crust formation, a common problem in the sandy loam soils, leading to better tillering in wheat and cane formation in sugarcane.
- ✓ For Madhubani, a high-rainfall district, improving water retention was key. The organic carbon build-up from vermicompost turned the sandy loam into a loamy sand with better water-holding capacity, directly benefiting the rain-fed rice crop.

Biological Activity: The "Worm" at Work

Biological activity is the true measure of soil health. The reversal of damage in our study plots was most visible in the return of life underground. The adoption of organic practices, particularly Jeevamrut and vermicompost, directly coincided with a dramatic increase in earthworm populations, a development repeatedly highlighted in research from institutions like BHU, which emphasizes the role of earthworms in restoring soil fertility.

The adoption study conducted across the KVKs of Samastipur, Muzaffarpur, and Madhubani found that over 50% of farmers had a "medium level

of adoption" of the vermicompost technology. More importantly, it was found that a majority of farmers who adopted it saw a "moderate level of impact" on their farm's productivity.

Navigating the Transition: Yield Economics

During the first year, farmers in our study experienced a yield drop of 10-16%, largely consistent with the state averages. This was most pronounced in high-input crops like sugarcane and hybrid maize. However, a key observation was that the economic loss was partially offset by a significant reduction in input costs (Urea, DAP, and pesticides). A phased transition plan was found to be most effective:

- ✓ In Sitamarhi, a farmer who implemented a 70%-organic and 30%-chemical approach in Year 1 stabilized yields and then moved to 100% organic by Year 3. By this time, his cotton yield matched that of his chemically-farmed neighbor, but with a lower cost of cultivation, as his soil structure and water availability had improved.
- ✓ For the widely cultivated 'Sharbati' wheat (durum) variety in the region, the taste and market price of the organically grown produce provided a buffer against any minor yield loss. Farmers in Samastipur reported that buyers were willing to pay a premium of 10-15% for organically grown durum wheat used in high-quality baked goods.

Conclusion

North Bihar has the potential to lead a second agricultural renaissance in India. This paper demonstrates that the foundation for this lies not in new chemicals, but in revitalizing the soil using organic production technologies rooted in local knowledge and enhanced by modern science. The data from Samastipur, Muzaffarpur, Madhubani, Sitamarhi, and Vaishali presents a clear message: the application of vermicompost, green manure, and microbial cultures like Jeevamrut directly addresses the specific fertility and structural deficits of the region's alluvial soils. The initial yield dip is a surmountable hurdle. The state government's allocation of over ₹23 crore under the PKVY scheme for organic farming in 12 Ganga-belt districts, including Samastipur and Vaishali, provides a critical policy push, offering farmers financial and certification support.

The path forward is a path back to the soil, rebuilt by the hands of its own custodians.

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Eco-friendly Crop Production through Organic Technology: A Pathway to Sustainable Agriculture and Food Security

Abhishek Kumar

Abstract

In the last few decades, agriculture has rapidly changed to meet the food needs of an increasing population. Traditional farming methods have improved productivity but have also led to environmental degradation, loss of soil fertility, water pollution and health hazards due to excessive use of chemical fertilizers and pesticides. The development of environmentally friendly crop production using organic technology has appeared as a viable alternative for sustainable productivity and environmental conservation. Natural inputs, ecological balance and biodiversity conservation are characteristic of organic farming. It avoids synthetic chemicals and promotes soil health biologically. This article describes the concept, principles, technologies, benefits and challenges of organic farming and the importance of organic farming in achieving sustainable agriculture and long term food security.

Introduction

Agriculture is a vital sector in Indian economy and supports the livelihood of large population. However, despite its success in increasing food production, the Green Revolution has had its share of serious ecological problems such as soil degradation, groundwater depletion and pollution. The natural balance of agro-ecosystems has been disturbed by continuous use of chemical inputs. In this context, the environment friendly crop production has come up as a sustainable solution. Organic farming is a form of agriculture that emphasizes environmentally-friendly practices such as soil health, reduced environmental impact, and production of safe and nutritious food. Organic farming is emerging as an important tool for sustainable development with increasing consumer and policy maker awareness.

Concept of Eco-friendly Crop Production

Eco-friendly crop production refers to agricultural practices that are environmentally safe, economically viable and socially acceptable. It is designed to minimize the negative impact of agriculture on natural resources and to ensure long-term productivity. That means:

- ✓ Optimum utilization of natural resources
- ✓ Soil and water conservation
- ✓ Reduction of chemical input

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- ✓ Supporting biodiversity

Organic farming is a holistic system that integrates these aspects and works with nature instead of exploiting it.

Principles of Organic Farming

The following internationally accepted principles form the basis of organic farming:

Health Principle: Organic agriculture should sustain and enhance the health of soil, plant, animal and man as one and indivisible system.

Ecology Principle: It should be based on living ecological systems and cycles, working with them and helping sustain them.

Principle of Justice: Organic farming should generate relationships that ensure fairness in terms of the common environment and life opportunities.

Principle of Care: Management should be precautionary and responsible to protect the health and well-being of present and future generations.

Organic Technologies in Crop Production

Organic farming employs a number of eco-friendly technologies to ensure productivity and sustainability:

Managing Soil Fertility: Healthy soil is the foundation of organic agriculture. Practices involve:

- ✓ Farmyard manure (FYM) application
- ✓ Composting and vermicomposting
- ✓ Using crop residues

They improve soil structure, microbial activity and nutrient availability.

Crop Rotation and Diversification: Crop rotation maintains soil fertility and breaks the cycles of pests and diseases. Legumes increase N fixation.

Green Manuring: Green manure crops such as dhaincha and sunhemp are grown and ploughed back into the soil. This enriches organic matter and increases soil fertility.

Biological Pest and Disease Control: Organic farming uses natural pest control methods, including:

- ✓ Application of neem biopesticides
- ✓ Release of beneficial insects
- ✓ Use of microbial preparations.

Benefits of Organic Farming

Benefits to the Environment

- ✓ Enhances soil fertility and structure
- ✓ Lessens water and air pollution
- ✓ Increases biodiversity and ecological balance

Benefits to the Economy

- ✓ Lowers chemical input costs
- ✓ Offers premium prices in the market
- ✓ Generates employment in rural areas

Health Benefits

- ✓ Food produced safely and free of chemicals
- ✓ Lowers pesticide health risks
- ✓ Enhances the nutritional value of food.

Challenges in Organic Farming

Organic farming has a lot of benefits, but it also has a lot of problems:

- ✓ Lower yield during the first transition period
- ✓ Farmers don't know enough or have the right skills
- ✓ Organic inputs are not always easy to find
- ✓ Certification is expensive and hard to get.
- ✓ Problems with marketing and the supply chain

To get past these problems, we need the right training, help from the government, and improvements to our infrastructure.

Role in Sustainable Agriculture

Organic farming is a big part of sustainable agriculture because it saves natural resources, makes soil healthier, and cuts down on pollution. It helps protect against climate change and keeps farming productive in the long term.

Organic Farming and Food Security

Food security means that food is easy to get, cheap, and available. Organic farming helps keep food safe by:

- ✓ Encouraging a variety of cropping systems
- ✓ Making the soil more productive over time
- ✓ Lessening reliance on outside resources

Even though yields may be lower at first, long-term sustainability makes sure that production stays stable.

Government Initiatives and Policies in India

The Indian government has started a number of programs to encourage organic farming:

- ✓ The Paramparagat Krishi Vikas Yojana (PKVY)
- ✓ National Program for Organic Production (NPOP)
- ✓ Mission Organic Value Chain Development for the North Eastern Region (MOVCDNER)

Farmers get money, training, and connections to markets through these programs.

Future Prospects

As people become more aware of their health, the demand for organic products is growing around the world. Organic farming has a lot of room to grow thanks to improvements in technology, better certification systems, and government support.

Conclusion

Using organic technology to grow crops in an environmentally friendly way is a long-term solution to the problems that modern farming faces. It protects the environment, keeps food safe, and gives farmers a stable economy. There are problems, but the long-term benefits of organic farming make it an important way to achieve sustainable agriculture and food security around the world.

Soil Health Management through Organic Production Technology for Long-Term Agricultural Sustainability

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Abstract

Soil health is the foundation of sustainable agriculture, yet it is increasingly threatened by intensive farming practices and excessive use of chemical inputs. Organic production technologies offer an effective approach to restore and maintain soil fertility while ensuring environmental sustainability. This article discusses the importance of soil health, the limitations of conventional practices, and the role of organic methods such as composting, crop rotation, and biological inputs in improving soil quality. It further highlights practical strategies for long-term agricultural sustainability through organic soil management.

Introduction

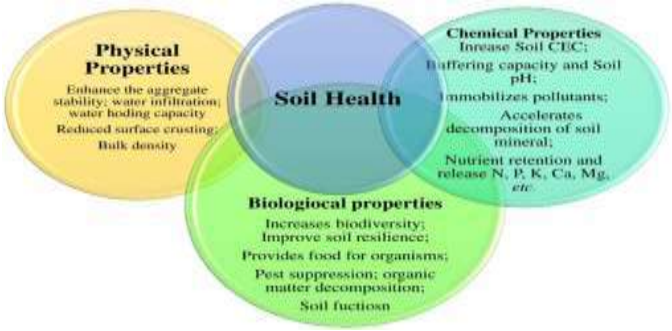
Soil is more than just a medium for plant growth; it is a living system that supports crops, microorganisms, and ecological balance. Healthy soil provides nutrients, retains water, and supports biodiversity, all of which are essential for productive agriculture. In recent years, the excessive use of chemical fertilizers and pesticides has led to soil degradation, reduced fertility, and loss of beneficial microorganisms. These changes have negatively affected crop productivity and environmental quality As a result, there is a growing need to adopt sustainable approaches that protect and enhance soil health. Organic production technology focuses on natural processes and inputs to improve soil conditions. It not only maintains productivity but also ensures long-term sustainability.

Importance of Soil Health in Agriculture

Soil health plays a critical role in determining crop yield and quality. A healthy soil system:

- ✓ Supplies essential nutrients to plants
- ✓ Improves water retention and reduces erosion
- ✓ Supports beneficial microorganisms
- ✓ Enhances plant resistance to pests and diseases

When soil health declines, crops become more dependent on external inputs, increasing production costs and environmental risks. Therefore, maintaining soil health is essential for sustainable farming systems.



Challenges in Maintaining Soil Health

Excessive Use of Chemical Inputs: The continuous application of synthetic fertilizers disturbs the natur-

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al balance of soil nutrients. While they provide quick results, they reduce organic matter and harm beneficial soil organisms over time.

Soil Degradation and Erosion: Poor land management practices, such as over-tilling and mono-cropping, lead to soil erosion and loss of fertility. This reduces the soil's ability to support crops effectively.

Decline in Soil Organic Matter: Organic matter is essential for soil structure and fertility. However, its levels are decreasing due to limited use of organic inputs.

Loss of Soil Biodiversity: Beneficial microorganisms play a key role in nutrient cycling. Chemical-based farming often destroys these organisms, weakening soil health.

Organic Production Technologies for Soil Health Management

Organic farming provides several techniques that help improve and maintain soil health naturally.

Composting and Vermicomposting: Composting involves the decomposition of organic waste into nutrient-rich manure. Vermicomposting uses earthworms to accelerate this process. These methods increase soil organic matter and improve nutrient availability.

Crop Rotation and Diversification: Growing different crops in a sequence helps maintain soil fertility and breaks pest cycles. Leguminous crops, for example, fix nitrogen in the soil, reducing the need for external fertilizers.

Green Manuring: Green manuring involves growing specific crops and incorporating them into the soil to improve fertility. It enhances soil structure and nutrient content.

Use of Biofertilizers: Biofertilizers contain beneficial microorganisms that help in nutrient fixation and availability. They are eco-friendly alternatives to chemical fertilizers.

Mulching: Mulching involves covering the soil with organic materials such as straw or leaves. It helps retain moisture, control weeds, and improve soil structure.

Benefits of Organic Soil Management

Organic production technologies offer multiple benefits for both farmers and the environment:

- ✓ Improved soil fertility and structure
- ✓ Increased water retention capacity
- ✓ Reduced dependency on chemical inputs

- ✓ Enhanced biodiversity and ecological balance
- ✓ Better crop quality and long-term productivity

These benefits contribute to a more resilient and sustainable agricultural system.

Strategies for Long-Term Agricultural Sustainability

Integrated Soil Management: Combining different organic practices ensures better results. For example, using compost along with crop rotation improves overall soil health.

Farmer Awareness and Training: Educating farmers about organic methods is essential. Practical training programs can help them adopt sustainable practices effectively.

Policy Support and Incentives: Government support in the form of subsidies, training, and certification assistance can encourage farmers to adopt organic technologies.

Research and Innovation: Continuous research is needed to develop region-specific organic solutions that are both effective and affordable.

Conclusion

Maintaining soil health is essential for ensuring long-term agricultural sustainability. Organic production technologies provide a natural and effective way to restore soil fertility and protect the environment. By adopting practices such as composting, crop rotation, and biofertilizer use, farmers can improve soil quality and reduce dependence on chemical inputs. With proper support, awareness, and implementation, organic soil management can play a key role in building a sustainable agricultural future.

The Green Renaissance: Future Prospects of Organic Production Technology

Shubham Kumar

Introduction: A Quiet Revolution in the Fields

Amazing changes are taking place throughout the world quietly and without any media hype they are taking place underground. Farmers, specialists, innovators, and even consumers are getting involved in a great shift known as a "Green Renaissance." Unlike the previous revolution that was based on chemicals and high-yielding crop species, today's agricultural revolution focuses more on sustainability, ecology, and technology innovations. The application of organic production technologies is at the forefront of this process. This innovative approach to agriculture is far from being only organic farming; it implies a new way of viewing agricultural production as an integral and interconnected ecosystem in which both productivity and environmental protection are combined. With the intensifying effects of climate change, reduction of biodiversity, and growing health risks, organic farming is becoming crucially important for future agriculture. However, what lies ahead? What role does technology play in organic farming? Is there enough potential in organic production technologies to satisfy global food needs in the future? What problems do need to be solved in order to move toward a new agriculture? The answers to all these questions can be found further in this article.

Understanding Organic Production Technology

Organic production technology can be defined as technologies that are involved in producing food crops or raising animals without using artificial fertilizers, pesticides, and genetically engineered material. This is done through the use of natural processes like composting, crop rotations, biological controls, and restoring soil fertility. The fundamental thing about organic agriculture is that it does not involve opposition to technology; rather, it only selectively uses technology. Modern organic farms are characterized by the following aspects:

- ✓ Biological technology, which involves the use of biofertilizers and biostimulants.
- ✓ Pest control through natural means, which includes pheromone traps.
- ✓ Ecosystems intensification to enhance agricultural output while protecting the ecosystem.

Driving Forces behind the Green Renaissance

Rising Consumer Awareness: The consumer of today is more knowledgeable than he has been before. Issues related to pesticides, food safety, and pollution have brought about an increase in demand for organic products. There is an urgent need for more information from today's consumers. Consumers do not only wish to be told that something is labeled as being organic, but they also want to know

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how it was produced, the treatment of farm laborers, and its effect on the environment.

Climate Change and Environmental Pressure: While agriculture is both a cause and a victim of climate change, organic farming provides an avenue for tackling this problem through:

- ✓ Increased carbon storage in the soil
- ✓ Decreased emissions of greenhouse gases
- ✓ Increased biodiversity

Additionally, organic farming systems can withstand adverse weather better than conventional farming systems.

Policy and Institutional Support: Organic farming is now being recognized as a public good by governments and institutions. There are moves to subsidize organic farming, certify it and carry out research into it to encourage its practice.

Technological Innovations Influencing Organic Farming

Another fascinating aspect of the Green Renaissance is the incorporation of advanced technological innovations in the field of organic farming.

Precision Organic Farming: Once considered exclusive to conventional farms, precision agriculture has become an essential tool for organic farming. It includes technologies such as:

- ✓ Monitoring drones
- ✓ Soil sensors
- ✓ AI-supported decision-making systems

All these help organic farmers increase productivity while optimizing the utilization of resources and minimizing waste generation.

Robotics and Automation: Labor-intensive processes have always been a challenge in organic farms. With the help of robotics, it is possible to perform tedious tasks, including:

- ✓ Weed control
- ✓ Harvesting
- ✓ Irrigation

These advances not only contribute to reducing labor costs but also make organic farming more scalable.

Bio-Based Inputs and Innovations: In organic farming, biological inputs play a crucial role. Some examples include:

- ✓ Biofertilizers
- ✓ Biopesticides
- ✓ Microbial inoculants

These biological inputs are becoming increasingly innovative and efficient in their function, allowing farmers to become self-reliant.

Blockchain Technology: Transparency in the food chain is one of the rising demands among consumers. In this regard, blockchain technology could prove revolutionary, as it helps achieve:

- ✓ Traceability from the field to the consumer
- ✓ Verification of organic practices
- ✓ Increased

Role of Agroecology and Regenerative Practices

Organic farming is gradually converging with regenerative practices in the context of restoring ecosystems.

Main practices:

- ✓ Use of cover crops
- ✓ Biodiverse planting
- ✓ Integration of livestock systems

Apart from improving soil conditions, these practices contribute to greater ecosystem sustainability. In particular, researchers claim that regenerative farms exhibit higher microbial diversity and better water retention compared to conventional ones.

Economic Potential and Market Growth

Emergence of the Global Organic Market: Nowadays, a rapidly-growing market of organic food has been established. At the turn of the last century, there were just two million acres used for organic production. Today, this number exceeds 37 million acres.

Economic Benefits for Farmers: Economically, organic agriculture brings multiple advantages:

- ✓ Premium prices of crops
- ✓ Decreased reliance on expensive inputs
- ✓ Multiple income sources through diversified farming systems

Moreover, in developing countries, organic farming stimulates rural development and employment creation.

Rising Costs for Consumers: Despite its development, organics remain relatively pricey for consumers. Luckily, further advancements should decrease the cost of organic products in the upcoming decades.

Challenges Associated with Organic Farming Technology

Despite the positive future outlook, there are certain problems that come along with organic farming.

Yield Gaps: Sometimes the yield of an organic farmer can be below average compared to a conventional one because of the transitional process involved. However, research confirms that the gap disappears when management techniques and diversification are properly applied.

Labor Costs: More physical work is required on organic farms in order to control weeds and other pests. Consequently, the cost of labor increases making large-scale production difficult.

Shortage of Technical Knowledge: There is a lack of technical skills necessary to apply organic production principles in practice. Education plays an important role in this situation.

Lack of Market Access and Poor Infrastructure: There might be certain difficulties with marketing among farmers who practice organic farming such as:

- ✓ Difficulty reaching organic markets
- ✓ Infrastructure issues within the supply chain
- ✓ Complexities associated with certification

Local and Urban Organic Farming Systems

One of the biggest trends associated with organic farming is developing local organic farms.

Urban Agriculture: Cities have become the centers of organic production with the help of:

- ✓ Urban rooftop farms
- ✓ Vertical farms
- ✓ Local CSA farms

Regional Chain of Supplies: Local organic agriculture lowers transportation expenses, reduces waste, and benefits local communities.

Organics in India: An Example

India is uniquely placed to take the leadership position in the movement towards organics given its rich agribiotic legacy and diverse biodiversity.

Traditional Practices and Modern Technologies: Traditional practices such as composting, crop rotation, and natural pest control are gaining traction alongside advanced technologies that increase productivity.

Policy Interventions: Government programs such as:

- ✓ Paramparagat Krishi Vikas Yojana (PKVY)
- ✓ National Programme for Organic Production (NPOP) are inspiring farmers to embrace sustainable practices.

Limitations and Opportunities

Some of the limitations faced by India include:

- ✓ Limited farmer awareness about organics
- ✓ Difficulty accessing certification
- ✓ Market access difficulties

Nevertheless, increased consumer demand for organics represents major opportunities.

Future Prospects

Role of AI and Big Data Analytics: The future of organics will be marked by advanced data analytics where artificial intelligence and big data will drive:

- ✓ Prediction of crop yields
- ✓ Soil health monitoring
- ✓ Decision making based on real-time information

Smart Organic Agriculture: Climate-smart organic farming will become the norm in future where practices such as:

- ✓ Carbon farming
- ✓ Water management techniques
- ✓ Drought-resistance varieties of crops will dominate

Transition from Conventional Agri-Business: Organic farming is moving beyond conventional crops to include:

- ✓ Aquaculture
- ✓ Seaweed farming
- ✓ Agroforestry farming systems

Democratizing Organic Farming

The availability of open-source and cheap agricultural technologies will help more people embrace organic farming practices.

A Human Perspective: Putting Farmers First

Despite all the innovations and developments, the core of agriculture always remains human-centered. Farmers need to become agents of change who:

- ✓ Connect with nature.
- ✓ Preserve traditional wisdom.
- ✓ Create sustainable livelihoods.

Of course, this process is possible only under certain conditions that include financial support, modern technologies, and psychological assistance. It should be noted that farmers do not have the status of professionals they are representatives of their villages.

Conclusion: Towards a Sustainable Future

The Green Renaissance implies an innovative approach to food production and consumption as well as the development of new methods and means of sustainable agriculture. Organic production technologies are associated with:

- ✓ Sustainability
- ✓ Robustness
- ✓ Accessibility
- ✓ Innovation

It is evident that despite some problems, such trends have a significant potential for development. Organic farms already benefit from the technological revolution and increased awareness of consumers. The question is no longer about the possibility of implementing sustainable agricultural innovations they are necessary for the survival of humanity. Therefore, the future of agriculture depends on the pace of innovations' implementation and the readiness of farmers to change the current system of production.

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The Silent Revolution Beneath Our Feet: A Guide to Organic Nutrient Management

Avneesh Verma

Introduction: Listening to the Soil's Whisper

Behind every successful crop, every green lawn, and every forest filled with life is another world-the soil. This hidden ecosystem that rarely garners attention but plays a critical role in sustaining everything above its surface is teeming with microorganisms, organic material, minerals, and water. Unfortunately, due to being largely invisible, this resource tends to be ignored until problems occur. Soil fertility through the use of artificial fertilizers may bring short-term results; however, such practice leads to numerous negative effects and, most importantly, long-lasting reliance on external inputs. In order to find an alternative solution, one needs to turn to the concept of organic nutrient management. In this guide, we will examine this method of maintaining soil health. Unlike regular soil science topics, this practice encompasses much more than simply providing information about some process or technique. Instead, organic nutrient management embodies an entirely new philosophy of cultivating crops.

Understanding Soil as a Living System

One should understand the role of organic nutrient management by viewing the soil not as mere dirt but as alive. A single fistful of soil can contain billions of microbes. These microbes engage in intricate food chains that decompose organic matter, recycle nutrients, and even engage in symbiotic relationships with plants. For example, fungi form mycorrhizal networks which extend the range of root systems, increasing their nutrient absorption capacity. Some bacteria, on the other hand, convert atmospheric nitrogen into usable forms of nitrogen.

Organic matter in soil is made up of decayed remains of plants and animals. Organic matter in soil functions as a source of nutrients as well as improves soil structure.

Use of excessive chemical fertilizers might cause imbalance in the soil system. Microbial population levels will be reduced, soil quality might get degraded, and leaching of nutrients into surrounding ecosystems might occur.

What Is Organic Nutrient Management?

ONM refers to the provision of plant nutrients by making use of natural sources instead of chemical fertilizers. ONM makes use of organic matter such as compost, animal manure, crop residues, green manure, and bio-fertilizers. However, ONM is much more than merely replacing one fertilizer with another. ONM is a comprehensive method which emphasizes:

- ✓ Improving soil quality
- ✓ Increasing biodiversity

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- ✓ Recycling of nutrients in the system
- ✓ Decreasing reliance on off-system inputs
- ✓ Sustainability

In other words, ONM is a process which works with nature.

Core Principles of Organic Nutrient Management

Nourish the Soil Instead of Just the Crop: In traditional farming practices, soil is treated as nothing but an inert substance and nutrients are applied only to crops. However, organic nutrient management is the reverse of this logic where through proper nourishment of the soil in terms of organic substances and biology, we give rise to favorable soil conditions in which plants will receive their required nutrients. Soil becomes something like a reservoir of water and nutrients, which retain moisture and release nutrients in a gradual manner when needed by plants.

Create a Closed Nutrient Cycle: Nutrients in nature never go to waste. Leaves decompose on their own to release nutrients back into the soil. Organic nutrient management imitates this process by reusing agricultural waste in order to replenish the soil.

Favor Biodiversity: Diverse systems are strong. This is why it is crucial that we increase the biodiversity of our agricultural land in order to facilitate nutrient cycling, plant resistance, and productivity in general.

Increase Organic Matter in the Soil: Organic matter in the soil forms the foundation for fertility. Organic matter contributes to good soil structure, water retention and nutrient supply. Nutrient management organically relies on practices that increase organic matter in the soil.

Sources of Organic Nutrients

Compost: The Black Gold: Compost refers to decayed organic substances that contain nutrients and living microorganisms. Composting is made using kitchen waste, crop residues, leaves, and manure. Through the composting process, raw materials become stabilized and humus-like substances. In addition to supplying nutrients, they provide soil enrichment and enhance microbial action. A good compost pile should have a balanced supply of carbon sources (dry leaves) and nitrogen sources (green waste) as well as sufficient oxygen and moisture.

Farmyard Manure (FYM): Farmyard manure refers to an accumulation of farmyard refuse consisting of dung, urine, refuse bedding materials, and unused fodder. It has been used for many centuries to improve soil fertility. While nutrient concentration is less than those from artificial fertilizers, they release their contents gradually.

Green Manures: Green manuring refers to cultivation of crops such as leguminous plants and incorporation into soil before complete maturity. Legumes help to fix atmospheric nitrogen in the soil. Examples include sunhemp, dhaincha, and clover.

Crop Residues: Crop residues are usually burned, contributing to air pollution. Burning should be avoided; instead, the residue can be left to degrade, improving soil fertility.

Biofertilizers: Biofertilizers are organic fertilizers

that contain useful microorganisms which increase the availability of nutrients. The common types of biofertilizers are as follows:

- ✓ Nitrogen-fixing bacteria (e.g. Rhizobium)
- ✓ Phosphorus-solubilizing bacteria
- ✓ Mycorrhizal fungi

Nutrient Cycling: Nature's Efficiency

Nutrient recycling is continuous in natural ecosystems. Dead leaves decomposed by micro-organisms, returning nutrients back into the soil, illustrate this process. Nutrient recycling through organic methods mimics the natural system in agriculture. For instance, the addition of compost to the soil allows microorganisms to decompose it, thus releasing nutrients gradually. Plants use these nutrients for growth, after which dead leaves are left in the soil. The cycle continues indefinitely, reducing nutrient loss.

Benefits of Organic Nutrient Management

Soil Health Improvement: Organic farming methods help boost organic matter in soil, increase microbial activity, and improve soil structure. This ensures increased aeration, moisture retention, and development of root systems.

Sustainability: Although yields might be lower than in intensive chemical agriculture at first, organic farming tends to be more sustainable and yield higher productivity in the long run.

Preservation of Environment: Nutrient management using organic techniques helps prevent pollution caused by chemical spills, protects the quality of water, and decreases greenhouse gas emissions.

Economic Sustainability: Using readily available resources for production minimizes input costs and decreases dependence on outside sources.

Healthy Food Production: Despite possible variation in the nutritional profile of foods produced using this method, organic farming promotes safer foods.

Challenges and Misconceptions

However, managing nutrients organically is not without its problems.

Slower Nutrient Availability: The availability of nutrients from organic sources is slower compared to artificial fertilizers.

Labor- and Knowledge-intensive Process: Processing of composts, manures, and crops needs time and expertise.

Transition Period: Land that has been subjected to chemicals for many years will need time to heal. During this period, productivity levels will vary.

Fallacy: "Organic Farming Results in Low Productivity"

This is not always the case. Given appropriate management, organic farming practices can result in comparable yields to conventional ones.

Practical Steps for Implementing Organic Nutrient Management

Check Soil Health: Conduct a soil test to determine the nutrient content, soil pH, and organic matter. This will help in determining improvements that need to be made.

Nutrient Management: Determine nutrient sources on the farm like manure, crop residues, and compost

to be used depending on crop requirements.

Composting: Construct a compost pit where the materials to be turned into compost will be deposited.

Practice Crop Rotation: Rotate the crops to ensure no exhaustion of nutrients and prevention of pest buildup. Leguminous crops should be included in rotation.

Use Biological Fertilizers: Fertilize seeds and soil using biological fertilizers to increase nutrient availability.

Mulching: Use organic mulch in the garden as it aids in soil fertility and weed control.

Minimize Tillage: Tillage reduces organic matter content and destroys soil structure. Reduced tillage should be practiced.

The Role of Farmers: Stewards of the Soil

Nutrient management in organic farming alters the position of the farmer. The farmer stops being an input provider and instead turns into an ecosystem manager. It needs patience, observation, and flexibility. It means knowing your land, its capabilities, its weaknesses, and its cycles. Those farmers who practice organic farming claim that they develop a closer relationship with their soil. They see the results they smell the rich soil, the earthworms come back, and the crops withstand drought.

Case Reflections: Learning from the Field

Around the globe, there is renewed emphasis on incorporating old practices into new ways of thinking. In some places, smallholders use practices such as composting and green manuring for fertility maintenance. Other areas rely on crop-livestock-tree integration for sustainable systems. From the above example, we see that organic nutrients management does not take a single form.

Organic Nutrient Management and Climate Change

The health of soils is essential in addressing climate change. The soils function as carbon sinks where carbon would otherwise end up in the atmosphere. Through the increase in organic matter in the soils, organic fertilizer management contributes to carbon sequestration and increased resilience against weather extremes like droughts, floods, and temperature variations. This revolution underground is part of the solution to climate change.

Bridging Tradition and Innovation

Organic nutrient management does not mean turning our backs on science; rather, it means delving further into its mysteries. Science is revealing the intricacies of soil ecologies and confirming the effectiveness of farming methods that have been practiced for many years. Advancements in soil analysis, microbial testing, and precision agriculture may help improve organic agriculture.

The Human Element: A Shift in Mindset

In essence, organic nutrient management starts with one's attitude. One has to transition from controlling nature to collaborating with it, from mining its resources to rejuvenating them, and from exploiting opportunities to fostering sustainability. While making such a transition may prove difficult at times, it certainly brings a feeling of meaningful-ness to what one does.

Conclusion: The Quiet Power of Healthy Soil

However, what takes place below our feet remains unnoticed, yet it brings enormous consequences. Organic nutrient management will hardly deliver any quick solutions or drastic changes. However, it guarantees the provision of sustainable processes and balance. We cultivate the soil to make our life sustainable by developing those systems which will ensure life for the coming generation on the conditions of our planet. Therefore, taking into account environmental problems of today and increasing requirements for food, this underground revolution may be one of our strongest means. The next time you step in the garden or a cultivated area, stop for a second and realize what happens beneath your feet: thousands of living organisms work ceaselessly performing nutrient cycles, providing structure, and supporting life. They do not require much, only the organic matter, some tolerance, and the opportunity to survive. But their gift to us is invaluable.

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Climate Resilient Crop Varieties: A New Hope for Agriculture

Ghanprakash Ghoretha, Deepak Gupta and Chelsi

Abstract

Climate change is posing serious challenges to agricultural productivity through irregular rainfall, rising temperatures, and increased pest and disease incidence. Climate resilient crop varieties are developed to tolerate environmental stresses such as drought, heat, and flooding while maintaining stable yields. These varieties help farmers reduce production risks and ensure sustainable crop production. Adoption of climate resilient crops can play a vital role in securing future food security and improving farmer livelihoods.

Agriculture is the backbone of many developing countries and plays a crucial role in food security, employment, and economic development. However, agriculture is highly dependent on climate conditions such as rainfall, temperature, and seasonal changes. In recent years, climate change has become one of the biggest challenges faced by farmers. Irregular rainfall, rising temperatures, droughts, floods, and the occurrence of new pests and diseases are increasingly affecting crop productivity. To overcome these challenges, scientists and agricultural researchers are focusing on the development of climate resilient crop varieties. These varieties are capable of tolerating environmental stresses such as drought, heat, salinity and flooding while maintaining stable yields. Climate resilient crops are considered a sustainable solution to ensure food production under changing climatic conditions. Climate resilient varieties provide a new hope for agriculture by helping farmers adapt to climate variability and ensuring stable agricultural production.

Impact of Climate Change on Agriculture

Climate change has significant effects on agricultural production systems. The increase in global temperature and unpredictable weather patterns are influencing crop growth and yield.

Irregular Rainfall: Rainfall patterns have become highly unpredictable in many regions. Some areas experience prolonged drought, while others face excessive rainfall and flooding. Both situations adversely affect crop production.

Rising Temperature: High temperatures can negatively affect crop growth by reducing photosynthesis, increasing water loss, and affecting flowering and grain formation. Many crops are sensitive to heat stress during critical growth stages.

Increased Pest and Disease Incidence: Warmer

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climatic conditions often create favorable environments for pests and diseases. As a result, farmers have to deal with new pest outbreaks and increased crop damage.

Soil Degradation and Water Scarcity: Climate change also contributes to soil degradation, salinity, and declining water availability, making crop production more difficult in several regions.

These challenges highlight the need for crop varieties that can survive and perform well under harsh environmental conditions.

What are Climate Resilient Crop Varieties?

Climate resilient crop varieties are specially developed varieties that can tolerate environmental stresses and maintain stable productivity even under adverse conditions. These varieties possess genetic traits that help them adapt to different climatic stresses. Some common characteristics of climate resilient crop varieties include:

- ✓ Drought tolerance
- ✓ Heat tolerance
- ✓ Flood tolerance
- ✓ Salinity tolerance
- ✓ Resistance to pests and diseases
- ✓ Early maturity and efficient water use

These traits allow crops to survive unfavorable environmental conditions and produce reasonable yields. Scientists identify and incorporate these traits through systematic breeding programs. Traditional breeding methods as well as modern molecular techniques are used to develop improved crop varieties capable of coping with climate challenges.

Importance of Climate Resilient Varieties

Ensuring Food Security: One of the major advantages of climate resilient crops is their ability to produce stable yields even under adverse weather conditions. This helps ensure food availability for growing populations.

Reducing Production Risks: Farmers often face heavy losses due to droughts, floods, or pest outbreaks. Climate resilient varieties reduce such risks by providing better tolerance to these stresses.

Improving Farmer Income: Stable production leads to consistent income for farmers. When crops survive climatic stresses and produce satisfactory yields, farmers are less likely to suffer financial losses.

Efficient Resource Use: Many climate resilient varieties are developed with improved water and nutrient use efficiency. This helps farmers achieve better productivity with fewer inputs.

Adaptation to Climate Change: Climate resilient crops enable farmers to adapt to changing climatic conditions and maintain agricultural sustainability.

Role of Plant Breeding in Developing Climate Resilient Crops

Plant breeders play a crucial role in developing climate resilient varieties. Through careful selection and hybridization, scientists combine desirable traits from different plant lines to produce improved varieties. The process of developing climate resilient crops generally includes:

- ✓ Collection of diverse genetic material or germ-

plasm

- ✓ Evaluation of plant traits under stress conditions
- ✓ Selection of superior plants with desired characteristics
- ✓ Hybridization and breeding to combine beneficial traits
- ✓ Field testing and evaluation of new varieties

Advanced tools such as molecular markers and biotechnology are also used to identify genes responsible for stress tolerance and incorporate them into improved varieties.

Management Practices for Climate Resilient Agriculture

Adopting climate resilient varieties alone is not sufficient. Farmers should also follow appropriate management practices to maximize the benefits.

Crop Diversification: Growing different crops reduces the risk of total crop failure and improves farm sustainability.

Efficient Water Management: Techniques such as drip irrigation, mulching, and rainwater harvesting help conserve water and support crop growth during dry periods.

Soil Health Management: Maintaining soil fertility through organic manure, crop rotation, and balanced fertilization improves crop resilience.

Integrated Pest Management: Monitoring pests and using biological control methods help reduce crop damage while minimizing pesticide use.

Timely Sowing: Adjusting sowing dates according to changing climatic conditions helps crops avoid extreme weather events.

Role of Farmers and Agricultural Institutions

Farmers play an important role in adopting and promoting climate resilient crop varieties. Agricultural research institutions and extension services should provide farmers with information about suitable varieties and improved farming techniques. Training programs, field demonstrations, and awareness campaigns help farmers understand the benefits of climate resilient agriculture. Organizations such as the Indian Council of Agricultural Research and agricultural universities are actively working on developing and promoting climate resilient crop technologies.

Future Prospects

Climate change will continue to influence agriculture in the coming decades. Therefore, continuous research is required to develop new crop varieties with enhanced stress tolerance. Future advancements in plant breeding, genomics, and biotechnology will help accelerate the development of climate resilient crops. Farmers will also need access to quality seeds, improved technologies, and proper guidance to adopt these innovations effectively.

Conclusion

Climate resilient crop varieties provide a promising solution to the challenges posed by climate change. These varieties help farmers maintain stable crop production despite environmental stresses such as drought, floods, and high temperatures. By adopting climate resilient crops along with improved agricultural practices, farmers

can reduce production risks, improve their income, and contribute to sustainable agriculture. With continuous research and strong support from agricultural institutions, climate resilient agriculture can ensure food security and strengthen the future of farming.

Chemicals for Enchancing the Post Harvest Life of Cut Flowers

Neelima Palagani, Sravanthi D., Reddy I. V. S. and Hemantha Kumar J.

Introduction

A flower is complex organ composed of different morphological units including sepals, petals, androecium, gynoecium, stem and leaves. The function of these units differs from each other and ultimately decides the longevity of the flower. Most of the cut flowers complete their life cycle in two distinct phases. First stage is bud growth and development of flower to full opening and the second stage is maturation, senescence and wilting. Second stage plays a vital role on enhancing the post harvest life of the cut flowers. After detaching the flower from the plant various enzymatic activities starts in the flower *viz.*, protease, lipoxygenase *etc*, which increases towards the senescence. Nearly, 30-50 % loss of cut flowers occurs due to improper postharvest handling during entire market chain. In this context chemical treatment in the form of pulsing, impregnation and using floral preservatives can significantly influence the post harvest life of cut flowers. Pulsing is the process of absorption of chemical solution having sugar and germicide through the lower cut portion of the flower stalk. Pulsing treatment constitute a sugar source, germicide and water which improves the flower opening, size, shape, colour and longevity of the cut flower (Singh *et al*., 2007). Sucrose replaces the depleted endogenous carbohydrates utilized during post harvest life of flowers (Salunkhe *et al*., 1990). Sucrose acts as food for cut flowers and reduces starch degradation which plays key role to increases the cut flower longevity (Mehraj *et al*., 2013). Effectiveness of pulsing prior to and after storage is mostly correlated with high concentration of sugars. This practice can be followed by growers, wholesalers or retail florists to enhance the vase life of the flower.

Gladiolus treated with Pulsing Solution

Chemicals as pulsing for different cut flowers

Rose	Sucrose (4-6%) for 12 h or Sucrose 3%+ silver thiosulphate 0.2mM for 3-4 h can be used
Chrysanthemum	Sucrose 5% for 10- 12 h.
Carnation	Sucrose (5-10%)+ 8HQ for 6-8 h
Gladiolus	Sucrose 15-20% for 10-15 h
Tuberose	Sucrose 8-10 % for 10 h
Bird of Paradise	Sucrose (10 %)+ citric acid (100-150 ppm) for 10-12 h.

Impregnation is the chemical treatment which protects the cut ends of the flowers from microbial blockage. Some of the commonly used chemicals for impregnation are Nickel chloride ($NiCl_2$), Cobalt chloride ($CoCl_2$), Silver nitrate

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($AgNO_3$) etc. As these chemicals have ions like Ni^{++}, Co^{++} and Ag^{++} which can't translocate to much distance and stays at the base of the stem thus prevents the microbial blockage. Impregnation should be done for a minimum of 10 minutes to a maximum of 30 minutes for different cut flowers like rose, chrysanthemum, gladiolus, carnation, orchids etc. Floral preservatives provides another kind of chemical treatments to cut flowers, which can be applied at any stage from harvesting to marketing which enhances the flower quality and longevity and on other hand, implies consumer appeal. A floral preservative consists of water to maintain the turgidity, sugar as a source of energy (sucrose and D-fructose), biocide to inhibit the microbial damage and an acidifying agent *viz.*, citric acid to maintain the pH at 3.5- 4.5. Biocides or germicides used in floral preservatives include 8-hydroxyquinoline sulphate, 8-hydroxyquinoline citrate, silver thiosulphate, silver nitrate, thiobendazole, lipoic acid, aluminium sulphate etc. These chemicals can be used at a concentration of 5-500 ppm for different cut flowers. Sucrose 1.5 and 1.0 per cent in combination with Sodium hypochlorite (0.3%) and Benzyladenine (20.0 ppm) treatments were improved flower quality by increasing vase life, eater uptake, relative fresh weight, membrane stability index and inhibit bacterial population(Kantharaj *et al*., 2018; Neelima *et al*., 2018).

Conclusion

Thus by employing the easy and adaptable techniques like pulsing, impregnation and using floral preservatives can significantly enhance the quality and vase life of cut flowers and ultimately fetches good market price.

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Solar Technology and Its Usage

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Abstract

Access to sustainable energy plays a crucial role in improving the quality of life in rural areas, particularly for women who are the primary managers of household energy. Solar technology offers a clean, cost-effective, and reliable alternative to conventional energy sources; however, its adoption largely depends on the level of awareness .The present study aims to assess the awareness, knowledge of solar technology and to identify factors influencing its adoption. The study highlights the need for targeted awareness programs to enhance the adoption of solar technology in rural households. Promoting solar energy and contribute to energy security, environmental sustainability.

Introduction

Energy is a vital component of rural development and plays a significant role in improving the living standards of households. In rural areas, women are the primary users and managers of household energy for cooking, lighting, and other domestic activities. Dependence on traditional energy sources such as firewood and kerosene not only affects women's health but also contributes to environmental degradation. Solar technology provides a clean, renewable, and cost-effective energy solution that can reduce drudgery, save time, and improve the quality of life of rural women. However, the successful adoption of solar technology largely depends on the level of awareness, knowledge, and accessibility among rural women. Understanding their awareness and perception is essential for promoting sustainable energy practices and empowering women in rural communities.

Kumar and Rani (2017) found that rural women were aware mainly of solar lamps and solar street lights, while awareness about solar cookers and solar water heaters was low. Meena *et al.* (2019) reported that lack of technical knowledge and inadequate demonstrations restricted the effective adoption of solar technology among rural women. Patil and Deshmukh (2020) observed that women exposed to extension activities had higher awareness levels compared to those without extension contact.

Factors Influencing Awareness and Adoption of Solar Technology

Awareness and adoption of solar technology are influenced by various socio-economic and institutional factors. Singh *et al*. (2018) reported that education, income, access to information sources, and training programs significantly influenced awareness of solar technology among rural women. Devi and Lal (2020) found that women's decision-making power within households played a crucial role in the adoption of solar technologies.

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Rao and Suresh (2021) emphasized that availability of subsidies, credit facilities, and after-sales services positively affected adoption behaviour.

Conclusion

Education level has a significant influence on awareness of solar technology. Farmers with higher levels of education were more aware of solar irrigation systems, government subsidies, and operational benefits compared to illiterate and primary-education is necessary. To progress solar technology awareness, launch public awareness campaigns, offer government incentives like subsidies and tax benefits, and promote rooftop and community solar installations.

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Tools, Machinery and Smart Farming in Organic Production

Jyoti Kumari

Introduction

Organic agriculture is rapidly evolving from a traditional, labor-intensive system into a modern, technology-driven sector. While the principles of organic farming emphasize natural processes, sustainability, and minimal external inputs, the integration of appropriate tools, machinery, and smart technologies has made it more efficient, productive, and scalable. Today, farmers are combining age-old wisdom with modern innovations to meet rising food demands while protecting the environment. This article explores the various tools, machinery, and smart farming technologies that are transforming organic production systems.

Importance of Tools and Machinery in Organic Farming

Organic farming relies heavily on manual and ecological processes such as composting, mulching, crop rotation, and biological pest control. However, without proper tools and machinery, these practices can become time-consuming and labor-intensive.

Key Benefits

- ✓ Reduces labor requirements
- ✓ Improves efficiency and productivity
- ✓ Ensures timely farm operations
- ✓ Enhances precision in farming practices
- ✓ Makes organic farming economically viable

Appropriate mechanization helps farmers maintain soil health while increasing yields without relying on synthetic chemicals.

Essential Tools Used in Organic Farming

Hand Tools: Hand tools remain the backbone of small-scale organic farms. They are simple, affordable and environmentally friendly. Examples:

- ✓ Hand hoe (for weeding and soil loosening)
- ✓ Spade and shovel
- ✓ Rake (for leveling soil)
- ✓ Sickles for harvesting
- ✓ Manual seed drills

These tools are especially useful for small farms, kitchen gardens, and hilly regions.

Weeding Tools: Weed management is crucial in organic farming since chemical herbicides are not used. Common Tools:

- ✓ Wheel hoe
- ✓ Cono weeder (used in paddy fields)
- ✓ Rotary weeder
- ✓ Hand weeders

These tools help in controlling weeds effectively while also aerating the soil.

Composting Tools: Organic farming depends heavily on compost and organic manure. Tools include:

- ✓ Compost turners
- ✓ Vermicompost units

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- ✓ Sieves for compost refinement
- ✓ Shredders for crop residue

These tools accelerate decomposition and improve compost quality.

Farm Machinery for Organic Production

As organic farms grow larger, machinery becomes essential for efficient operations.

Tractors and Attachments: Tractors are widely used even in organic farming, but with eco-friendly practices. Attachments include:

- ✓ Ploughs (for primary tillage)
- ✓ Harrows (for soil preparation)
- ✓ Seed drills (for sowing seeds)
- ✓ Cultivators (for weed control)

Modern tractors are designed to minimize soil compaction and fuel consumption.

Planters and Seeders: Precision seeders ensure proper spacing and depth, which improves crop growth. Benefits:

- ✓ Reduces seed wastage
- ✓ Ensures uniform plant growth
- ✓ Saves time and labor

Irrigation Equipment: Efficient water management is a key part of organic farming. Examples:

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

These systems conserve water and deliver it directly to plant roots.

Harvesting Machinery: Harvesting tools and machines help reduce crop losses and labor costs. Examples:

- ✓ Reapers
- ✓ Threshers
- ✓ Combine harvesters (adapted for organic systems)

Smart Farming Technologies in Organic Agriculture

Smart farming refers to the use of modern technologies such as sensors, automation, and data analytics to improve farm productivity.

Internet of Things (IoT): IoT devices collect real-time data from farms. Applications:

- ✓ Soil moisture monitoring
- ✓ Temperature and humidity tracking
- ✓ Automated irrigation systems

This helps farmers make informed decisions and optimize resource use.

Mobile Applications: Farmers can now manage their farms using smartphones. Features:

- ✓ Weather forecasts
- ✓ Pest identification tools
- ✓ Crop management guidance
- ✓ Market price updates

These apps make farming more accessible and knowledge-driven.

Drones in Organic Farming: Drones are becoming increasingly popular for monitoring crops. Uses:

- ✓ Crop health monitoring
- ✓ Identifying pest infestations
- ✓ Spraying bio-pesticides
- ✓ Mapping farmland
- ✓ Drones reduce labor and provide accurate field data.

Precision Farming: Precision farming involves applying inputs in the right amount at the right time. Technologies used:

- ✓ GPS mapping
- ✓ Soil sensors
- ✓ Data analytics

This reduces waste and enhances productivity while maintaining organic standards.

Solar-Powered Technologies: Renewable energy plays a significant role in sustainable farming. Examples:

- ✓ Solar water pumps
- ✓ Solar dryers
- ✓ Solar-powered fencing

These technologies reduce dependence on fossil fuels and lower operational costs.

Advantages of Smart Farming in Organic Systems

- ✓ Improves efficiency and productivity
- ✓ Reduces resource wastage
- ✓ Enhances crop quality
- ✓ Supports sustainable practices
- ✓ Helps in climate-resilient farming

Smart technologies make organic farming more attractive to young farmers and entrepreneurs.

Challenges and Limitations

Despite the benefits, there are some challenges:

- ✓ High initial investment
- ✓ Lack of technical knowledge
- ✓ Limited access in rural areas
- ✓ Maintenance and repair issues

To overcome these challenges, training and government support are essential.

The future of organic farming lies in the integration of technology with ecological practices. Innovations such as artificial intelligence, robotics, and blockchain for traceability are expected to revolutionize organic production. With increasing awareness about health and environmental sustainability, the demand for organic products is growing rapidly. This creates opportunities for farmers to adopt modern tools and smart farming techniques.

Conclusion

Tools, machinery, and smart farming technologies are transforming organic agriculture from a traditional practice into a modern, efficient, and sustainable system. By combining eco-friendly principles with technological advancements, farmers can achieve higher productivity while preserving natural resources. The adoption of these innovations will play a crucial role in ensuring food security, environmental protection, and economic prosperity in the future of agriculture.

Organic Farming: An Eco-Friendly Approach for Safe Food Production

Nikita Chauhan

Introduction

Organic farming is a holistic and sustainable agricultural system that focuses on producing food in harmony with nature. It avoids the use of synthetic fertilizers, pesticides, herbicides, and genetically modified organisms (GMOs). Instead, it relies on natural processes such as crop rotation, composting, biological pest control, and the use of organic manures. In recent years, there has been a growing awareness among consumers about the harmful effects of chemical-based farming on human health and the environment. As a result, the demand for organic food products has increased significantly. Organic farming not only ensures safe and healthy food production but also helps in maintaining ecological balance and conserving natural resources for future generations.

Concept and Meaning of Organic Farming

Organic farming is derived from the idea of maintaining the health of soil, ecosystems, and people. It is based on ecological processes, biodiversity, and cycles adapted to local conditions. The system works in harmony with nature rather than against it. The main objective of organic farming is to create a sustainable agricultural system that maintains soil fertility, promotes biodiversity, and produces high-quality food without harming the environment.

Principles of Organic Farming

Organic farming is guided by four fundamental principles:

Principle of Health: This principle emphasizes maintaining and enhancing the health of soil, plants, animals, and humans. Healthy soil leads to healthy crops, which in turn ensure good health for humans and animals.

Principle of Ecology: Organic farming should be based on living ecological systems and cycles. It should work with them, emulate them, and help sustain them. This principle promotes biodiversity and ecological balance.

Principle of Fairness: Organic farming ensures fairness in relationships between farmers, workers, traders, and consumers. It promotes equitable distribution of resources and ensures animal welfare.

Principle of Care: This principle highlights the importance of precaution and responsibility in managing agriculture. It ensures that farming practices do not harm the environment or future generations.

Key Practices in Organic Farming

Crop Rotation: Crop rotation involves growing different types of crops in a sequential manner on the same field. It helps in:

- ✓ Maintaining soil fertility
- ✓ Reducing pest and disease cycles

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- ✓ Improving soil structure

For example, growing legumes after cereals helps in nitrogen fixation.

Green Manuring: Green manuring involves growing crops like sunhemp or dhaincha and then incorporating them into the soil. It improves:

- ✓ Soil organic matter
- ✓ Nitrogen content
- ✓ Soil structure

Composting: Composting is the process of decomposing organic waste such as crop residues, animal manure, and kitchen waste. Compost improves:

- ✓ Soil fertility
- ✓ Water holding capacity
- ✓ Microbial activity

Use of Biofertilizers: Biofertilizers are living micro-organisms that enhance nutrient availability to plants. Examples include:

- ✓ Rhizobium
- ✓ Azotobacter
- ✓ Blue-green algae

Biological Pest Control: Instead of chemical pesticides, organic farming uses natural enemies like predators and parasites to control pests. Neem-based products and plant extracts are also commonly used.

Vermicomposting: Vermicomposting uses earth-worms to convert organic waste into nutrient-rich compost. It improves soil fertility and structure.

Advantages of Organic Farming

Environmental Protection: Organic farming reduces soil, water, and air pollution. It promotes biodiversity and helps conserve natural resources.

Improved Soil Health: Organic practices increase soil organic matter and enhance microbial activity, leading to better soil fertility.

Safe and Nutritious Food: Organic food is free from harmful chemicals and pesticides, making it healthier for consumption.

Climate Change Mitigation: Organic farming reduces greenhouse gas emissions and enhances carbon sequestration in soil.

Economic Benefits: Farmers can get premium prices for organic products, which increases their income. It also reduces dependency on costly chemical inputs.

Disadvantages and Challenges of Organic Farming

Lower Yield in Initial Years: During the transition period, farmers may experience reduced crop yields.

High Labor Requirement: Organic farming is labor-intensive as it requires manual practices like weeding and composting.

Certification Issues: Obtaining organic certification is costly and time-consuming for small farmers.

Pest and Disease Management: Controlling pests without chemicals can be challenging and requires proper knowledge.

Market Limitations: Lack of proper marketing channels and awareness can affect the sale of organic products.

Role of Organic Farming in Sustainable Development

Organic farming plays a vital role in achie-

ving sustainable development goals. It contributes to:

- ✓ Food security
- ✓ Environmental conservation
- ✓ Rural development
- ✓ Reduction in chemical pollution

It supports long-term agricultural sustainability by maintaining ecological balance.

Government Initiatives in India

The Government of India promotes organic farming through various schemes such as:

- ✓ Paramparagat Krishi Vikas Yojana (PKVY)
- ✓ National Programme for Organic Production (NPOP)
- ✓ Mission Organic Value Chain Development

These initiatives aim to increase organic farming area and improve farmers' income.

Conclusion

Organic farming is an eco-friendly and sustainable approach for safe food production. It ensures the production of healthy and chemical-free food while protecting the environment. Although there are some challenges, the long-term benefits of organic farming outweigh its limitations. With increasing awareness, government support, and scientific advancements, organic farming has the potential to transform agriculture into a more sustainable and profitable system. Adopting organic farming is essential for ensuring food safety, environmental protection, and a healthier future for generations to come.

Organic Vegetable Production: Techniques and Benefits

Ritika Bhagat

Introduction

Organic vegetable production is an agricultural system that relies on natural processes, biodiversity, and ecological balance rather than synthetic chemicals. It emphasizes soil health, environmental sustainability, and the production of safe, nutritious food. With increasing awareness of health and environmental issues, organic farming has gained significant importance worldwide.

Techniques of Organic Vegetable Production

Soil Management

Healthy soil is the foundation of organic farming. Farmers enhance soil fertility through:

Composting: Decomposed organic matter such as crop residues and animal manure enriches soil nutrients.

Green Manuring: Growing and incorporating plants like legumes into the soil improves nitrogen content.

Crop Rotation: Alternating crops prevents nutrient depletion and reduces pest buildup.

Mulching: Covering soil with organic materials conserves moisture, controls weeds, and improves soil structure.

Seed Selection and Sowing

- ✓ Use of organic, non-GMO seeds adapted to local conditions.
- ✓ Preference for disease-resistant varieties.
- ✓ Proper spacing and timely sowing to ensure healthy plant growth.

Nutrient Management

Instead of chemical fertilizers, organic systems rely on:

- ✓ Farmyard manure (FYM)
- ✓ Vermicompost
- ✓ Biofertilizers (e.g., Rhizobium, Azotobacter)
- ✓ Liquid organic fertilizers like compost tea

These inputs improve soil fertility and microbial activity.

Pest and Disease Management

Organic farming uses eco-friendly methods such as:

Biological control: Using natural predators like ladybirds and parasitoids.

Botanical pesticides: Neem oil, garlic extract, and chili sprays.

Trap crops: Growing specific plants to attract pests away from main crops.

Cultural practices: Crop rotation and sanitation to reduce disease spread.

Weed Management

- ✓ Manual weeding and mechanical tools
- ✓ Mulching to suppress weed growth
- ✓ Crop rotation and cover cropping

Water Management

- ✓ Efficient irrigation methods such as drip irrigation

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- ✓ Rainwater harvesting
- ✓ Maintaining soil moisture through mulching

Certification and Standards

Organic farmers follow specific standards set by certification bodies to ensure that no synthetic inputs are used. Certification helps build consumer trust and ensures premium pricing.

Benefits of Organic Vegetable Production

Environmental Benefits

Reduced pollution: No synthetic pesticides or fertilizers contaminate soil and water.

Biodiversity conservation: Supports beneficial insects, birds, and microorganisms.

Improved soil health: Enhances soil structure, fertility, and microbial life.

Climate resilience: Organic soils store more carbon and retain water better.

Health Benefits

- ✓ Vegetables are free from harmful chemical residues.
- ✓ Often richer in vitamins, minerals, and antioxidants.
- ✓ Reduced risk of health issues related to pesticide exposure.

Economic Benefits

- ✓ Premium market prices for organic produce
- ✓ Reduced dependency on expensive chemical inputs
- ✓ Opportunities for small-scale and sustainable farming

Social Benefits

- ✓ Promotes sustainable rural livelihoods
- ✓ Encourages traditional knowledge and farming practices
- ✓ Builds consumer confidence in safe and healthy food

Sustainability

Organic farming ensures long-term agricultural productivity by maintaining ecological balance and conserving natural resources for future generations.

Challenges in Organic Vegetable Production

- ✓ Lower yields during initial transition period
- ✓ Labor-intensive practices
- ✓ Limited availability of organic inputs
- ✓ Certification costs and procedures

However, with proper knowledge, training, and support, these challenges can be overcome.

Conclusion

Organic vegetable production is a sustainable and environmentally friendly approach to agriculture. By using natural inputs and ecological principles, it not only protects the environment but also produces healthier food. Despite some challenges, its long-term benefits for soil health, human well-being, and economic sustainability make it an essential component of modern agriculture.

Organic Production Technology for Enhancing Crop Quality and Export Potential

Masoom Alam

Abstract

Organic production technology has emerged as a sustainable alternative to conventional agriculture, addressing growing concerns related to food safety, environmental degradation, and soil health. This approach emphasizes the use of natural inputs and ecological processes to maintain productivity while minimizing environmental impact. Organic farming not only enhances crop quality by improving nutritional value and eliminating chemical residues but also opens new opportunities in international markets where demand for organic products is rapidly increasing. This article examines the principles, components, benefits, and challenges of organic production technology, with a focus on its role in improving crop quality and strengthening export potential. It also highlights policy support and future prospects for expanding organic agriculture.

Introduction

Agriculture is witnessing a gradual shift towards sustainability due to increasing awareness of environmental and health concerns associated with conventional farming. Excessive use of chemical fertilizers and pesticides has led to soil degradation, environmental pollution, and the presence of harmful residues in food products. These issues have raised global concerns regarding food safety and long-term agricultural sustainability. Organic production technology has emerged as a viable solution, focusing on natural inputs such as compost, green manure, and biological pest control. This approach enhances soil fertility, supports biodiversity and reduces ecological damage. In addition, organic farming improves crop quality and aligns with international standards, making it highly relevant for export-oriented agriculture. With rising global demand for safe and nutritious food, organic production technology plays a crucial role in enhancing both crop quality and export potential.

Principles of Organic Farming

Organic farming is guided by key principles that promote sustainability and ecological balance. These include maintaining soil health, conserving biodiversity, and minimizing external inputs. The system relies on natural processes such as nutrient recycling, biological pest control, and crop diversification. The principle of health emphasizes the interdependence of soil, plants, animals, and humans. Ecology focuses on working in harmony with natural systems, while fairness ensures equitable relationships among stakeholders. The principle of care encourages precautionary measures to protect

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the environment for future generations. Together, these principles form the foundation of organic production technology.

Components of Organic Production Technology

Organic Manures: Organic manures such as farmyard manure, compost, and vermicompost play a vital role in maintaining soil fertility. They improve soil structure, enhance microbial activity, and increase water retention capacity.

Green Manuring and Crop Rotation: Green manuring involves incorporating leguminous crops into the soil to enrich nitrogen content. Crop rotation helps break pest cycles, improve soil health, and enhance productivity.

Biofertilizers: Biofertilizers such as Rhizobium, Azotobacter, and phosphate-solubilizing bacteria improve nutrient availability by fixing atmospheric nitrogen and mobilizing nutrients.

Biopesticides and Biological Control: Organic farming uses natural pest control methods, including beneficial insects, microbial pesticides, and plant-based extracts like neem oil.

Soil Health and Nutrient Management: Soil health is a fundamental component of organic production systems, as it directly influences crop productivity, quality, and sustainability. Organic farming emphasizes the improvement of soil physical, chemical, and biological properties through the use of natural inputs and ecological practices. By increasing soil organic matter, organic systems enhance soil structure, aeration, and water-holding capacity, which are essential for healthy plant growth. One of the key benefits of organic practices is the enhancement of microbial diversity. Beneficial microorganisms such as bacteria, fungi, and actinomycetes play a vital role in decomposing organic matter, fixing atmospheric nitrogen, and mobilizing essential nutrients. This biological activity supports efficient nutrient cycling and reduces dependency on external inputs. Techniques such as composting, mulching, green manuring, and cover cropping are widely used to maintain soil fertility. These methods ensure a continuous supply of nutrients while protecting the soil from erosion and moisture loss. Organic carbon, a critical component of soil organic matter, improves soil stability and nutrient retention. Overall, healthy soils promote better root development, increased resistance to pests and environmental stress, and improved crop quality. Thus, soil health management is central to achieving sustainable productivity and high quali-

ty output in organic farming systems.

Organic Pest, Disease and Weed Management: Organic production technology relies on integrated approaches to manage pests and diseases without synthetic chemicals. Cultural practices such as crop rotation, intercropping, and use of resistant varieties are commonly adopted. Biological control methods utilize natural predators and microorganisms to control pests. Weed management is achieved through mechanical methods, mulching and crop competition. These practices help maintain ecological balance and reduce environmental risks.

Crop Quality Enhancement through Organic Practices: Organic farming significantly improves crop quality by enhancing nutritional value and ensuring residue-free produce. Organic crops often contain higher levels of vitamins, minerals, and antioxidants. They also exhibit better taste, aroma, and shelf life. The absence of chemical residues increases consumer confidence and meets international quality standards. Improved crop quality is a key factor driving the demand for organic products in global markets.

Certification and Standards: Certification is essential for marketing organic products, especially in export markets. Standards such as the National Programme for Organic Production (NPOP), USDA Organic, and European Union regulations ensure product authenticity. Certification involves strict guidelines on production, processing, and labeling. Traceability systems help maintain transparency and build consumer trust. Although certification can be costly and complex, it is necessary for accessing premium markets.

Export Potential of Organic Products: The global market for organic products has grown rapidly in recent years. Developed countries such as the United States, Germany, and Japan are major importers of organic produce. Consumers in these markets are willing to pay premium prices for high-quality, chemical-free products. Organic products such as spices, cereals, fruits, vegetables, tea, and coffee have strong export potential. Countries with favorable agro-climatic conditions can benefit significantly from organic farming by tapping into these markets.

Economic Aspects of Organic Farming: Organic farming reduces dependence on expensive chemical inputs, thereby lowering production costs over time. Although yields may decline during the initial transition period, long-term benefits include improved soil fertility and stable productivity. Premium pricing in organic markets enhances profitability. However, higher labor requirements and certification costs can pose challenges. Overall, organic farming offers a sustainable and economically viable alternative for farmers.

Challenges in Organic Production

Despite its benefits, organic farming faces several constraints. These include lack of awareness among farmers, limited availability of organic inputs, certification complexities, and inadequate market infrastructure. Initial yield reduction during the transition phase is another major concern.

Addressing these challenges requires effective extension services, research support, and improved access to markets and inputs.

Government Policies and Support

Government initiatives play a vital role in promoting organic farming. Various programs provide financial assistance, training, and infrastructure support to farmers. Promotion of organic clusters and export-oriented production systems can further enhance adoption. Policy support is essential to overcome barriers and ensure the growth of organic agriculture.

Future Prospects

The future of organic production technology is promising due to increasing global demand and growing awareness about sustainable agriculture. Advances in organic inputs, digital technologies, and supply chain management are expected to further enhance productivity and market access. Organic farming also contributes to climate change mitigation by improving carbon sequestration and reducing greenhouse gas emissions.

Conclusion

Organic production technology offers a sustainable approach to agriculture by improving crop quality, protecting the environment, and enhancing export potential. The increasing demand for organic products presents significant opportunities for farmers to access premium markets and improve their livelihoods. While challenges such as certification, initial yield reduction, and market access remain, they can be addressed through policy support, awareness programs, and technological advancements. Organic farming is not only a method of production but a pathway toward sustainable agricultural development and global food security.

Organic Production Technology for Enhancing Crop Quality and Export Potential

Abdur Rahman

Abstract

Organic production technology can be considered an appropriate form of agricultural production that can serve as a solution for all negative outcomes associated with agricultural technology based on chemicals. Excessive usage of chemicals in agriculture is associated with such problems as soil degradation, soil and water pollution, and many others. These factors make people think about the introduction of a more eco-friendly technology for growing crops. Organic production utilizes natural fertilizers and other materials, including composts, green manures, biofertilizers, and pest control methods. Organic production is designed to improve soil structure and enhance sustainability. Using organic agricultural production, people can grow food crops without using any dangerous synthetic chemicals. Organic food crops have been proven to be of high quality, since such foods usually contain no residues of chemicals used. In addition, organic foods have better taste and nutritional qualities; thus, they are in great demand all over the world, especially in developed countries. India is able to provide a number of agricultural products that would be sold abroad due to climatic advantages of this country and its traditions in agriculture. Moreover, Indian farmers know everything about growing certain crops under specific climatic conditions.

Introduction

Organic production technology is gaining increasing importance in modern agriculture as a sustainable alternative to conventional farming practices. The growing concerns over environmental degradation, soil health decline, and the presence of chemical residues in food have led to a shift towards eco-friendly and safe agricultural systems. Organic farming emphasizes the use of natural inputs such as compost, green manure, biofertilizers, and biological pest management to maintain soil fertility and crop productivity. This approach not only supports environmental sustainability but also improves the overall quality of agricultural produce. Organic crops are often preferred for their superior taste, higher nutritional value, and absence of harmful chemicals. With rising global awareness about health and food safety, the demand for organic products has increased significantly in international markets. As a result, organic production technology plays a crucial role in enhancing both crop quality and export potential, offering new economic opportunities for farmers and contributing to sustainable agricultural development.

Principles of Organic Farming

Organic production technology is built upon

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fundamental principles that promote sustainability and ecological harmony. These principles include:

Health: Maintaining the health of soil, plants, animals, and humans as one interconnected system.

Ecology: Working with natural ecosystems rather than dominating them.

Fairness: Ensuring equity in relationships between farmers, workers, and consumers.

Care: Adopting precautionary measures to protect the environment and future generations.

Organic farming avoids synthetic chemicals and instead focuses on enhancing natural biological processes. Crop diversity, soil conservation, and efficient resource utilization are central to this system.

Components of Organic Production Technology

Organic farming integrates several components that collectively improve soil fertility, crop health, and productivity:

Organic Manures: Organic manures such as farmyard manure (FYM), compost and vermicompost are essential for maintaining soil fertility. They improve soil structure, water-holding capacity, and microbial activity.

Green Manuring and Crop Rotation: Green manuring involves growing crops like legumes and incorporating them into the soil to enrich nitrogen content. Crop rotation helps break pest cycles, improve soil fertility, and reduce disease incidence.

Biofertilizers: Biofertilizers such as Rhizobium, Azotobacter, and phosphate-solubilizing bacteria enhance nutrient availability by fixing nitrogen and solubilizing phosphorus.

Biopesticides and Biological Control: Organic farming relies on natural pest control methods, including beneficial insects, microbial pesticides, and botanical extracts such as neem-based formulations.

Botanical Inputs: Plant-based products like neem oil, garlic extract, and cow-based formulations (e.g., panchagavya) are used to manage pests and improve plant health.

Soil Health and Nutrient Management

Soil is the foundation of organic farming. Organic production technology prioritizes the improvement of soil health through:

- ✓ Increased organic matter content
- ✓ Enhanced microbial diversity
- ✓ Improved soil structure and aeration
- ✓ Better nutrient cycling

Organic carbon plays a critical role in maintaining soil fertility. Practices such as composting, mulching, and cover cropping ensure a continuous supply of nutrients while reducing dependency on external inputs. Integrated nutrient management using organic sources helps sustain long-term productivity.

Organic Pest, Disease and Weed Management: Organic farming adopts an integrated approach to manage pests, diseases, and weeds without chemical inputs.

Pest and Disease Management

- ✓ Use of resistant varieties
- ✓ Crop rotation and intercropping

- ✓ Biological control using predators and parasites
- ✓ Application of biopesticides (e.g., *Bacillus thuringiensis*)

Weed Management

- ✓ Mechanical weeding
- ✓ Mulching
- ✓ Crop competition
- ✓ Manual removal

These methods not only control pests effectively but also maintain ecological balance and biodiversity.

Crop Quality Enhancement through Organic Practices

One of the most significant advantages of organic production technology is its positive impact on crop quality. Organic produce is often characterized by:

Higher nutritional value: Increased levels of vitamins, minerals, and antioxidants

Better taste and aroma: Due to balanced nutrient uptake and natural growth processes

Absence of chemical residues: Ensuring food safety

Improved shelf life: Due to stronger plant structure and reduced water content

Organic practices promote slow and steady crop growth, resulting in superior quality produce that meets consumer expectations in premium markets.

Certification and Standards

Certification is essential for marketing organic products, especially in international trade. Organic certification ensures that products are produced according to established standards.

Key Certification Systems

- ✓ National Programme for Organic Production (NPOP)
- ✓ USDA Organic (USA)
- ✓ European Union Organic Standards

Certification involves strict guidelines on production, processing, packaging, and labeling. Traceability is a crucial component, ensuring transparency throughout the supply chain. Although certification can be complex and costly, it is necessary to access high-value export markets.

Export Potential of Organic Products

The global market for organic products has expanded significantly over the past decade. Major importing regions include North America, Europe, and East Asia. Consumers in these regions are increasingly willing to pay premium prices for organic products due to their perceived health and environmental benefits.

Key Export Opportunities

- ✓ Organic cereals and pulses
- ✓ Spices (turmeric, ginger, pepper)
- ✓ Fruits and vegetables
- ✓ Tea and coffee

Countries with diverse agro-climatic conditions have a competitive advantage in producing a wide range of organic commodities. Export-oriented organic farming can significantly enhance farmers' income and contribute to national economic growth.

Economic Aspects of Organic Farming

Organic farming offers both economic adve-

ntages and challenges:

Advantages

- ✓ Reduced expenditure on chemical inputs
- ✓ Premium prices for organic produce
- ✓ Long-term soil fertility and productivity

Challenges

- ✓ Lower yields during the transition period
- ✓ Higher labour requirements
- ✓ Certification and compliance costs

Despite initial challenges, organic farming can be more profitable in the long run due to improved soil health and access to premium markets.

Challenges in Organic Production

The adoption of organic production technology faces several constraints:

- ✓ Lack of awareness and technical knowledge among farmers
- ✓ Limited availability of organic inputs
- ✓ High certification costs
- ✓ Inadequate market infrastructure
- ✓ Risk of lower yields during initial years

Addressing these challenges requires coordinated efforts from governments, research institutions and private stakeholders.

Government Policies and Support

Government support plays a crucial role in promoting organic farming. Various initiatives focus on:

- ✓ Financial assistance and subsidies
- ✓ Training and capacity building
- ✓ Development of organic clusters
- ✓ Promotion of export-oriented production

Such policies help farmers transition from conventional to organic farming and improve market access.

Future Prospects

The future of organic farming looks promising due to:

- ✓ Increasing global demand for organic products
- ✓ Growing awareness of environmental sustainability
- ✓ Advancements in organic technologies
- ✓ Integration with digital agriculture and supply chain systems

Organic farming also contributes to climate change mitigation by enhancing carbon sequestration and reducing greenhouse gas emissions.

Conclusion

Organic production technology represents a holistic and sustainable approach to agriculture that addresses both environmental and economic concerns. By focusing on natural processes, soil health, and ecological balance, it enhances the quality of agricultural produce while ensuring long-term sustainability. The growing demand for organic products in international markets provides significant opportunities for farmers to increase their income through exports. Although challenges such as certification, initial yield reduction, and market access exist, these can be overcome through proper policy support, training, and infrastructure development. In conclusion, organic production technology is not only a pathway to producing high-quality, safe, and nutritious food but also a strategic approach to strengthening export potential and achieving sustainable agricultural development.

Organic Production Technology and Carbon Sequestration: A Step towards Climate Change Mitigation

Bhumika Verma

Abstract

Climate change, driven largely by greenhouse gas emissions, poses a serious threat to global agriculture and ecosystems. Organic production technology has emerged as a sustainable alternative to conventional farming by enhancing soil health, reducing emissions, and promoting biodiversity. One of its most significant contributions is carbon sequestration the process of capturing atmospheric carbon dioxide (CO_2) and storing it in soil organic matter.

Introduction

Agriculture is both a contributor to and a victim of climate change. Conventional farming practices rely heavily on synthetic fertilizers and fossil fuels, leading to increased greenhouse gas emissions. In contrast, organic production systems focus on ecological balance and sustainability.

Organic Production Technology

Organic technology isn't just "farming without chemicals"; it is a sophisticated system of biological management.

Principles of Organic Farming

Organic production is based on ecological balance, soil health enhancement, biodiversity conservation, and sustainable resource use. It is a suite of strategic interventions designed to maximize the Earth's natural regenerative cycles.

Key Practices Elucidated

Crop Rotation: By changing plant families each season, farmers break pest cycles and ensure different root structures explore various soil depths, distributing carbon throughout the soil profile.

Composting: This transforms "waste" into "gold." Composting stabilizes carbon; instead of organic matter rotting and releasing CH_4 (methane), it is converted into stable humus.

Green Manuring: Planting legumes (like Alfalfa) specifically to be ploughed back into the soil acts as a "solar-powered" fertilizer, sequestering carbon while naturally adding nitrogen.

Biological Pest Management: By eliminating petroleum-based pesticides, we protect the soil biota; the "micro-engineers" responsible for carbon humification.

Practice	Description	Climate Benefit
Crop Rotation	Alternating crops in sequence	Enhances soil fertility and carbon storage
Composting	Use of organic waste as fertilizer	Increases soil organic matter
Green Manuring	Growing legumes for soil enrichment	Fixes nitrogen and improves SOC
Biological Pest Control	Use of natural predators	Reduces chemical emissions
Cover Cropping	Growing crops to cover soil	Prevents erosion and stores carbon

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The Science of Carbon Sequestration

Carbon sequestration is the long-term storage of atmospheric CO_2 in the soil to mitigate global warming.

The Biological Carbon Pump: Nature's Hidden Climate Solution

The biological carbon pump is a natural process through which carbon dioxide (CO_2) is captured from the atmosphere and transferred into the soil, where it can remain stored for decades or even centuries. This process is driven by plants, soil microorganisms and complex biochemical interactions occurring beneath the soil surface. It plays a crucial role in carbon sequestration and climate change mitigation, particularly in organic farming systems.

Photosynthesis: Capturing Atmospheric Carbon

Photosynthesis is the primary entry point of carbon into the terrestrial ecosystem. Green plants absorb carbon dioxide (CO_2) from the atmosphere through tiny pores in their leaves called stomata. Using sunlight as an energy source, plants convert CO_2 and water into glucose (a simple sugar) and oxygen. This process can be represented as:

$$6CO_2 + 6H_2O + \text{sunlight} \rightarrow C_6H_{12}O_6 + 6O_2$$

The glucose produced is used by plants for growth and development, forming structural components such as cellulose, lignin, and starch. A significant portion of this fixed carbon is eventually transferred below ground, making plants the first critical agents in carbon sequestration.

Key Insight: Plants act as natural "carbon vacuum cleaners," continuously removing CO_2 from the atmosphere and converting it into organic matter.

Root Exudation: Feeding the Rhizosphere

Not all the carbon fixed during photosynthesis is retained in plant tissues. Remarkably, plants actively release a substantial portion (up to 20-40%) of this carbon into the soil through their roots. This process is known as root exudation. These exudates include:

- ✓ Simple sugars (glucose, fructose)
- ✓ Amino acids
- ✓ Organic acids
- ✓ Enzymes and secondary metabolites

The region of soil influenced by these root secretions is called the rhizosphere, a highly dynamic and biologically active zone. In the rhizosphere:

- ✓ Soil microbes (bacteria, fungi, actinomycetes) utilize these carbon compounds as food.
- ✓ Microbial populations increase rapidly, enhancing nutrient cycling.
- ✓ Beneficial symbiotic relationships form, such as with mycorrhizal fungi, which extend the root system and improve nutrient uptake.

Key Insight: Root exudation is a strategic investment by plants to get benefitted from soil microbes, which in return help in nutrient acquisition and soil carbon stabilization.

Microbial Transformation and Soil Food Web Dynamics

Once carbon enters the soil through exudates and plant residues, it becomes part of the soil food web. Microorganisms decompose organic material

and transform it into more stable forms. This involves:

Primary decomposition: Breakdown of fresh plant material by bacteria and fungi

Secondary consumption: Protozoa and nematodes feeding on microbes

Tertiary interactions: Predatory organisms regulating microbial populations. During these processes:

- ✓ Some carbon is released back into the atmosphere as CO_2 through respiration.
- ✓ A portion is converted into microbial biomass.
- ✓ The remaining carbon is transformed into more complex, stable compounds.

Humification: Formation of Stable Soil Organic Carbon (SOC)

Humification is the final and most critical stage of the biological carbon pump. It refers to the transformation of decomposed organic matter into humus, a stable and long-lasting component of soil organic carbon (SOC). Humus is:

- ✓ Dark in color
- ✓ Rich in carbon
- ✓ Resistant to further decomposition
- ✓ Capable of persisting in soil for decades to centuries

This stable carbon is often physically protected within soil aggregates or chemically bound to minerals such as clay, making it less susceptible to microbial breakdown.

Forms of Soil Organic Carbon

Active Carbon: Easily decomposable (short-term storage)

Slow Carbon: Intermediate stability

Passive Carbon (Humus): Highly stable, long-term storage

Key Insight: Humification locks carbon into the soil, effectively removing it from the atmospheric cycle and contributing to long-term climate mitigation.

Process

Atmospheric CO_2

↓

Photosynthesis (Plants)

↓

Plant Biomass (Roots & Shoots)

↓

Organic Matter Decomposition

↓

Soil Organic Carbon Storage

Role of Organic Farming in Carbon Sequestration

Organic farming increases soil organic matter, reduces greenhouse gas emissions, and improves soil health. Organic systems outperform conventional ones in carbon storage primarily because they prioritize Soil Organic Matter (SOM).

Stable Carbon Pools: Organic farming tends to build "recalcitrant" carbon-carbon that stays in the soil for decades or centuries rather than being released quickly.

The Microbial Factor: Organic soils have higher microbial biomass. These microbes bind the soil particles together, trapping carbon in aggregates where it is protected from erosion and oxidation.

Comparative advantages

Parameter	Organic Farming	Conventional Farming
Soil Carbon	High	Low
GHG Emissions	Lower	Higher
Soil Fertility	Improved	Degraded over time
Biodiversity	High	Low

Climate Change Mitigation Potential

Beyond carbon storage, organic farming systems contribute to global cooling through multiple indirect mechanisms. One such factor is the albedo effect, where soils enriched with organic matter develop improved structure and vegetation cover, which can influence surface reflectivity and help regulate local microclimates. Another important aspect is energy efficiency. Organic agriculture avoids the use of synthetic fertilizers and chemicals, the production of which depends heavily on fossil fuels like natural gas. By eliminating these inputs, organic systems significantly reduce the hidden carbon footprint associated with everyday food products such as bread and vegetables. Additionally, organic farming enhances water resilience. An increase in soil organic carbon (SOC) improves the soil's capacity to retain water, approximately 20,000 extra gallons per acre for every 1% rise in SOC. This increased water-holding ability helps buffer agricultural systems against extreme weather events such as droughts and floods, which are becoming more frequent due to climate change.

Challenges and Limitations

While the benefits are significant, it is equally important to acknowledge the challenges associated with organic systems. One major concern is the yield gap, as farms transitioning to organic practices may initially experience a reduction in productivity of around 10-20%. This requires careful planning and management to maintain food security during the transition phase. Another limitation is the higher labor demand. Organic farming relies heavily on manual and biological practices such as weeding, compost preparation, and crop management, making it more labor-intensive. This can pose difficulties, particularly in regions where labor is scarce or expensive. Additionally, verification of carbon sequestration remains a complex issue. Accurately measuring the amount of carbon stored in soil involves advanced scientific methods that are often costly and technically demanding. As a result, many organic farmers face challenges in accessing carbon credit markets, which depend on reliable measurement and certification systems.

Green Manure in Organic Farming Systems: A Sustainable Approach to Soil Management

Kumar Rigved Rishi

Abstract

Soil health degradation is one of the most important problem faced by the farmers. Due to it the land is becoming barren. Therefore, to overcome this problem the concept of organic farming came into existence. Therefore, green manuring is one of the most important type of manure used in organic farming. Green manures are fertility building crops and may be broadly defined as crops grown for the benefit of the soil. The green manuring crops improve the humus, organic carbon, nitrogen and soil microbial growth. Green manuring can bring a number of advantages to the grower. It leads to the addition of organic matter to the soil. Green manuring crops increase the biological activity in the soil. These crops improve soil structure.

Introduction

Green manures are crops grown specifically for building and maintaining soil fertility and structure, though they may also have other functions. They are normally incorporated back into the soil, either directly, or after removal and composting.

- ✓ This practice was initiated in China as early as 1134 B.C.
- ✓ In 1988-89, 6.2 million ha. were reported to be under green manuring comprising 60% area and 80% area was located in 6 (six) State of U.P., A.P., M.P., Karnataka, Orissa and Punjab.

Green Manuring

It is a practice of plugging in the green plants tissue grown in the field or adding green plants with tender twigs or leaves from outside and incorporating them into the soil for improving the physical structure as well as fertility of the soil.

Importance of Green Manuring

- ✓ Green Manuring contributes 40 to 80 kg nitrogen ha^{-1}.
- ✓ Besides supplying nitrogen, it prevents loss of nitrogen by leaching and erosion.
- ✓ Vigorous root system of green manure keeps the soil particles bound together.
- ✓ Green manure reclaims saline and alkaline soils.
- ✓ Some green leaf manure crops serve as fodder.
- ✓ The growth of green manure crops is very fast

- **Enhances soil structure:** Green manuring improve the tilth and porosity. This helps to increase the aeration, drainage, and water-holding capacity of the soil.
- **Improves soil moisture retention:** Green manuring improves the moisture retention capacity
- **Reduces soil erosion:** Green manuring helps

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in increasing the organic matter content of the soil.

- **Reduces weed growth:** Green manuring helps to suppress weed population.
- **Increases water infiltration:** Green manuring helps to increase the infiltration rate of water

✓ Improves soil aggregation

- **Improves soil biological activity:** Green manuring helps to improve the biological activity of the soil. Benefits microorganisms and earthworms in the soil.
- Improves crop yields

✓ Reduces the need for chemical fertilizers

- **Helps to reduce greenhouse gas emissions:** Green manuring helps to reduce the emissions of greenhouse gases like carbon dioxide, methane, and nitrous oxide, as it helps to increase the carbon content of the soil.
- **Enhances carbon sequestration:** Green manuring helps to enhance carbon sequestration by increasing the organic matter content of the soil. This helps to reduce atmospheric carbon dioxide concentrations.
- **Enhances crop diversity:** Green manuring helps to enhance crop diversity by improving the fertility of the soil.

Desirable Characteristics Green Manure Crops

For green manure crops to be agro-nominally attractive and economically viable, the plants should have the following characteristics:

✓ Rapid and aggressive initial growth and efficient soil cover.

✓ Producing large amounts of bio-mass (green and dry matter)

✓ Capacity to recycle nutrients

✓ Ease of establishment and management in the field

✓ Resistance to attacks by pests and diseases and not act as a host

Green Manure is of two types

✓ Green leaf manure

✓ In-situ Green manure

Conclusion

Green manuring is an important and essential form of organic farming and is the practice of growing and incorporating green manure crops into the soil to improve the fertility and physical structure of the soil. Green manuring is a way of adding nutrients to the soil and improving its fertility. It can be used to reduce the need for external fertilizers, increase soil organic matter content, improve soil structure, and reduce erosion into the soil. The cover crops are typically legumes, grasses, or other plants which are capable of fixing nitrogen from the atmosphere and adding it to the soil. The crop is grown for a short period of time and then plowed back into the soil.

Enhancing Crop Productivity through Organic Inputs and Sustainable Production Technologies

Kamal Kishor Pradhan and Amit Anand

Introduction

Agriculture is the backbone of India's economy and a primary source of livelihood for a majority of the population. However, over-reliance on chemical fertilizers and pesticides has resulted in soil degradation, reduced biodiversity, water pollution, and declining productivity over time. Sustainable agriculture focuses on maintaining productivity while conserving natural resources for future generations. Organic inputs and sustainable production technologies provide an eco-friendly and economically viable approach to agriculture. They improve soil fertility, enhance crop yield in the long term, and reduce environmental risks.

Organic Inputs in Agriculture

Organic inputs include natural substances used to improve soil fertility and crop growth. These include farmyard manure (FYM), compost, vermicompost, green manure, biofertilizers and biopesticides. FYM improves soil texture and nutrient availability. Compost and vermicompost enhance microbial activity and soil structure. Green manuring improves nitrogen content in the soil. Biofertilizers such as Rhizobium and Azotobacter increase nutrient availability, while biopesticides like neem-based products control pests without harming beneficial organisms.

Benefits of Organic Inputs

Organic inputs improve soil structure, increase water retention, and enhance microbial activity. They reduce dependency on chemical fertilizers and improve crop quality. Long-term use of organic inputs leads to sustainable productivity, improved soil health, and reduced environmental pollution. They also help in maintaining ecological balance and biodiversity.

Sustainable Production Technologies

Sustainable production technologies aim to optimize resource use and maintain long-term agricultural productivity. Integrated Nutrient Management (INM) combines organic and chemical fertilizers to maintain soil fertility. Integrated Pest Management (IPM) uses biological and cultural methods to control pests. Conservation agriculture promotes minimum tillage, crop rotation, and residue retention. Precision farming uses modern technologies such as GPS and sensors to optimize input use, while efficient irrigation systems like drip and sprinkler methods conserve water and improve productivity.

Water Management and Crop Practices

Water is a critical resource in agriculture. Efficient irrigation methods like drip and sprinkler irrigation help conserve water and improve crop

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yield. Crop rotation and diversification improve soil fertility and break pest cycles. Multi-cropping systems enhance productivity and provide economic stability to farmers.

Role in Enhancing Productivity: Organic inputs enhance soil health by improving structure, aeration, and nutrient availability. They promote microbial activity, which helps in nutrient cycling. Although initial yields may be slightly lower, long-term productivity improves significantly. Organic farming systems are more resilient to climate change and environmental stress.

Challenges in Adoption

Despite the benefits, several challenges hinder the adoption of organic inputs and sustainable practices. These include lack of awareness, limited availability of organic inputs, higher labor requirements and initial yield reduction. Market access and certification for organic produce are also major challenges faced by farmers.

Government Initiatives

The Government of India has introduced various schemes to promote sustainable agriculture. These include Paramparagat Krishi Vikas Yojana (PKVY), National Mission for Sustainable Agriculture (NMSA), Soil Health Card Scheme, and Pradhan Mantri Krishi Sinchai Yojana (PMKSY). These initiatives support farmers in adopting organic inputs, improving soil health, and enhancing water use efficiency.

Case Studies and Field Impact

Field studies show that farmers using organic inputs and sustainable technologies have improved soil fertility, reduced input costs, and increased resilience to climate variability. Examples include the use of vermicompost in vegetable farming and drip irrigation in horticulture crops, which have shown significant improvements in yield and quality.

Future Prospects

The future of agriculture lies in sustainable practices. Increasing awareness about environmental issues and health concerns is driving demand for organic produce. Technological advancements and policy support will further promote sustainable agriculture. Integration of traditional knowledge with modern techniques will play a key role.

Sustainable Agriculture for Improved Productivity and Soil Health

- ✓ Agriculture in modern times faces multiple challenges including soil degradation, declining productivity, water scarcity, and environmental pollution. The excessive use of chemical fertilizers and pesticides has disturbed ecological balance and reduced soil fertility over time. Sustainable agriculture, supported by organic inputs, provides a viable solution.
- ✓ Organic inputs such as farmyard manure, compost, vermicompost, green manure, and biofertilizers improve soil health by increasing organic matter and microbial activity. Sustainable production technologies like INM, IPM, conservation agriculture, and precision farming ensure efficient resource utilization.
- ✓ Soil health is crucial for crop productivity.

Organic matter improves soil structure, aeration, and water retention. Microorganisms help in nutrient cycling.

- ✓ Efficient irrigation systems such as drip and sprinkler irrigation conserve water and improve yield. Crop rotation and diversification enhance soil fertility and reduce pest cycles.
- ✓ Despite challenges like lack of awareness and initial yield reduction, long-term benefits of organic farming are significant. Government schemes support adoption of sustainable practices.

In conclusion, organic inputs and sustainable technologies ensure productivity, environmental protection, and farmer welfare.

Makhana: A Functional Food with Nutritional and Therapeutic Value

Priyanka Deka

Abstract

Euryale ferox Salisb. commonly known as makhana, is an aquatic plant of significant nutritional, medicinal, and economic importance. Its seeds are rich in carbohydrates, proteins, minerals, and bioactive compounds, which contribute to various health benefits, including antioxidant, antidiabetic, and cardioprotective effects. Owing to its low fat content and low glycemic index, makhana is widely recognized as a healthy and functional food. It is also utilized in a variety of value-added products such as ready-to-eat snacks, protein bars, and traditional dishes. Overall, makhana represents a promising nutraceutical resource with expanding applications in the food and pharmaceutical industries.

Introduction

Euryale ferox Salisb. commonly known as fox nut, gorgon nut, or makhana, is an annual aquatic plant belonging to the family Nymphaeaceae. It is the sole extant species of the genus Euryale and is native to tropical and subtropical freshwater regions of South and East Asia, including India, China, Japan, and Korea. The plant typically grows in stagnant water bodies such as ponds and lakes and is characterized by its large floating leaves and prickly structures. The seeds of *E. ferox* are highly valued for their nutritional and functional properties, being rich in carbohydrates, proteins, minerals, and bioactive compounds. Studies have reported the presence of phenolic compounds, flavonoids, and antioxidants in the seeds, which contribute to their health-promoting potential (Liaquat *et al.*, 2022; Kapoor *et al.*, 2022). These bioactive constituents are associated with various pharmacological activities, including anti-oxidant and hypoglycemic effects, making makhana a suitable component of low glycemic and functional diets (Liaquat *et al.*, 2022). In addition to its nutritional importance, *E. ferox* holds significant economic value, particularly in regions such as Bihar, India, where its cultivation supports rural livelihoods. Owing to its combined nutritional, medicinal, and economic significance, the plant has gained increasing attention as a potential functional food and nutraceutical resource (Kapoor *et al.*, 2022).

Health Benefits of Makhana

- ✓ It has high fibre content, has a low glycemic index and phytochemical constituents. It is low in fat and rich in protein.
- ✓ Prevents high blood pressure and controls blood sugar levels.
- ✓ Including Makhana in the regular diet prevents early ageing and reduces the greying of hair and wrinkles.
- ✓ Its high calcium content, along with low saturat-

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ed fat helps strengthens bones and muscles.

- ✓ Makhana contains a low amount of sodium and a high amount of potassium, which is good for cardiac health.

Pharmaceutical Properties

- ✓ Antioxidant activity
- ✓ Antimicrobial activity
- ✓ Antidiabetic activity
- ✓ Antidepressent activity
- ✓ Cardioprotective activity
- ✓ Anticancer activity

Nutritional composition of *Euryale ferox* Salisb. Seed (Devi, 2022)

Nutrients	Popped Seeds	Roasted Seeds
Fat (% by wt.)	0.5	0.68
Protein (% by wt.)	8.7	14.57
Carbohydrates (% by wt.)	79.8	79.4
Phosphorus (mg/100 g)	53.2	56.4
Potassium (mg/100g)	42.0	47.2
Iron (mg/100 g)	1.4	12.7
Calcium (mg/100 g)	18.5	19.2
Magnesium (mg/100 g)	13.9	26.3
Sodium (mg/100 g)	71.0	23.8
Copper (mg/ 100 g)	0.5	-
Manganese (mg/100 g)	1.3	-
Zinc (mg/100 g)	1.1	1.8

Makhana based Food Products

- ✓ Ready to Eat Snacks.
- ✓ Used in protein bars, health foods and as a health snack alternative to popcorn.
- ✓ Masala Makhana: Roasted with ghee or oil adding spices.
- ✓ Makhana Salad.
- ✓ Makhana Kheer.

Conclusion

Euryale ferox (makhana) stands out as a valuable aquatic crop due to its rich nutritional composition and diverse therapeutic properties. Its role in promoting health, along with its suitability for developing various food products, highlights its growing importance in modern diets. Moreover, its cultivation contributes significantly to the livelihood of farmers, especially in regions like Bihar. With increasing awareness about healthy eating and functional foods, makhana has strong potential for further development and wider utilization in both the food and pharmaceutical sectors.

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Role of Organic Farming in Promoting Biodiversity and Ecological Balance in Agro-ecosystems

Abhishek Kumar

Introduction

Organic farming is a sustainable agricultural system that emphasizes ecological balance, biodiversity conservation, and soil health. It avoids synthetic fertilizers, pesticides, and genetically modified organisms. Instead, it relies on natural inputs and ecological processes. This system is increasingly important in addressing environmental challenges such as biodiversity loss, soil degradation and climate change. Organic farming contributes to the development of resilient agro-ecosystems that support long-term agricultural productivity and environmental sustainability.

Agro-ecosystems and Biodiversity: An agro-ecosystem consists of living organisms interacting with their physical environment within an agricultural setting. Biodiversity includes genetic, species and ecosystem diversity. Organic farming enhances all these levels by promoting diverse cropping systems, maintaining habitats and minimizing chemical inputs. This diversity stabilizes ecosystems and improves productivity.

Enhancement of Biodiversity: Organic farming supports biodiversity through crop rotation, intercropping, mixed farming, and agroforestry. These practices create habitats for pollinators, birds, and beneficial insects. The absence of harmful chemicals allows natural ecosystems to thrive, increasing resilience and ecological balance.

Soil Health: Soil is a living ecosystem rich in microorganisms. Organic farming improves soil fertility using compost, green manure, and organic inputs. This enhances microbial diversity, nutrient cycling, and soil structure. Healthy soil is essential for sustaining biodiversity and agricultural productivity.

Pest Management: Organic farming uses biological pest control methods such as predators and parasites. Crop diversification and ecological balance reduce pest outbreaks naturally. This minimizes environmental damage and protects non-target organisms.

Water Conservation: Organic practices such as mulching and cover cropping improve water retention and reduce runoff. Avoiding chemicals prevents water pollution and protects aquatic biodiversity. Efficient water use is critical for sustainable agriculture.

Climate Change Mitigation: Organic farming reduces greenhouse gas emissions and increases carbon sequestration in soil. Practices like composting and agroforestry improve resilience against climate variability and extreme weather conditions.

Genetic Diversity: Organic farming preserves traditional crop varieties that are more resilient to

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local conditions. This ensures food security and reduces dependency on uniform crop systems vulnerable to pests and diseases.

Case Studies

Regions practicing organic farming show higher biodiversity levels. For instance, organic farming initiatives have improved ecological balance and farmer livelihoods. These examples highlight the effectiveness of sustainable practices.

Challenges

Organic farming faces challenges such as lower initial yields and higher labor requirements. However, awareness, training, and policy support can help overcome these barriers and promote wider adoption.

Conclusion

Organic farming plays a crucial role in promoting biodiversity and ecological balance. It aligns agricultural practices with natural systems, ensuring sustainability and environmental protection for future generations.

Annual Chrysanthemum (*Glebionis coronaria* L.): A Promising Ornamental Crop for Diversified Floriculture Systems

Sachin and Aksh

Introduction

Chrysanthemum, commonly known as Guldaudi in India, is among the most admired ornamental flowers cultivated globally for its stunning floral aesthetics, wide color range, and cultural significance. The genus belongs to the family Asteraceae and represents an important group used in gardens, flower arrangements, and as cut flowers. Among the various types grown worldwide, the annual chrysanthemum (*Chrysanthemum coronarium* L.) occupies a special niche due to its fast growth, vibrant blooms, and adaptability to diverse climatic conditions. Annual chrysanthemum is valued for its rapid life cycle and utility in seasonally changing garden compositions. Unlike perennial chrysanthemums, which require careful maintenance and propagation, annual types fit well within the seasonal planting schedule, making them a vital choice for bedding plants and landscape beautification programs.

Origin and Distribution

The annual chrysanthemum is believed to have originated in the Mediterranean region and parts of Asia, primarily China and Japan, where the plant has been cultivated for centuries. Its cultivation later spread to Europe and other regions of the world, including India. Today, annual chrysanthemum is extensively grown in tropical, subtropical, and temperate climates for ornamental as well as edible purposes, as young leaves and shoots are sometimes consumed as vegetables in East Asian cuisines.

Botanical Description

Annual chrysanthemum is an herbaceous plant, usually growing 30 to 90 cm tall, depending on the variety and growing conditions. The stem is erect, branched, and sometimes slightly ribbed. Leaves are alternate, pinnately divided, with a characteristic strong aroma. Flowers are borne in terminal heads, either solitary or in loose clusters, with a wide range of colors including yellow, white, orange, and bi-colored types. The inflorescence is a capitulum composed of ray florets on the periphery and disc florets in the center. The fruits are small, dry achenes that contain a single seed. The plant completes its life cycle within one season, from germination to seed production, which typically spans around 90 to 120 days.

Importance and Uses

Annual chrysanthemum serves several impo-rtant roles in horticulture, economics and culture.

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Ornamental use: Widely planted in gardens, borders, and pots for seasonal color displays.

Cut flower industry: Valued for long-lasting blooms and aesthetic appeal.

Edible and medicinal uses: In several Asian regions, young leaves and flowers are used in salads and teas for their antioxidant and anti-inflammatory properties.

Cultural significance: Chrysanthemum symbolizes joy, optimism, and longevity in East Asian traditions and is used in religious ceremonies and decorations.

Climatic Requirements

Annual chrysanthemum is a cool-season flower crop that thrives best in regions with mild climates. An ideal temperature range for growth is 15°C to 25°C. High temperatures adversely affect flower formation and color intensity. Photoperiod also influences flowering; the plant generally prefers short-day conditions for floral initiation. In tropical climates, chrysanthemum is usually grown during winter months when days are short and temperatures are moderate. Excess rainfall, frost, or extreme heat are unfavorable for successful growth and flowering.

Soil and Land Preparation

The crop grows best in well-drained loamy soil rich in organic matter. A soil pH between 6.0 and 7.0 is ideal. Heavy clay or highly alkaline soils should be avoided as they interfere with root aeration and nutrient uptake. Land should be thoroughly plowed and brought to a fine tilth before transplanting. Incorporation of well-decomposed farmyard manure (20-25 tons ha^{-1}) during field preparation improves soil fertility and moisture retention. Raised beds are commonly used for better drainage.

Propagation

Annual chrysanthemum is propagated by seed. Seeds are sown in nursery beds or trays about 4-6 weeks before transplanting. The seed rate is approximately 1.0-1.5 kg ha^{-1}. Seeds are sown thinly and lightly covered with a fine layer of soil. The nursery should be watered gently and kept under partial shade until germination, which usually occurs within 7-10 days.

Transplanting

Seedlings are ready for transplanting when they reach 6-8 cm height and possess 4-6 true leaves. Transplanting is done during the cooler part of the day, preferably in the evening or on cloudy days to avoid transplant shock. The recommended spacing is 30 cm between rows and 25 cm between plants, depending on variety.

Manures and Fertilizers

For optimal growth and flowering, a balanced nutrient supply is essential. A general fertilizer recommendation is:

Farmyard manure: 20-25 tons ha^{-1} (basal)

Nitrogen: 100 kg ha^{-1}

Phosphorus: 50 kg ha^{-1}

Potassium: 50 kg ha^{-1}

Half of the nitrogen and full doses of phosphorus and potassium are applied at planting, while the remaining nitrogen is applied as top dressing after 4-6 weeks to promote healthy vegetative growth and better flowering.

Irrigation Management

Proper irrigation ensures robust plant growth and prolonged blooming. The crop demands moderate but regular watering. Excessive moisture should be avoided to prevent root and stem rot.

- ✓ During initial establishment, light and frequent irrigation is preferred.
- ✓ In the flowering stage, irrigation frequency is adjusted according to soil moisture conditions.
- ✓ Overhead irrigation should be avoided in full bloom to prevent petal discoloration.

Intercultural Operations

Weeding, hoeing, and pinching are necessary intercultural operations.

Weeding: Regular weeding at 15-20-day intervals helps maintain soil aeration and reduces nutrient competition.

Pinching: Removal of the apical bud at the 4-6 leaf stage induces branching and enhances flower production.

Staking: For tall varieties, stakes are provided to support plants and prevent lodging.

Growth and Flowering Behaviour

Growth of annual chrysanthemum involves three major phases vegetative growth, floral initiation and flowering. Temperature and photoperiod play key roles in determining the timing of these stages. Short days and moderate temperatures trigger flower bud initiation, which is followed by blooming within 40-60 days after transplanting.

Harvesting and Post-Harvest Handling

Flowers should be plucked early in the morning and handled carefully to avoid bruising. They can be stored under cool conditions for short-term preservation or used immediately for decoration and marketing.

Yield

Under optimum conditions, an average yield of 8,000-10,000 kg of loose flowers or 1.5 to 2 lakh cut flowers per hectare can be obtained, depending on the variety and management practices.

Ornamental and Landscape Use

Chrysanthemum occupies a premier place among garden flowers. Annual types are extensively used for:

- ✓ Bedding in public parks and institutional gardens.
- ✓ Border planting along walkways.
- ✓ Potted display on terraces and balconies.
- ✓ Mass planting for visual appeal in lawns and roundabouts.

Their bright hues and simultaneous blooming make them excellent for designing seasonal flower beds and creating striking colour contrasts in garden compositions.

Economic Importance

Annual chrysanthemum contributes significantly to the ornamental plant industry. It provides livelihood opportunities for small-scale farmers, nursery operators, and florists. In India, it is a major winter season flower crop and a source of export revenue for fresh and dried flower markets.

Environmental Benefits

The cultivation of chrysanthemum enhances

landscape aesthetics and contributes to ecological stability. Planting along urban roadsides, parks, and institutional premises aids in air purification, soil protection and biodiversity support through pollinator attraction.

Challenges in Cultivation

- ✓ Short vase life of certain varieties.
- ✓ Labor-intensive management practices.
- ✓ Climate sensitivity, especially to high temperature and humidity.

Conclusion

Annual chrysanthemum is a valuable ornamental crop combining beauty, utility, and cultural charm. With its vast adaptability and aesthetic diversity, it continues to play a vital role in floriculture and landscaping. Scientific cultivation practices, varietal improvement, and efficient post-harvest handling can further enhance its productivity and market potential in both domestic and international floriculture sectors.

Urban Horticulture and Rooftop Gardening

Adarsh Raj

Introduction

Cities worldwide are grappling with mounting concerns over food security, environmental decline, and a diminished quality of life, driven largely by rapid urbanization and the proliferation of concrete-heavy landscapes. In response, urban horticulture the cultivation of fruits, vegetables, ornamentals and herbs within city limits has emerged as an essential pathway toward creating greener, more sustainable living environments. Rooftop gardening stands out as a particularly impactful method, converting underutilized building tops into vibrant, productive green spaces that yield fresh produce, stabilize microclimates, and boost urban biodiversity. This article examines the significance and practical implementation of these practices, emphasizing their role in cultivating resilient urban ecosystems.

Concept and Importance of Urban Horticulture

At its core, urban horticulture involves the intensive farming of high-value crops such as fruits, vegetables, flowers, and various herbs within both fully urban and peri-urban settings. It leverages highly efficient techniques, including container gardening, vertical farming, the use of raised beds, and hydroponic systems, to maximize the utility of constrained spaces like balconies, small terraces, vacant lots, and flat roofs. By doing so, urban horticulture serves as a critical mechanism for bolstering local food security, decreasing an over-reliance on distant agricultural suppliers, and significantly shortening food supply chains. This not only results in fresher, more nutrient-dense produce for city dwellers but also creates a valuable buffer against the potential failures of conventional food distribution systems. Beyond the immediate benefits of food production, these horticultural practices play an essential role in environmental stewardship by purifying the air, actively mitigating the urban heat-island effect, and supporting biodiversity through the creation of essential green corridors for pollinators and small urban wildlife.

Rooftop Gardening: Transforming Unused Spaces

Rooftop gardening offers a powerful solution to the problem of underutilized space in high-density urban environments by repurposing flat, dormant building tops into vibrant, productive landscapes. Through the strategic use of soil-based beds, containers, or elevated structures, these spaces can be dedicated to growing a wide array of vegetables, fruits, and herbs, or to establishing green roofs that enhance building insulation and reduce the energy needed for climate control. In many modern cities, these rooftops represent a massive, untapped land

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resource; studies indicate that the suitable roof area in some urban zones is equivalent to hundreds of hectares of potential, yet currently vacant, green space. Furthermore, when engineered with care, these rooftop systems serve a functional role in stormwater management by effectively absorbing rainfall, reducing runoff, and delaying peak discharge, which, in turn, helps to lower the risk of flooding in urban catchment areas.

Fig. 1: Rooftop gardening

Environmental and Social Benefits

The environmental contributions of urban horticulture and rooftop gardening are extensive, encompassing carbon sequestration, the filtration of airborne pollutants, and the establishment of essential microhabitats for birds, insects, and other beneficial organisms. Green roofs and rooftop gardens have consistently demonstrated their ability to lower building surface temperatures, which directly translates into reduced energy demands for air conditioning and improved local thermal comfort throughout the heat of summer. Beyond these ecological impacts, there is a profound social dimension to this practice: community engagement in gardening fosters a sense of collective purpose, reduces personal stress, and significantly boosts mental well-being by providing much-needed access to nature amidst concrete-heavy environments. Furthermore, school-based or community-led roof-top gardens serve as powerful educational platforms, acting as outdoor classrooms where children and adults alike learn first hands about ecological principles, the realities of climate change, and the importance of responsible, sustainable resource management.

Key Practices and Design Considerations

Successful urban horticulture relies on space-efficient strategies like vertical gardening and hydroponics, though rooftop installations require rigorous attention to structural factors like load-bearing capacity, drainage, and wind protection. To ensure long-term viability, especially in warmer climates, practitioners should prioritize water conservation through techniques such as mulching, drip irrigation, and rainwater harvesting. Integrating organic inputs, such as compost derived from household waste, and employing integrated pest management are crucial for maintaining the environmental integrity of these gardens.

Policy and Future Scope

Policymakers and urban planners are increasingly viewing rooftop gardens as vital “green infrastructure” that should be woven into building codes and climate-adaptation strategies. Pilot initiatives in major Indian cities like Delhi, Mumbai, and Bengaluru have already proven that rooftop vegetable gardening is both technically feasible and

socially popular. Moving forward, the adoption of advanced technologies such as automated irrigation and smart-sensor nutrient monitoring will likely increase yields and make these systems even more effective. With the right blend of supportive policy, public awareness, and hands-on training, rooftop horticulture has the potential to fundamentally transform Indian cities into more livable, climate-resilient, and food-secure landscapes.

Conclusion

Urban horticulture and rooftop gardening represent practical, sustainable, and highly effective approaches to making modern cities greener, healthier and significantly more self-reliant. As global urban populations continue to climb, the integration of these gardening practices into mainstream city planning is essential for addressing the environmental and social challenges of the twenty-first century. By encouraging active community participation, robust government support and dedicated awareness programs, we can ensure that these initiatives continue to grow in scale and impact, ultimately fostering a more sustainable future for our urban centers.

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Vermicomposting: A Sustainable Waste Management

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Vermicompost is an organic fertilizer produced through the decomposition of organic waste by earthworms often Red wigglers (*Eisenia fetida*). In agriculture, it serves as a nutrient-rich soil amendment that enhances soil fertility, structure, and water retention. The process integrates proper feedstock selection, pre-treatment, earthworm management and periodic turning and harvesting to ensure fast decomposition and high-quality compost. Below is a structured, step-wise explanation of vermicompost production with emphasis on field-practical points, suitable for a semi-commercial or nursery-scale setup. Vermiwash is another important product that obtained from the further processing of vermicomposting, it is the liquid that is obtained when vermicompost is passed or treated with water through a column of worm action. It is rich in enzymes, Plant growth regulators and as well as macro-nutrients and micro-nutrients which plays an important role in plant growth and their management practices. It also removes excessive amount of heavy metals like copper and lead which toxicity is harmful for proper growth of plants. In recent year, increasing farmers concern about issues such as food quality, environmental safety and soil conservation has leads to a substial increase in the use of sustainable agricultural practices. Sustainable agriculture can be defined as a set of practices that supply food and other useful materials to current population of world by conserve of resources and minimum supply of inorganic fertilizers to the crop fields.

Fig. 1: Vermicompost Process

Vermicomposting Methods

Vermicomposting methods described under 2 types of system:

Batch System: Batch system are ones in which the bedding and food are mixed, the worms added, and nothing more is done until the process is complete. In a batch system, the waste is included with earthworm, which then process the entire quantity of water into vermicompost the cast are collected and separated from the earthworms,

Continuous flow System: Continuous-flow system are one in which worms are placed where upon feed and new bedding are added incrementally on a regular basis.

Key Steps in Vermicompost Production

Setup and Bedding: Prepare a container or pit (approx. 1-2 ft deep) with drainage holes. Layer the bottom with bedding materials such as shredded

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cardboard, newspaper, dry leaves or coconut coir.

Pre-composting Wastes: Partially decomposes organic waste (cow dung, Vegetable scapes) for 20-30 days to remove heat and toxic gases.

Introduction Worms: Add 1 kg of earthworms per 30 meter ridge or per bin (depending on scale).

Maintenance

Moisture: Keep the material as moist as a "squeezed sponge" by spraying water.

Temperature: Maintain a cool, shaded environment (18°C -25°C).

Feeding: Add kitchen waste (peels, tea waste) regularly, avoiding oily/dairy food.

Harvesting: After 45-60 days, stop watering and wait for the compost to turn into a dark, crumbly, odourless material. Collect the top layers and sieve to separate the worms, which are then reintroduced.

Essential Tips

- ✓ Avoid adding meat, Dairy, Oil or Spicy food to the bin.
- ✓ Cover the bed to protect worms from light, heat and rain.
- ✓ Use specialized earthworm species like *Eisenia fetida*, *Eudrillus eugeniae* or *Perionyx excavates*.

Key Constituents and Characteristics include

Nutrient Profile: Rich in macro-nutrients (N, P, K) and micro-nutrients (iron, zinc, copper) readily available to plants.

Organic Matter: Composed of humified organic matter and carbon (15-29%).

Microbial Activity: Contains high levels of beneficial micro-organisms like Pseudomonas that fight plant pathogens.

pH and Structure: Generally neutral to slightly alkaline (6.8-8.9) with high moisture retention.

Raw Materials: typically derived from cattle manure, kitchen waste, crop residues and bedding materials (shredded cardboard or paper).

Key Aspects of Vermicompost as a Sustainable Management

Waste Reduction: Efficiently processes kitchen scraps, agricultural residues and bio-waste.

Soil Nutrient Enhancement: Final product is rich in essential nutrients, Nitrogen (1.5-1.7), Phosphorus (0.98-1.19%) and Potassium (1.1-1.49%).

Environmental Benefits: Reduces greenhouse gas emissions by decreasing reliance on chemical fertilizers and reducing methane from landfill waste.

Process efficiency: Involves non-thermophilic breakdown using Red wigglers earthworms that can produce high-quality fertiliser in two to three months.

Economic Opportunity: Supports rural development and provides smallholder farmers with a low cost, high value alternative to fertilisers.

Future Prospective of Vermicompost

Market Growth: The global vermicompost market is expanding rapidly, valued at around $95.72 billion in 2025 and projected to reach $263.31 billion by 2034 at a CAGR of 11.9%. Growth is fueled by organic agriculture demand, with Asia-Pacific (including India) leading due to government initiatives and smallholder adoption.

Environmental Benefits: Vermicomposting conve-

rts organic wastes into nutrient-rich compost, enhancing soil biodiversity, water retention (up to 40-60%), and carbon sequestration while cutting GHG emissions compared to landfilling or incineration. It reduces fertilizer needs by 60-70%, lowers irrigation frequency, and supports non-carbon waste policies by minimizing methane and N_2O releases.

Technological Advances: Innovations like smart vermicompost reactors cut processing time by 50% and boost worm growth by 30%, with AI for real-time monitoring and nanotechnology improving nutrient efficiency.

Economic and Social Prospects: Producing vermicompost costs as low as 15.68 rupees kg^{-1} in regions like Nepal, selling at 25 rupees kg^{-1} for net profits, and reduces farm input costs by up to INR 4,000 ha^{-1}. Women's self-help groups in India gain income and empowerment through micro-enterprises, though eastern regions face adoption barriers.

Conclusion

Vermicompost embodies sustainable management, synergizing waste reduction, soil regeneration and food security. Its low-cost, high-impact profile empowers smallholders, restores degraded lands, and curbs environmental harm, positioning it as indispensable for resilient agroecosystems. Widespread adoption, backed by policy and innovation, promises a greener future essential for India's 3.5 million hectares and beyond.

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Mechanization and the Restructuring of Agricultural Labour

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Abstract

Agricultural mechanization has emerged as a critical response to labor shortages, rising wages, and structural transformations in rural economies. This paper examines the dual impact of mechanization on agricultural labor use, highlighting both its labour-saving and labor-inducing effects. While mechanization significantly reduces labor requirements per hectare by substituting human and animal power, it simultaneously promotes higher cropping intensity and farm productivity, thereby generating new labor demand. The study further explores task-specific limitations of mechanization, labor reallocation effects, and barriers faced by small and marginal farmers, with reference to Assam. The analysis demonstrates that mechanization is not purely labor displacing but instead reshapes labor demand across time, space, and skill categories. The paper concludes that inclusive policy interventions are essential to ensure equitable access to mechanization and balanced rural development.

Introduction

Agriculture in India has been undergoing a gradual but significant transformation driven by demographic pressures, rural-urban migration, and rising wage rates. These changes have resulted in increasing labor scarcity, particularly during peak agricultural seasons, thereby compelling farmers to adopt mechanization as a substitute for human and animal labor. However, the relationship between mechanization and labor use is neither simple nor unidirectional. While mechanization is often perceived as a labor-displacing technology, its actual impact is more complex, involving simultaneous processes of labor substitution, productivity enhancement and labor reallocation. From an economic standpoint, mechanization represents a form of factor substitution in which capital replaces labor in production. At the same time, it facilitates expansion in agricultural activity by reducing time constraints and enabling more intensive use of land. This dual character makes mechanization a transformative force rather than merely a labor-saving device. The present study examines these dynamics with particular reference to India and Assam, where smallholder dominance and agro-ecological diversity shape the adoption and outcomes of mechanization.

Reduction in Labor Requirements: Mechanization exerts a direct and measurable effect on labor use by reducing the number of labor days required for various agricultural operations. The substitution of mechanical power for human and animal labor is particularly evident in activities such as land preparation, threshing, and transportation.

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Empirical comparisons indicate that traditional bullock-operated farms require substantially higher labor inputs than mechanized farms equipped with tractors and threshers. The reduction in labor use is accompanied by declines in family labor participation, hired labor engagement, and permanent agricultural employment. These changes reflect an increase in labor productivity, as fewer workers are needed to cultivate a given area within a shorter period.

Cropping Intensity and Labor Demand: Despite these reductions in per-unit labor requirements, mechanization does not necessarily lead to a decline in total labor demand. Instead, it often induces an increase in cropping intensity by enabling faster turnaround between successive crops. Farmers can cultivate more crops within a year and expand the effective use of their land. This intensification of agricultural production generates additional labor demand, particularly for operations that remain time-sensitive and labour-intensive. Consequently, labor demand becomes more concentrated during peak periods, creating seasonal spikes rather than a uniform decline. This apparent contradiction highlights the paradoxical nature of mechanization, which simultaneously reduces labor requirements per operation while increasing aggregate labor demand.

Task-Specific Constraints of Mechanization: The persistence of labor demand is further explained by the task-specific limitations of mechanization. Agricultural production involves a range of activities that require precision, adaptability, and context-specific judgment. Operations such as transplanting, weeding, and harvesting in small or irregular fields remain difficult to mechanize effectively. In regions like Assam, where landholdings are often fragmented and environmental conditions are highly variable, these constraints are particularly significant. As a result, human labor continues to play an essential role even in partially mechanized farming systems, indicating that mechanization complements rather than completely replaces labor.

Labor Reallocation and Structural Transformation: Mechanization also contributes to structural transformation in rural labor markets by reallocating labor across sectors. The adoption of machinery creates new employment opportunities in areas such as equipment manufacturing, repair and maintenance services, machinery rental systems, and skilled machine operation. This shift represents a transition from unskilled manual labor to semi-skilled and skilled occupations, thereby contributing to the diversification of rural economies. While some forms of traditional agricultural employment decline, new forms of employment emerge, reflecting broader processes of economic development.

Constraints to Mechanization Adoption: The benefits of mechanization are not evenly distributed across all categories of farmers. Small and marginal farmers, who constitute the majority of landholders in India, face significant barriers to adoption. High initial investment costs, limited access to institutional credit, and the absence of economies of scale

restrict their ability to invest in machinery. In addition, inadequate rural infrastructure, including repair facilities and access to spare parts, further constrains effective utilization. Fragmented land-holdings reduce the operational efficiency of machinery, making mechanization less economically viable for smallholders. These factors contribute to a dualistic pattern of agricultural development, in which large farmers benefit disproportionately from mechanization while smaller farmers remain reliant on labor-intensive practices.

Conclusion

The impact of mechanization on agricultural labor use is best understood as a process of transformation rather than simple substitution. While mechanization reduces labor requirements per unit of production, it simultaneously increases overall labor demand through higher cropping intensity and expanded agricultural activity. It also alters the composition of labor demand by shifting employ-ment from manual farm work to more skilled and diversified roles within the rural economy. In regions such as Assam, where structural constraints limit the widespread adoption of mechanization, inclusive and context-specific strategies are necessary to ensure equitable outcomes. Ultimately, mechanization should be viewed not as a threat to labor but as an opportunity to enhance productivity, reduce drudgery and facilitate a more dynamic and resilient agricultural system.

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Organic Production Technology: A Viable Solution for Sustainable and Climate-Smart

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Introduction and Core Concepts

Agriculture in its modern Green Revolution's form not only impacts negatively on the society by causing hunger but also leads to severe environmental degradation, soil depletion, pollution of water bodies as well as high Greenhouse Gas (GHG) emissions. Organically Production Technology is a 'nature-oriented' approach, which is a combination of tradition, innovation, and science to sustain the health of soils and ecosystem.

Core Organic Production Technologies

Organic farming is not a random action of avoiding chemicals, but a set of technologies:

Crop Rotation and Intercropping: Growing different crops one after the other or at the same time breaks the pest cycle and introduces nitrogen in the soil naturally through leguminous plants.

Nutrient Management (Bio-fertilizers): Use of vermicompost, green manures (Sesbania), microbial inoculants (Azolla, Blue-Green Algae) to give balanced nutrition.

Biological Pest Control: Insects (ladybugs, parasitic wasps) and herbal extracts (Neem) instead of chemical pesticides.

Conservation Tillage: Avoid or reduce soil disruption to maintain soil structure and microbial populations.

Climate-Smart Agriculture (CSA) Benefits

Climate-Smart Agriculture (CSA) has three pillars, which include productivity, resilience, as well as mitigation. Organic systems combined address all three:

Carbon Sequestration: Organic soils are 'carbon sinks' which contain more CO_2 in form of soil organic matter. Evidence shows organic systems can lead to an increase of soil carbon stocks by up to 63% in a decade.

Lower Emissions: By foregoing synthetic nitrogen fertilizers, which are energy-intensive to manufacture and discharge nitrous oxide (a very potent GHG), organic farming reduces the carbon footprint of agriculture significantly.

Climate Resilience: Organic crops can do up to 40% better compared to conventional crops in extreme weather like droughts due to the 15-20% higher water holding capacity in organic-rich soil.

Restoration of Soil Health

Soil is a living ecosystem; Organic technologies restore its "biological engine":

Microbial Diversity: Organic management increases the populations of fungi (like Mycorrhizae) and bacteria which are beneficial to plant nutrient absorption and resistance to diseases.

Soil Structure: Organic matter is inversely related

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to soil porosity, reducing erosion, and soil loss from heavy rains that leach nutrients effectively.

Biodiversity Conservation

Conventional farming of monocultures and pesticides has resulted in a silent spring. Organic farms provide for:

Above-ground Biodiversity: Pollinators (bees/ butterflies) and birds.

There is a tightly interconnected below-ground network of earthworms and microorganisms providing valuable 'ecosystem services' such as nutrient cycling.

Economic Viability

Organic yields can initially be 20-25% lower than yields from conventional methods, but the system is often more profitable to farmers because of:

Reduced Costs of Inputs: Less expenditure on costly seeds, fertilizers, and pesticides.

Premium Pricing: High prices of organic products are examples of global markets.

Employment: Organic farming is labor intensive, and it can provide more employment opportunities on rural areas.

Challenges and Limitations

There are some faults in organic transition too:

Knowledge Gap: It demands very high expertise in managing the complex biological cycles.

Certification Costs: The process for third-party certification can be costly and complicated for small farmers.

Initial Yield Gap: There is a general reduction of yield in the 3 years 'transition period' while the soil is 'recovery'.

Conclusion & Future Outlook

Organic Production Technology is a viable and a necessary solution to a sustainable future. It directly benefits the grand UN SDG initiatives, directly including Zero Hunger (SDGs 2), Good Health (SDGs 3), as well as indirect Climate Action (SDGs 13). By combining the modern 'smart' technologies, from precision irrigation to AI, with organic approaches, the yield gap can be bridged, and the planet fed without destroying it.

Internet of Things (IoT) in Agriculture

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Abstract

Agriculture, being a keystone of global food security and economic development, is increasingly challenged by factors such as climate change, resource degradation, and a rapidly growing population. The integration of the Internet of Things (IoT) into agriculture offers a transformative approach to address these challenges by enabling smart, data-driven farming practices. This article explores the role of IoT in modern agriculture, highlighting its components, including sensors, connectivity technologies, and data communication systems. It further examines key applications such as precision farming, smart irrigation, micro-climate monitoring, asset tracking, drone-based surveillance, livestock monitoring, geo-fencing, and smart greenhouse management. IoT-based systems facilitate real-time monitoring, efficient resource utilization, predictive maintenance, and automation, thereby enhancing productivity and sustainability. Additionally, the adoption of IoT technologies can significantly reduce labor dependency and operational costs while improving yield quality and farm profitability. The study emphasizes that IoT-driven agriculture holds immense potential for both large-scale agribusinesses and smallholder farmers, contributing to sustainable agricultural development and future food security.

Introduction

Agriculture is the primary source of food all over the world. It not only provides the food but raw materials for many industries and contribute significantly to the growth of GDP and economy. With the evolution of urbanization, weather change and increasing population, agriculture sector is facing many challenges. There is a strong need to increase the production per unit area. Traditional method farming has led to degradation of farms because of uncontrolled use of resources, fertilizers and pesticides. The Internet of Things (IoT) has the potential to transform the agricultural landscape in many ways. The ever-growing global population would touch around 9.6 billion by 2050. So, to feed this immense population, the agriculture industry needs to embrace IoT. The demand for more food has to meet overcoming challenges such as, rising climate change, extreme weather conditions and environmental impact that results from intensive farming practices. ITU (International Telecommunication Union) defined the Internet of things as: “IoT is a technology that mainly resolves the interconnection between human to a thing, thing to thing, and human to human.” It is based on the communication between intelligent sensors, RFID (radio-frequency identification), GPS (global positioning systems), infrared sensors, remote sensing, mobile communic-

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ation and other communication networks. IoT innovations for small agricultural operations can significantly increase profit margins by minimizing the need for manual labour with automation, expediting machinery commands with remote and real-time monitoring, and allowing farmers to utilize resources more efficiently with preventative maintenance and environmental prediction. Mass embracement of these technology advancements in agriculture will allow small land holding farmers to manage more acreage, provide higher potential for profit, and higher yields on the upfront investments.

Components of IoT in Agriculture

The components of IoT in agriculture form the backbone of smart farming systems, enabling data collection, communication, analysis, and automated decision-making. These components work together to transform traditional agriculture into a precision-based, technology-driven system. A typical IoT system in agriculture consists of following blocks:

Sensors: Sensors are used to detect external inputs which act as a basis of any IoT system. The various sensor used in Agriculture IoT systems are:

- ✓ Accelerometers are used to detect motion, activity level, intrusion in the farm etc.
- ✓ Humidity and Temperature sensors are used for soil monitoring, ambient Air monitoring and livestock health monitoring. These sensors provide critical input for IoT enablement in agriculture use cases.
- ✓ Pressure sensor can detect atmospheric pressure that is eventually used to measure altitude as well. Since a pressure sensor requires an opening for a diaphragm to detect the pressure, they also prone to water and chemical contamination. Therefore, a pressure sensor is needed that can remain safe from chemicals such as Chlorine and Bromine.

Connectivity

Once data is collected, it must be transmitted to other devices or cloud platforms. Connectivity in agricultural IoT system may be viewed from below application requirements:

Range: For indoor monitoring short range RF technologies such as Bluetooth, BLE (Bluetooth Low Energy) and Wi-Fi are preferred as they can collect data from sensor nodes and send them to gateway for further propagation. For monitoring large farms long range technologies such as GPRS and LPWAN such as Sigfox are preferred as they give connectivity directly to telecom infrastructure. Mesh technologies such as BLE Mesh and 6LowPan can enhance the range of short-range technologies and make them suitable to be used outdoor.

Power Consumption: Most of the use cases in agriculture are powered by non-rechargeable batteries so technologies such as BLE, RF, sub GHz and LPWAN such as Sigfox are preferred over Wi-Fi, Bluetooth and GPRS that consume exponentially higher power.

Data Processing: The collected data is processed either locally (edge computing) or on remote servers (cloud computing). Cloud platforms store large volu-

mes of farm data. This data is further analysed to generate insights such as irrigation schedules or disease prediction. This component basically converts raw data into meaningful information.

Applications of IoT in Agriculture

Precision Farming

Crop Monitoring: To get the maximum productivity, the environment needs to be monitored for humidity and temperature and other crop parameters. It is important not only to monitor but to record the change over a shorter and longer period of time. This data can be correlated with ideal profile for the crop. This monitoring also helps to identify when and how much pesticides and fertilizer need to be used to minimize their usage.

Remote Irrigation: Remote Irrigation is the next step of monitoring. They control the irrigation depending upon the soil and ambient temperature and humidity. IoT enabled irrigation systems not only save water but also ensure that crops are provided with just the right quantity of water. In IoT enabled irrigation, the irrigation depends on the soil moisture rather than a prefixed or pre-determined interval-based irrigation.

Environment and Micro-Climate Tracking: IoT is transforming traditional semi-automated weather stations into wireless units that give core climate framework information and give exact micro-climate data. These weather monitoring units alert farmers through an application on their phone or data centre when acute risks, such as damaging frosts and heat waves, arise in areas local to their farms.

Real-Time Asset Monitoring: With assets distributed over several acres of land, travel, labour, and time; expenses can be cut by diminishing cross-property excursions to investigate fluid, fuel, feed tanks, ponds and comparable resources. IoT monitoring technology does precisely that, permitting farmers to continuously track resource usage rates and improve delivery truck schedules to have the perfect measure of fuel, water, or feed available consistently.

Preventative maintenance: It is a strong suit of IoT technology. It is accomplished by equipping machineries, such as mining pumps, generators, and wind machines, with embedded IoT sensors. The technology alerts farmers in real-time when potential failures arise, eliminating the requirement for in-depth, hands-on diagnosis. Preventative maintenance for agricultural machinery can minimize unexpected costs and machine downtime due to progressive damages caused by overlooked issues leading to machine failure.

Remote Equipment Controls: Like monitoring assets, remote equipment can be controlled from centralized data centres, and even smartphones and wireless devices, to reduce travel time and costs. Remote power throttling can minimize electricity usage on equipment like generators, wind machines, pumps and valves located throughout the property. Equipment can be powered on or off at any time of the day from anywhere to expedite work cycles. Remote monitoring technology can also optimize refuelling schedules by measuring the exact run

times for a given quantity of fuel and preventing pump issues from dry running.

Driverless Machines: Machine automation is not a new concept, as agriculturalists consistently have found ways to automate their equipment through IoT powered driverless machines bring automation to the next level. First, there is a slice in the costs required to pay laborers to man farm machines like tractors, seed drills, cultivators, and tillers, though the benefits of driverless machines do not stop with labour reductions. Driverless machines become far more compact and lightweight when air conditioning units, seating, and the entire cab sections are removed. Less power is required to run the smaller machines.

Agriculture Drones

Agricultural drones are a very good example of IoT applications in Agriculture. Agriculture industries today, have become one of the major industries where drones can incorporate. Two types of drones, that is, ground-based and aerial-based drones are being incorporated in agriculture in many ways such as, for crop health assessment, irrigation, planting, and soil & field analysis. The benefits that the usage of drones brings to the table include, ease of use, time-saving, crop health imaging, integrated GIS mapping, and the ability to increase yields. The drone technology will give a high-tech makeover to the agriculture industry by making use of strategy and planning based on real-time data collection and processing.

Livestock Monitoring

One of the most interesting IoT applications for agriculture is livestock monitoring. Cattle movement can be tracked with network-connected collars and knowing their exact locations can prevent cattle loss or theft. Furthermore, eating patterns and health-related activities can be monitored with a leg- or neck-mounted sensor to identify and monitor health issues efficiently. In IoT enabled farms, livestock such as sheep, pig, chicken and cows are monitored for their health to identify any disease, insemination period and activeness. IoT enabled farms also monitor the ambience in which livestock are kept to ensure they are in proper living condition.

Geo Fencing

In large farms livestock are allowed to roam and live in natural condition. While they are not locked, it is important to ensure their safety and that they do not stray out of the farms. So, they need to be monitored using GPS enabled tracker. The tracker consists of motion sensor to monitor their motion and GPS enabled geo fencing to generate alert if livestock moves out of designated area.

Smart Greenhouses

As the demand of variety of fruits and vegetables is growing it becomes more important to create ideal condition for a particular type of plant to grow and flourish. IoT enabled greenhouses monitor their ambient condition (Temperature, Pressure, Humidity and Light Intensity) and adjust to avoid any deviation. Greenhouses control environmental parameters in two ways; either through manual intervention or a proportional control mechanism.

However, since manual intervention has disadvantages such as production loss, energy loss, and labour cost, these methods are less effective. A smart greenhouse through IoT embedded systems not only monitors intelligently but also controls the climate. Thereby eliminating any need for human intervention.

Conclusion

The integration of IoT in agriculture represents a significant shift from conventional farming to intelligent, data-driven practices. By combining sensors, connectivity technologies, real-time data processing, and automation, IoT enables precise monitoring and efficient management of agricultural resources. Applications such as precision farming, smart irrigation, livestock monitoring, drone-based surveillance, geo-fencing, and smart greenhouse systems demonstrate the vast potential of IoT to enhance productivity, reduce input costs, and improve decision-making. India is expected to achieve the ambitious goal of doubling farm income by 2022. The agriculture sector in India is expected to generate better momentum in the next few years due to increased agricultural infrastructure investment such as irrigation facilities, warehousing and cold storage. There is vast potential for IoT applications in agriculture to increase productivity not only for the large landholding agriculture business giants but also for family-owned farms and small landholding farmers in the country.

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Comparative Study of Mulching Methods and their Effect on Crop Yield

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Abstract

This study is based on a field trial, Saikheda (Taluka: Saunsar, District: Pandhurna, Madhya Pradesh), to understand the effect of different mulching methods on crop yield. Four treatments were used in the field, namely polythene mulch, open soil without mulch, straw mulch, and stone mulch. All plots were maintained under similar conditions throughout the crop period. Based on my practical observations, polythene mulch produced the highest yield, followed by open soil, straw mulch, and stone mulch. The study shows how mulching plays an important role in improving crop growth and yield under local climatic conditions.

Introduction

Mulching is a method of covering the soil surface around plants using different materials to improve soil conditions and plant growth. It helps in conserving moisture, reducing weed growth, and maintaining soil temperature.

Background of Study Area

The study was conducted in Saikheda village, located in Saunsar taluka of Pandhurna district, Madhya Pradesh. This region generally experiences warm weather conditions, which leads to faster evaporation of soil moisture. Due to this, maintaining soil moisture becomes an important factor for better crop production.

Need for the Study: In this area, farmers use different mulching methods or sometimes no mulching at all. There is a need to understand which method is more suitable under local field conditions so that better yield can be achieved.

Objective of the Study: The main objective of this study was to compare different types of mulching methods under the same conditions and identify which method gives better crop yield in my field.

Description of Mulching Methods: In this study, four types of mulching methods were used. Polythene mulch involves covering the soil with plastic sheets to reduce moisture loss and control weeds. Open soil refers to the traditional method where no

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mulch is used and the soil is left exposed. Straw mulch is an organic method in which dried crop residues are spread over the soil surface to conserve moisture. Stone mulch involves placing small stones on the soil surface, which is sometimes practiced in dry areas.

Methodology

Field Preparation: For this experiment, the field was divided into four equal parts so that each mulching method could be tested separately under similar conditions.

Application of Treatments: Each part of the field was assigned one treatment. One plot was covered with polythene mulch, the second was left as open soil, the third was covered with straw mulch, and the fourth was covered with stone mulch.

Uniform Conditions Maintained: All the plots received the same amount of irrigation, sunlight, and care throughout the crop growth period. This ensured that any difference in yield was mainly due to the mulching method used.

Field Observations

Soil Moisture Condition: During the crop period, We observed that the soil under polythene mulch remained moist for a longer time compared to other plots. The open soil lost moisture quickly, especially during hot days. Straw mulch helped in retaining some moisture, but not as effectively as polythene. Stone mulch did not show much improvement in moisture retention.

Weed Growth: Weed growth was very less in the polythene mulch plot. In the open soil plot, weeds were more visible. Straw mulch reduced weed growth to some extent, while stone mulch showed moderate weed presence.

Plant Growth Performance: Plant growth was best in the polythene mulch plot, where plants appeared healthier and stronger. Open soil showed good growth but slightly less than polythene mulch. Straw mulch resulted in average plant growth, while stone mulch showed the weakest growth among all.

Results and Yield Analysis: After harvesting, we compared the yield from each plot. The results clearly showed that polythene mulch gave the highest yield, followed by open soil, straw mulch, and stone mulch. The higher yield in polythene mulch can be linked to better moisture conservation and effective weed control. Open soil performed better than expected due to proper irrigation. Straw mulch gave moderate results, possibly due to uneven application and decomposition. Stone mulch showed the lowest yield, indicating that it was not effective under my field conditions.

Advantages and Disadvantages of Mulching Methods

Polythene mulch offers several advantages, including excellent moisture conservation, effective weed control, and improved plant growth, which

ultimately results in higher yield. However, it has disadvantages such as higher cost, difficulty in disposal, and environmental concerns due to its non-biodegradable nature. Open soil cultivation is simple and cost-effective, requiring no additional materials. It allows natural water infiltration and is easy to manage. However, it leads to rapid moisture loss and higher weed growth, increasing labor and water requirements. Straw mulch is an eco-friendly option that improves soil fertility as it decomposes. It helps in conserving moisture and controlling weeds to some extent. However, it is less effective compared to polythene mulch and may attract pests or require proper handling for best results. Stone mulch is durable and not easily disturbed by environmental factors. However, it is less effective in moisture retention and weed control. It may also increase soil temperature and make field operations difficult, resulting in poor crop performance.

Discussion

The results of this study match with the practical conditions of Saikheda village. Since the climate is warm and moisture loss is high, methods that conserve water perform better. Polythene mulch proved to be the most suitable in this condition. Open soil can still give good results with proper management, but it requires more water. Straw mulch can be improved with better handling, while stone mulch may not be suitable for this type of soil and crop.

Conclusion

From this field trial conducted in Saikheda village, it can be concluded that mulching plays an important role in improving crop yield. Among all the methods tested, polythene mulch was the most effective, followed by open soil, straw mulch, and stone mulch. This study helped us to understand the practical importance of selecting the right mulching method based on local conditions. From our field, polythene mulch is the most suitable option for achieving higher productivity.

Diseases of Mango and Its Management

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Powdery mildew: *Oidium mangiferae* / *Acrosporum mangiferae*

Symptoms: It attacks the leaves, flowers, stalks of the panicle and fruits. Shedding of infected leaves occurs when the disease is severe. The affected fruits do not grow in size and may drop before attaining pea size. Generally, the infection starts from the inflorescence and spreads downwards covering the floral axis, tender leaves and stem. Infected leaves become twisted, curled and fall. Primary spread: Dormant mycelium and conidia in infected plant debris. Secondary spread: Wind-borne oidium type conidia. Disease spread is favoured by warm, humid weather with cool nights.

Management: Primary inoculam are decreased by pruning sick leaves and deformed panicles. It is advised to apply three systemic fungicide sprays at intervals of 12 to 15 days throughout the flowering season. When 25% of the flowers are opening, the first spray is advised. Growing of Resistant varieties: Amrapali, Ambika and Arka Puneet.

Anthracnose: *Colletotrichum gloeosporioides*

Symptoms: Anthracnose can appear on several mango tree sections. The development of blackish brown dots on peduncles and flowers is one of the disease's first signs on the inflorescence. Panicles and open flowers get tiny black spots that eventually grow larger and kill the blossoms. Serious crop loss (10-90%) results from the diseased flowers falling off and leaving the more persistent spikes on the peduncles. Temperature 25-30°C and 95-97% relative humidity. Primary spread: Saprophytic mycelium and conidia in infected plant debris. Secondary spread: Wind-borne and rain splashed conidia.

Management: All sick twigs from the tree should be cut and burned, and any diseased leaves, flowers, twigs, and fruits that have fallen on the orchard floor should be gathered. During the spring season, two to three contact or systemic fungicide applications spaced 12 to 15 days apart can effectively prevent blossom infection.Growing of Resistant varieties: Arka Puneet, Arka Aruna and Ambika.

Mango Malformation: *Fusarium moniliforme*

Symptoms: There are three different kinds of symptoms: vegetative malformation, floral malformation, and bunchy top phase. The nursery's bunchy-top phase is characterised by thickened, tiny shoots that carry small, rudimentary leaves. Shoots continue to be short and stunted, giving the appearance of a bunchy top. Excessive vegetative branches with restricted growth in seedlings are known as vegetative malformations. The tops of the seedlings seem bunchy, and they are swollen with short internodes that produce bunches of different sizes. Variation in the panicle is evident in the

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inflorescence deformity. A malformed skull remains for a long time and dries up into a black mass. Primary spread: Chlamydospores and saprophytic mycelium in contaminated plant waste. Secondary spread: Micro and macro conidia are spread by mites and wind. Eryophyid mite prevalence. The weather is cold and misty.

Management: There are currently no proven ways to prevent mango deformity. Nonetheless, the following could lessen the frequency of malformations. Scion sticks from trees with deformed inflorescences should be avoided for spreading. For propagation, only approved saplings should be utilized. The afflicted terminals should be clipped along with the adjacent 15-20 cm seemingly healthy area and burned as soon as the disease symptoms are clearly visible. Growing of resistant varieties: Pusa Manohari, Bangalora and Moovandan.

Stem end rot: *Diplodia natalensis*

Symptoms: The fruit abruptly turns dark to black as it ripens, usually near the stem end. The entire fruit turns black in two to three days, and the disease spreads downward, affecting half of the fruit's surface. Even still, wrinkles are frequently seen in addition to the fruit's overall flush. The affected skin stays tight, but deterioration penetrates the pulp beneath it and releases an unpleasant smell.

Management: The incidence of disease can be reduced by handling the fruit promptly and properly. A 10mm stalk should be used for harvesting fruit. The incidence of SER is decreased by applying systemic fungicides or fungicides based on copper before harvest. To control the disease, dip fruit in hot water laced with either carbendazim or thiophanate methyl (0.05%) for 15 minutes at 52±1°C after harvest. Growing of Resistant varieties: Neelum, Pusa Surya, Totapuri.

Red Rust: *Cephaleuros virescens*

Symptoms: Young twigs and foliage are attacked by algae. On leaves, velvety spots start as round, slightly raised patches that eventually combine to form uneven patches. The leaves' surface has a cream to white velvety texture once the mature spores fall off. Primary spread: Sporangia and algal filaments in diseased leaves. Secondary spread: Zoospores and sporangia were splattered by rain. High planting density.

Management: Improving air circulation, lowering humidity, and using chemicals are the main ways to control. Pruning afflicted branches, providing adequate nourishment and using copper-based fungicides (such as Bordeaux mixture 1% or Copper Oxychloride) during the rainy season or early stages of infection are important tactics. Growing of resistant varieties: Ambika, Arunika,

Grey Blight: *Pestalotia mangifera*

Symptoms: On the leaf lamina's edge and tip, brown patches appear. They get bigger and get dark brown. The spots, which are the fungus's acervuli, show black dots. For more than a year, survive on mango leaves. Spreads via conidia carried by the wind. During the monsoon, when temperatures are between 20 and 25°C and humidity is high, heavy infections are observed. Under ideal circumstances, the fungus

found in the stem multiplies. Conidia carried by the wind caused it to spread.

Management: It is managed by eliminating contaminated plant detritus, making sure plants are spaced appropriately for airflow, and cutting back on excessive wetness. In addition to biocontrol solutions like *Trichoderma viride or Pseudomonas fluorescens*, effective chemical controls include spraying copper oxychloride (0.25%), Mancozeb (0.2%), or carbendazim (0.1%). Growing of resistant varieties: Amrapali, Totapuri.

Sooty mould: *Capnodium mangiferae*

Symptoms: The mycelium that the fungus creates is black and superficial. They eat the plant hoppers' sweet secretions. Photosynthetic activity is impacted by the formation of black encrustation. On the leaf surface, the fungus develops on the sugary materials that scale insects, aphids, and jassids exude. Primary spread: Spores and saprophytic mycelium in diseased leaves. Secondary spread: *Lecanium hemisphaericum, L. viride, L. nigrum, Hemilecanium imbricans, Pulvinaria psidii*, and scale insects and aphids that spread conidia. Infestation by sucking insects that secrete honey dew, especially plant hoppers.

Management: Using systemic pesticides, such as methyl demeton, to control insects. Next, mix the starch solution (1 kilogram of starch/maida in 5 litres of water). Diluted to 20 litres after boiling. When the starch dries, it forms flakes that are removed with the fungus. Growing of resistant varieties: Banganapalli, Totapuri and Neelum.

Die back: *Botryodiplodia (Lasiodiplodia) theobromae*

Symptoms: Although the condition is present all year round, October and November are when it is most evident. It is typified by twigs drying up from top to bottom, especially in elder trees, and then leaves drying up, giving the appearance of fire scorch. The higher leaves gradually dry out and lose their colour. The margin rolls upward as the entire leaf dries. The typical symptom of the advanced stage of the disease is that these leaves shrink and fall off within a month, leaving the withered twigs completely bare.

Management: The best way to control the illness is to prune the afflicted twigs three feet below the infection location and then apply fungicides based on copper. In severe cases, it is also advised to apply three consecutive sprays of copper-based fungicides spaced 15 days apart after removing soil up to 9 inches deep beneath the diseased tree's canopy and replenishing it with canal silt, as well as recommended dosages of chemical fertilisers and FYM with pruning of affected twigs.

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Importance of Medicinal Herbs in Aquaculture

Divyanshu Kumar Upadhyay, Avdhesh Kumar, Tarang Kumar Shah and Priyanka Rani

Abstract

Medicinal plants have been used for thousands of years as natural immunostimulants and are now widely applied in aquaculture as safe alternatives to antibiotics and synthetic chemicals. Their use is increasing globally due to their low cost, easy availability, simple preparation, and minimal harmful effects on aquatic organisms and the environment. A wide variety of plants, including herbs, spices, seaweeds, and traditional herbal medicines, have been studied for their beneficial effects on fish and shellfish. These plants can be used in different forms such as whole plants, or specific parts like roots, leaves, seeds, and flowers, as well as in extract form using solvents like ethanol or methanol. They can be administered through feed, water, or in combination with other immunostimulants. Medicinal plants are known to enhance growth, improve immunity, and provide antibacterial and antiviral protection. However, their exact mechanisms, optimal dosages, and long-term effects are still not fully understood, requiring further research for effective and standardized use.

Introduction

Microbial diseases in aquaculture cause significant economic losses, and the excessive use of antibiotics can lead to harmful side effects. As a result, alternative approaches such as the use of medicinal plants have gained attention for improving aquaculture sustainability. Many plant-based compounds exhibit growth-promoting, antimicrobial and immunostimulatory properties in aquatic organisms. These phytochemicals are considered potential substitutes for conventional chemotherapeutics and can be used as feed additives or immunoprophylactic agents. Medicinal plants including herbs, spices, seaweeds, and plant extracts are widely used due to their low cost, ease of preparation, and minimal environmental impact. They contain bioactive compounds such as phenolics, alkaloids, and terpenoids, which enhance immunity, stimulate growth, and improve disease resistance. Although widely applied, their mechanisms of action, especially at the molecular level, are not fully understood. Further research is needed to optimize their application and better understand their species-specific effects in aquaculture.

Source of medicinal herb

Medicinal plants have been used as natural immunostimulants in traditional medicine systems for thousands of years and are now increasingly applied in aquaculture as safe alternatives to antibiotics. Their use helps improve fish health while

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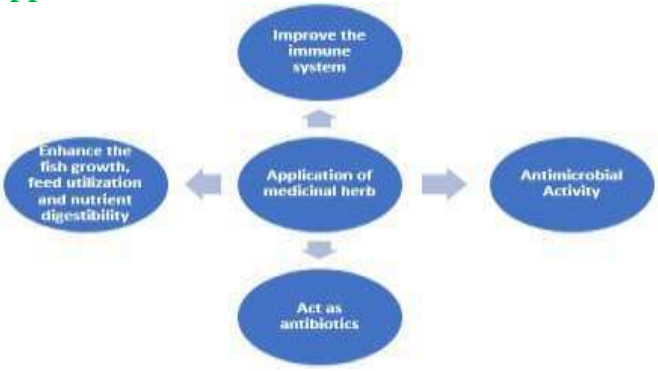
reducing the risks associated with chemical treatments. A wide range of herbs such as aloe vera, garlic, ginger, ginseng, green tea, tulsi, guava, peppermint, and seaweeds are commonly used to enhance growth, boost immunity, and increase resistance against diseases in aquatic organisms. More than 60 different plant species have been studied for their role in fish health management. These plants can be used in various forms, including whole plants or specific parts like leaves, roots, seeds, fruits and flowers. They are often incorporated into fish diets as powders or extracts, either alone or in combination with other natural additives. Some plant-based products are also commercially available and are known for their effectiveness in strengthening the immune system of fish. The extraction of bioactive compounds from medicinal plants is relatively simple and can be carried out using solvents such as ethanol, methanol, acetone, or even by boiling in water. The type and yield of extract may vary depending on the plant species and method used. Overall, medicinal plants offer a natural, cost-effective, and environmentally friendly approach for disease prevention and health management in aquaculture, although further research is still needed to better understand their mechanisms of action.

Administration and application methods

Medicinal plants in aquaculture can be administered through injection, immersion (bathing), or orally, with oral delivery via feed being the most practical and commonly used method. Herbal extracts are often added to fish diets either individually or in combination, as mixtures of herbs generally provide stronger immunostimulatory and growth-promoting effects than single herbs. Various herbal combinations have been shown to enhance immune responses, including increased phagocytic activity, respiratory burst, and lysozyme activity in different fish and shrimp species. These mixtures can also improve growth performance, feed efficiency, and resistance to bacterial and viral infections. In some cases, herbal formulations are used as preventive measures to replace antibiotics in disease control. Combining herbs with micronutrients such as boron, selenium, or zinc, or with probiotics like *Bacillus*, can produce synergistic effects, further improving immunity, survival, and growth. Another effective approach is bioencapsulation, where herbal extracts are delivered through live feed such as *Artemia* or rotifers, enhancing nutrient uptake and disease resistance in larvae and juveniles. Although injection and immersion methods are also used, especially for specific treatments, oral administration remains the most efficient and cost-effective. Overall, medicinal plants offer a promising, eco-friendly strategy for disease management and health improvement in aquaculture.

Application of medicinal herb



Improve the immune system: Many medicinal plants show antimicrobial activity and help improve growth, maturation, and immunity in fish, leading to increased interest in their use as immunostimulants in aquaculture. These plant-based compounds mainly enhance the innate (non-specific) immune system, which plays a key role in protecting fish from infectious diseases. Herbs such as *Astragalus membranaceus*, *Angelica* species, turmeric (*Curcuma longa*) and garlic (*Allium sativum*) have been widely used to strengthen immune responses in various fish species. Medicinal plants contain active compounds like polysaccharides, alkaloids, and flavonoids that stimulate important immune parameters such as lysozyme activity, complement system, phagocytosis, respiratory burst, and antioxidant enzymes. For example, plant extracts like green tea and *Prunella vulgaris* have been shown to improve immune activity, stress resistance, and overall health. Phagocytic cells are a major part of the fish immune system, and their activity often increases with herbal supplementation. Many plant extracts enhance phagocytosis and respiratory burst activity, improving the fish's ability to fight pathogens. Overall, medicinal plants act as effective natural immunostimulants, although their exact mechanisms still require further study.

Antimicrobial Activity: Medicinal plants and their active compounds have been widely studied for their strong antimicrobial properties in aquaculture. Herbal extracts show effective antibacterial activity against both Gram-positive and Gram-negative bacteria, and they can also help control viral, fungal, and parasitic diseases. For example, plant extracts such as Indian almond, rosemary, cinnamon, and tulsi have been used to treat infections like *Aeromonas hydrophila* and *Streptococcus* in fish, while also improving immunity and disease resistance. Many herbs also exhibit antiviral properties by reducing viral replication and enhancing the host's non-specific immune response. Extracts from plants like *Clinacanthus nutans*, *Cynodon dactylon*, and mango kernel have shown protection against serious viral diseases such as white spot syndrome virus (WSSV) and yellow head virus (YHV) in shrimp. Similarly, olive leaf extracts have been effective against viral infections in fish. In addition, medicinal plants are useful in controlling parasitic and fungal diseases in aquaculture species. Overall, herbal extracts provide a natural, eco-friendly, and effective alternative to synthetic chemicals for managing a wide range of aquatic diseases while also boosting the immune system.

Act as antibiotics: Several studies show that medicinal plants can act as effective natural alternatives to antibiotics in aquaculture. Fish and shrimp fed with herbal immunostimulants often show higher survival rates after being challenged with pathogens. Many herbal extracts, such as *Withania somnifera*, *Psidium guajava*, tulsi, green tea, cinnamon, and ginseng, have been found to improve resistance against infections like *Aeromonas hydrophila* and *Vibrio* species. Herbal treatments can control a wide range of pathogens, including bacteria, and are

effective in species like tilapia, grouper, and prawns. For example, guava extract has been shown to be even more effective than some antibiotics in reducing bacterial load, while seaweed and garlic extracts have successfully controlled viral and bacterial diseases in shrimp. Overall, dietary supplementation with medicinal plants enhances immune responses, reduces mortality, and improves disease resistance in aquatic organisms. This makes them a promising, eco-friendly, and cost-effective alternative to conventional antibiotics in aquaculture.

Enhance the fish growth, feed utilization and nutrient digestibility: Medicinal plants have been proven to act as natural growth promoters in aquaculture. They improve digestion by enhancing the activity of enzymes such as protease, amylase, and lipase, which leads to better feed utilization, higher survival, and faster growth of aquatic animals. Herbal supplementation also increases important nutrients like proteins, vitamins, amino acids, and minerals in fish and prawns. Various herbs such as ginseng, green tea, cinnamon, tulsi, and papaya leaf have shown positive effects on growth performance, feed conversion ratio (FCR), and specific growth rate (SGR) in different species. Herbal mixtures and plant extracts can further improve nutrient digestion, fatty acid utilization, and overall health. In addition, their antimicrobial and anti-stress properties help increase survival rates. Overall, the use of medicinal plants in diets enhances growth, improves feed efficiency, and supports better physiological performance, making them an effective and eco-friendly alternative to synthetic growth promoters in aquaculture.

Conclusion

In conclusion, medicinal plants offer a promising and sustainable approach for improving health management in aquaculture. Their natural origin, cost-effectiveness, and eco-friendly nature make them suitable alternatives to antibiotics and synthetic chemicals. The ability of these plants to enhance growth, strengthen immune responses, and provide protection against pathogens highlights their significant potential in aquaculture practices. Moreover, their flexibility in application through feed, water, or combined treatments further supports their practical use. However, despite these advantages, there is still a need for detailed studies to better understand their mechanisms of action, appropriate dosages, and long-term effects. Standardization and scientific validation are essential to ensure consistent results and safe application. Therefore, continued research and development will play a key role in fully utilizing medicinal plants for sustainable and efficient aquaculture production.

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Sowing Sustainability: How Organic Farming is Changing the World

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Abstract

The majority of fertilizers used in current soil management are based on inorganic chemicals, which pose substantial risks to the environment and public health. In the agricultural sector, the use of beneficial microorganisms as biofertilizers has gained significant relevance due to their ability to contribute to food safety and sustainable crop production. Plant growth-promoting rhizobacteria (PGPRs), endo- and ectomycorrhizal fungi, cyanobacteria, and many other beneficial microscopic organisms may be applied in a variety of ways using environmentally benign methods, which promote nutrient absorption, plant development, and plant tolerance to biotic and abiotic stress. This review focuses on the functional features of crops that biofertilizers mediate, including plant growth and productivity, nutritional profile, and plant defense.

Soil Health & Agricultural Practices: Overview

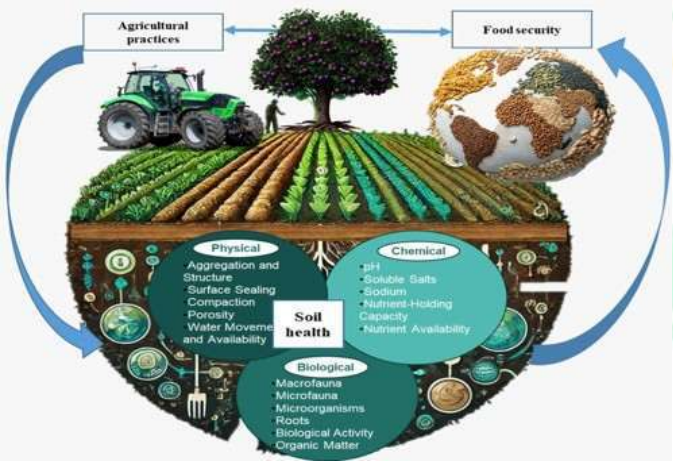

Figure 1: Interconnection between agricultural practices, soil health (physical, chemical, and biological aspects), and food security

Introduction

In the realm of modern agriculture, the quest for sustainability has become increasingly paramount. Biofertilizers, hailed as a cornerstone of sustainable farming practices, have emerged as pivotal agents in the endeavor to enhance agricultural productivity while minimizing environmental degradation. These natural and eco-friendly inputs harness the power of living microorganisms to augment soil fertility, fortify plant resilience against stresses, and elevate overall crop productivity. At the core of their functionality lies a profound ability to foster symbiotic relationships between micro-organisms and plants, fundamentally altering the agricultural landscape. By capitalizing on the symbiosis between certain bacteria, fungi, or algae and crop plants, biofertilizers facilitate essential nutrient acquisition, disease resistance, and stress tolerance. A significant facet of biofertilizers is their capacity to fix atmospheric nitrogen a process crucial for sustaining plant growth. Specific strains of nitrogen-fixing bacteria establish symbiotic associations with the roots of certain plants, enabling the conversion of atmospheric nitrogen into a usable form. This alleviates the reliance on synthetic nitrogen fertilizer,

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mitigating environmental pollution and enhancing soil fertility. Furthermore, mycorrhizal fungi another vital component of biofertilizers form beneficial associations with plant roots, extending their reach and aiding in the absorption of water and vital nutrients. This fosters plant tolerance to drought and nutrient deficiencies, ultimately bolstering crop yields.

Types of Biofertilizers: Biofertilizers are natural substances that contain living microorganisms which, when applied to soil, enhance its fertility and promote plant growth. Various types are available depending on crop and soil requirements:

Type	Key Micro-organisms	Primary Function
Nitrogen-Fixing	Rhizobium, Azotobacter, Azospirillum	Convert atmospheric nitrogen into plant-usable form
Phosphate-Solubilizing	PSB, Mycorrhizal Fungi	Break down insoluble phosphates in soil
Potassium-Mobilizing	*Frateuria, Bacillus spp.*	Mobilize potassium from mineral soil sources
Cyanobacteria	Anabaena, Nostoc	Fix nitrogen in waterlogged or paddy soils

Benefits of Using Biofertilizers

Improved Soil Fertility	Biofertilizers enhance nutrient availability, leading to better soil health and increased crop productivity through enriched microbial activity.
Reduced Environment-al Impact	By reducing reliance on chemical fertilizers, biofertilizers minimize environmental pollution, soil degradation, and water body contamination.
Cost-Effectiveness	Over time, biofertilizers can significantly decrease input costs for farmers, improving the overall economic sustainability of farming operations.
Enhanced Plant Tolerance	Nitrogen-fixing bacteria and mycorrhizal fungi improve plant tolerance to drought, salinity, and heavy metal toxicity through established symbiosis.
Increased Crop Productivity	By fostering a healthy soil microbiome and promoting better nutrient availability, biofertilizers contribute to higher and more consistent crop yields.
Long-term Soil Health	Biofertilizers improve soil structure, water retention, and microbial diversity, ensuring sustained agricult-ural productivity for future generations.

Limitations and Challenges

While biofertilizers offer numerous advent-ages in sustainable agriculture, their use may present certain limitations. Understanding these helps in designing effective management strategies.

Limitation	Details
Specificity and Effectiveness	Some biofertilizers work only for certain crops or soil conditions; effectiveness can vary with temperature, pH, and soil type.
Contamination Risk	Improper handling may introduce pathogens, weed seeds, or unwanted microorganisms into the soil.
Limited Nutrient Content	Biofertilizers may not supply all essential nutrients in required amounts, necessitating supplementary fertilization.
Slow Nutrient Release	Nutrients are released gradually, which may not meet the immediate demands of high-yield crops during critical growth stages.
Quality Control Issues	Inconsistencies in microbial strains or contamination during manufacturing can affect field results unpredictably.
Environmental Risk	Excessive use may lead to imbalances such as elevated nitrogen levels, causing eutrophication in nearby water bodies.
Cost and Availability	In some regions, biofertilizers are more expensive or less accessible compared to conventional chemical fertilizers.

Plant tolerance to Environmental Stress

Biofertilizers play a significant role in enhancing plant tolerance to various environmental stresses. Their relevance lies in their ability to establish symbiotic relationships with plants, fostering mechanisms that help plants cope with adverse conditions.

Drought Tolerance: Mycorrhizal fungi form associations with plant roots and create a network that extends the plant's access to water in the soil, improving water absorption and retention during periods of drought.

Salinity Stress Mitigation: Mycorrhizal fungi and certain bacterial biofertilizers help manage ion uptake and regulate osmotic balance within plant cells, reducing the negative effects of excessive salts in the soil.

Nutrient Deficiency Alleviation: Nitrogen-fixing bacteria and phosphate-solubilizing microbes improve nutrient availability, helping plants overcome deficiencies that hamper growth and development under stress conditions.

Pathogen Resistance: Some biofertilizers stimulate the plant's natural defense mechanisms and produce compounds that inhibit harmful pathogen growth, indirectly aiding the plant in resisting infections and diseases.

Temperature Stress Management: By improving overall plant health and nutrient uptake, biofertilizers indirectly support plants in managing stress caused by extreme temperature fluctuations during critical growth periods.

Heavy Metal Tolerance: Certain biofertilizers can immobilize heavy metals in the soil, preventing their uptake by plants and enabling tolerance to higher concentrations of these harmful elements.

Conclusion

The integration of biofertilizers into agricultural practices represents a transformative shift towards sustainable farming. By reducing reliance on synthetic chemicals, mitigating soil degradation, and promoting a balanced ecosystem, biofertilizers offer a pathway to not only improve soil fertility and plant health but also to ensure long-term agricultural sustainability. The utilization of biofertilizers in agriculture offers a multitude of benefits that are both environmentally friendly and economically viable. Their role in improving soil fertility, enhancing plant resilience, and boosting crop yields signifies their importance as a key player in the pursuit of sustainable agricultural practices. While biofertilizers offer significant advantages, proper application and management are crucial. Factors such as storage conditions, application methods, and compatibility with other agricultural inputs should be carefully considered to maximize their effectiveness. Biofertilizers may not entirely replace chemical fertilizers but can be used in combination to optimize crop yields while minimizing environmental impact.

Biofertilizers vs. Chemical Fertilizers

Aspect	Biofertilizers	Chemical Fertilizers
Environmental Impact	Low eco-friendly	High - polluting
Nutrient Release	Slow and sustained	Fast but short-term
Soil Health	Improves over time	Degrades over time
Cost	Low long-term cost	High recurring cost
Sustainability	Highly sustainable	Unsustainable long-term

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Significance of Nano Urea in Indian Agriculture

Mrinal Choudhury and Britan Rahman

Introduction

Nutrition at adequate level is essential for ensuring optimal yield of crops. Continuous cultivation for centuries and intensification of the cropping system during the past few decades have exhausted majority of crop fields in our country. Introduction of highly exhaustive crops and varieties have further aggravated the situation. The introduction of chemical fertilizers might have compensated the nutrient supply to an extent. However, the burden on the exchequer in the form of fertilizer-subsidy over a long period of time is untenable for the national economy. Further the environmental issues associated with the unscientific use of chemical fertilizers are matters of serious concern. The ground water pollution, eutrophication of water bodies, declining soil health etc. are such issues. Considering these and many other factors, the search for alternate materials and methods to supply plant nutrients has been underway for quite some time. Integrated nutrient management incorporating inorganic and organic materials, microbial strains fixing, solubilizing and mobilizing nutrients etc. have evolved during the recent times. Each one of these methods has its share of advantages and disadvantages and none of these gained traction in a wider scale among the Indian farmers. Given the wide-scale nitrogen deficiency in the Indian soils, continuous efforts in search of cheaper and environ-friendly materials to supply it have been made by various workers. The element is involved in the formation of proteins, nucleic acids, growth hormones and vitamins and is an integral part of chlorophyll. Therefore, its adequate supply is associated with vigorous vegetative growth during the early phase of the crop that ensures optimum yield at the final stage. Considering its high demand by the crop and large scale soil-deficiency, the recommended dose of nitrogen is usually 3-4 times higher than the other two major nutrients (P & K) for most of the crops. Further, the crop varieties and other inputs (like irrigation) have considerable impact on the nutrient requirement and its use efficiency. In general, the expert opinion is that the demand for external supply of the nutrient in steadily increasing as the factor use efficiency (in this case, nitrogen) is declining over time.

A Peek into the Historical Milestones of Nano fertilizers

The 21st century has seen the arrival of nano fertilizer in India. Though the research on nanotechnology has been going on for quite some time around the globe, the arrival of nano fertilizer is a very recent development. In the year 2021, IFFCO successfully launched the world's first liquid nano urea. Next year (2022) the world's first Nanpo Urea

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Liquid Plant was inaugurated in Kalol, Gujarat. Maintaining their unenviable position, IFFCO introduced the world's first nano DAP (liquid) fertilizer in the year 2023. Maintaining the tempo, scientists working at Tamil Nadu Agricultural University were able to obtain patents for specific slow-release nanocomposite fertilizers in the year 2024.

A Brief Account of Nano fertilizers

The term nano is of Greek origin that means dwarf. More precisely, the word nano means 10^{-9} or one billionth of a meter. Nano materials are defined as the materials with individual particle size less than a hundred nm in any dimension. Nano fertilizers are fertilizers, bulk materials or extracts of botanical, microbial or animal origin manufactured through chemical, physical, mechanical or biological methods. They are produced mostly either through top-down or bottom-up manufacturing process. Nano-fertilizers are categorized into three groups such as:

- ✓ Nanoscale fertilizer (carrier of plant nutrients)
- ✓ Nanoscale additives (traditional fertilizers with nanoscale additives)
- ✓ Nanoscale coating (Nono coated traditional fertilizers)

Nano-fertilizer is a new concept of nutrient management in crop. It is still in its nascent stage and there is a great amount of enthusiasm among the scientists, farmers, industrialists and policy makers about its applications. It is assumed that nano fertilizers are environmentally friendly materials and hence may safely be incorporated into the sustainable agricultural management practices. Recent technological advances have enabled the exploitation of the small (nano-size) materials for manufacturing the "smart fertilizer", which is able to enhance nutrient use efficiency and reduce the cost of environment protection. Studies indicate that the use of nano-fertilizers causes an increase in plant nutritional efficiency, reduces their toxicity to soil organisms, as well as reduces the effects of potential stress due to over application of fertilization and reduces amounts of fertilizers used. Post effect of nano fertilizer application in soil showed better pH, moisture, EC and available nitrogen under nano fertilizer treatment than the conventional fertilizer.

Major advantages of nano fertilizers

There are lots of advantages of nano fertilizers over the conventional chemical fertilizers. Some of these are:

- ✓ Increase nutrient use efficiency (3 times)
- ✓ Minimize the requirement to chemical fertilizer (50-60 times),
- ✓ Enhance stress tolerance (10-12 time)
- ✓ Eco-friendly
- ✓ 30-35% more nutrient mobilization by the plants
- ✓ 10-50% improvement in the crop yield.

Nano Urea

Nano Urea, a liquid nitrogenous fertilizer, was introduced in India by IFFCO to supplement nitrogen to the crops. Nitrogen, a major essential nutrient required for better growth and development of crops which is deficient in majority of crop fields

in the country. The conventional nitrogenous fertilizers used to supply the nutrient put a heavy financial burden on the farmers in spite of their subsidized market price. Further, the environmental issues associated with these fertilizers are a matter of major concern. Nano urea can substitute a large chunk of these nitrogenous fertilizers and effectively fulfils crop nitrogen requirement when sprayed at critical crop growth stages. Its use in place of conventional urea and other nitrogenous fertilizers may ensure better environment, soil health and farmers profitability as well. Nano urea contains 4% N (w/v) and the particle size ranges from 20 to 50 nm. The nano-nitrogen particles offer 10,000 times more reactive surface area compared to 1mm urea prills. The manufacturer claims that nano urea boosts nitrogen use efficiency by over 80%. If handled properly, it acts as a sustainable, foliar-applied alternative to traditional urea, increasing yield and quality while reducing soil pollution and lowering input costs by replacing conventional, top-dressed urea. nitrogen by weight in its nano form. Further, nano-urea is compatible with most agro-chemicals, bio-stimulants and water-soluble fertilizers. A half-litre bottle of nano urea can effectively replace upto one bag of urea. Usually, 2 to 4 ml of nano urea liquid is mixed in one litre of clean water and sprayed. For better result it is sprayed twice, i.e. at initial growth stage (tillering/branching) and one week before flowering.

Key points

About nano urea

- ✓ It is a nutrient (liquid) to provide nitrogen to plants as an alternative to the conventional urea.
- ✓ It is developed to replace conventional urea and it can curtail the requirement of the same by at least 50%.
- ✓ Conventional urea is effective 30-40% in delivering nitrogen to plants, while the effectiveness of the nano urea liquid is over 80%. Its effectiveness has been tested in over 11,000 farmers' fields for 94 crops like rice and wheat. An average 8% increase in yield has been witnessed.
- ✓ It has been indigenously developed at Nano Biotechnology Research Centre, Kalol, Gujrat in line with Atmanirbhar Bharat and Atmanirbhar Krishi.
- ✓ The price of IFFCO Nano Urea is around Rs. 240 per bottle (500 ml) for the farmers.

Significance

Improves plant nutrition

- ✓ It has been found effective and efficient for plant nutrition which increases the production with improved nutritional quality.
- ✓ It will boost a balanced nutrition program by reducing the excess use of urea application in the soil and will make the crops stronger and healthier.

Improves Environment: It is expected to have a huge positive impact on the quality of groundwater and a very significant reduction in global warming thereby mitigating the impact of climate change.

Increase Farmers' Income: It is easy on the pocket

of farmers and will be effective in increasing farmers' income. It will also significantly bring down the cost of logistics and warehousing.

Benefits of Nano urea

- ✓ Reduces the requirement of conventional urea by 50% or more.
- ✓ Required less and produces more: Efficacy of one bottle of Nano urea (500 ml) is equivalent to one bag of urea.
- ✓ Environment friendly product, can improve soil, air and water quality thus, helps in addressing the concerns of Global Warming and in meeting the UN SDGs.
- ✓ Cheaper than conventional urea.
- ✓ Reduce input cost to farmers, leads to increase in farmers' income.
- ✓ Improves crop productivity, soil health and nutritional quality of produce.
- ✓ Nano urea is developed to replace conventional urea and it can curtail the requirement of the same by at least 50 per cent. It contains 40.000 ppm of nitrogen in a 500 ml bottle, which is equivalent to the impact of nitrogen nutrient provided by one bag of conventional urea means 50 kg.
- ✓ To test its efficacy, around 11,000 farmer field trials were undertaken on more than 94 crops across India and results showed an average 8 per cent increase in crop yields.
- ✓ Nano urea has been included in the government's Fertilizer Control Order after the field trials were undertaken under National Agriculture Research System (NARS), 20 ICAR research institutes, State Agriculture Universities and Krishi Vighyana Kendras on 43 crops.
- ✓ The new nano urea liquid will increase the production of crops with improved nutritional quality. Cheaper than conventional urea, the new product is also expected to reduce the environmental pollution caused by the granular form, by reducing its excessive application that exacerbates soil, water and air pollution with climate change problems.
- ✓ The size of one nano urea liquid particle is 30 nm and compared to the conventional granular urea it has about 10,000 times more surface area to volume size. Due to the ultra-small size and surface properties, the nano urea liquid gets absorbed by plants more effectively when sprayed on their leaves.

Applications

2-4 ml of nano urea is mixed in one liter of water and sprayed on crop leaves at active growth stages. For best results, it should be applied in 2 foliar sprays: 1st t spray at active tillering/branching stage (30-35 days after transplanting) and 2nd spray 20-25 days after 1st spray or before flowering in the crop. It should be noted that nitrogen application through DAP or complex fertilizer as the basal dose should be continued. Only the top-dressed urea applied in 2-3 splits is replaced with nano urea as foliar sprays. The number of sprays of nano urea can be adjusted depending upon crop and its nitrogen requirement.

Application instructions

- ✓ Shake well the bottle before use.
- ✓ Use flat fan or cut nozzles for spraying on the leaves.
- ✓ Spray during morning or evening hours avoiding dew.
- ✓ If rain occurs within 12 hours of the spray of nano urea, it is advised to repeat the spray.
- ✓ Nano urea can easily be mixed with biostimulants, water-soluble fertilizers and agrochemicals.
- ✓ For better result nano urea should be used within 2 years from the date of its manufacturing.

Precautions

- ✓ Nano urea has been tested for bio safety and toxicity as per the guidelines of the Department of Biotechnology (DBT), Government of India and OECD international guidelines.
- ✓ Nano urea is safe for user and non toxic. However, as a precaution, it is recommended to use a face mask and gloves at the time of spraying it on the crop.
- ✓ Store in a dry place avoiding high temperature and keep away from children and pets.

Herbicide-Resistant Crops: A Breakthrough in Modern Weed Management

Chidanand Gowda M. R., Prajwala B. and Rudresh S.

Abstract

Weeds cause major yield losses by competing for nutrients, water, light, and space. Traditional control methods are labour-intensive and costly, leading to the development of herbicide-resistant crops (HRCs). These crops tolerate specific herbicides through genetic strategies such as target-site modification, enzyme overexpression, or metabolic detoxification. Glyphosate resistance is achieved by modifying the EPSPS enzyme, while glufosinate resistance involves detoxification by phosphinothricin acetyltransferase. The rapid global adoption of HRCs highlights their importance in modern weed management. However, sustainable use requires careful resistance management and environmental consideration.

Introduction

Weeds are a major constraint in crop production, competing with crops for light, water, nutrients, and space, and causing about 10-15% yield losses globally. They also harbour pests and diseases, further reducing productivity. Traditional methods like manual weeding and mechanical cultivation are labour-intensive and costly. Due to rising labour shortages and production expenses, the need for efficient weed control led to the development of herbicides and herbicide-resistant crops, transforming modern agriculture.

Herbicide-Resistant Crops (HRCs)

To make weed control easier and more effective, scientists developed Herbicide-Resistant Crops in the mid-1990s. These are special crop varieties that can survive the application of specific herbicides that would normally kill ordinary plants (Dill, 2005). In simple terms, while the herbicide destroys the weeds, the crop remains safe. This allows farmers to spray herbicides directly over the field without worrying about crop damage. Herbicide resistance is developed in two main ways:

- ✓ Through biotechnology (transgenic crops) by introducing a specific gene that gives resistance.
- ✓ Through conventional breeding methods such as mutation and selection.

Development and Global Adoption of Transgenic Herbicide-Resistant Crops

The development of transgenic herbicide-

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resistant crops (HRCs) began with bromoxynil-resistant cotton (1995) and canola (2000), but limited weed control reduced their commercial success. A major breakthrough occurred in 1996-1997 with the introduction of glyphosate-resistant (GR) soybean, canola, and cotton. These crops allowed safe in-season glyphosate application, revolutionizing weed management. Glyphosate's broad-spectrum activity, cost-effectiveness, and favourable environmental profile accelerated its global acceptance. Later, additional GR crops such as corn, alfalfa, and sugar beet were introduced. Glufosinate-resistant crops were also commercialized, and stacked varieties combining glyphosate and glufosinate resistance provided multiple modes of weed control. Many transgenic cotton and corn hybrids also incorporated *Bt* traits, offering combined weed and insect management. Global adoption expanded rapidly from 1.7 million hectares in 1996 to 148 million hectares by 2010. Herbicide-resistance traits accounted for nearly 60% of transgenic events, making them a cornerstone of modern agricultural biotechnology.

Strategies for Engineering Herbicide Resistance in Plants

Overexpression of the Target Gene

- ✓ Herbicides act by inhibiting a specific target enzyme essential for plant growth.
- ✓ By increasing the production of this enzyme, the crop maintains sufficient functional protein even after herbicide application.
- ✓ The inhibitory effect of the herbicide becomes relatively insignificant because excess enzyme remains active (Beckie *et al*., 2003).

Mutation or Modification of the Target Protein

- ✓ The gene encoding the target protein is modified through mutation.
- ✓ The altered enzyme retains its normal physiological function in the crop.
- ✓ However, structural changes reduce or prevent herbicide binding to the target site (Castle *et al*., 2004).

Detoxification of the Herbicide by a Foreign Gene

- ✓ The expressed enzyme converts the herbicide into a non-toxic or less toxic compound.
- ✓ This metabolic detoxification prevents cellular damage.
- ✓ Consequently, the crop survives herbicide treatment while susceptible weeds are eliminated

Mechanism of Glyphosate Resistance

Glyphosate is a broad-spectrum, systemic herbicide that inhibits the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), a key enzyme in the shikimate pathway. This pathway is responsible for the biosynthesis of aromatic amino acids such as phenylalanine, tyrosine and tryptophan. In susceptible plants, inhibition of EPSPS blocks amino acid synthesis, disrupts protein formation, and ultimately leads to plant death. Glyphosate-resistant crops are engineered by introducing a modified EPSPS gene that encodes an enzyme with low affinity for glyphosate. The altered enzyme continues to function even in the presence of the herbicide. Consequently, aromatic amino acid synthesis proce-

eds normally in the crop, while susceptible weeds experience metabolic inhibition and die. Thus, resistance is achieved through target-site modification, allowing selective weed control without affecting crop growth (Duke and Powles, 2008).

Mechanism of Glufosinate Resistance

Glufosinate is a non-selective herbicide that inhibits the enzyme glutamine synthetase, which plays a crucial role in nitrogen metabolism by converting ammonia into glutamine. In susceptible plants, inhibition of glutamine synthetase leads to the accumulation of toxic ammonia within plant tissues, causing disruption of photosynthesis and eventual plant death. Glufosinate-resistant crops are developed by introducing the *bar* or *pat* gene, which encodes the enzyme phosphinothricin acetyl transferase (PAT). This enzyme detoxifies glufosinate by acetylating it into a non-toxic compound before it can inhibit glutamine synthetase. Therefore, resistance is conferred through metabolic detoxification, enabling the crop to survive herbicide application while weeds are effectively controlled (Gianessi, 2005).

Advantages of HRC's

Herbicide-resistant crops allow the safe use of non-selective herbicides without damaging the crop. They provide greater flexibility in the timing of herbicide application and ensure effective weed control, which can contribute to higher yields. These crops reduce the risk of herbicide injury and lower cultivation costs by minimizing field operations and spray frequency. They can also be engineered to tolerate different herbicides, reducing the need for highly toxic and residual chemicals. In some cases, the use of non-selective herbicides may also help reduce certain plant pathogen problems.

Disadvantages of HRC's

Continuous use of the same herbicide may lead to the evolution of herbicide-resistant weeds. Widespread adoption of HRCs can encourage monoculture and increase dependence on chemical weed control. Excessive herbicide use may negatively affect soil health, non-target organisms, and water quality through runoff. Public concerns regarding genetically modified crops also influence their acceptance. Moreover, the long-term sustainability of HRCs depends on responsible management practices, as non-selective herbicides can harm crops if misused.

Conclusion

Herbicide-resistant crops have revolutionized weed control by enabling safe and effective use of broad-spectrum herbicides. Technologies such as glyphosate and glufosinate resistance have improved weed management efficiency and farm productivity. However, long-term sustainability depends on integrated weed management, resistance monitoring, and responsible herbicide use to prevent environmental risks and resistance development.

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Effects of Wastewater Irrigation on Soil Properties: Implications for Soil Health and Sustainable Agriculture

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Abstract

Water scarcity has intensified the use of wastewater as an alternative irrigation source in agriculture. Wastewater contains essential nutrients such as nitrogen and phosphorus that can enhance soil fertility and reduce dependence on synthetic fertilizers. However, its application also introduces salts, heavy metals and other contaminants that influence soil physical, chemical and biological properties. This review examines the multifaceted impacts of wastewater irrigation on soil systems. Physically, it alters soil structure, aggregation, porosity and bulk density, potentially improving water retention but increasing compaction and salinity risks. Chemically, it contributes to nutrient enrichment while promoting salt accumulation, pH shifts and heavy metal buildup. Biologically, wastewater affects microbial community composition, enzyme activities and soil fauna diversity. Although short-term benefits include improved fertility and crop productivity, long-term use may compromise soil health. Sustainable management practices, including soil monitoring, amendments and optimized irrigation techniques, are essential to balance benefits and minimize environmental risks.

Introduction

Water scarcity is a growing concern in many parts of the world, leading to an increased reliance on wastewater as an alternative irrigation source. Wastewater, including treated sewage and industrial effluents, is rich in nutrients such as nitrogen and phosphorus, which can improve soil fertility (Chauhan *et al*., 2025). However, the application of wastewater for irrigation is a double-edged sword. While it can enhance crop growth and reduce the need for synthetic fertilizers, it also introduces a range of contaminants that may affect the soil's physical structure, chemical balance and biological activity (Sao *et al*., 2025). The multifaceted effects of wastewater irrigation on soil properties are significant. Recent research highlights how wastewater inputs alter organic matter dynamics, nutrient availability, salinity and pH. Additionally, contaminants influence the soil microbial community and overall soil health (Wang *et al*., 2025). Understanding these interactions is crucial for managing wastewater irrigation in a way that maximizes

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benefits while minimizing risks, ensuring the long-term sustainability of agricultural practices (Mola *et al*., 2024).

Effects on soil physical properties

Changes in soil structure: Prolonged irrigation with wastewater may promote the formation of larger aggregates due to enhanced microbial activity and organic matter inputs. However, excessive water can also cause compaction in certain layers by reducing air-filled porosity, especially when applied via surface methods (Abou *et al*., 2025).

Alterations in soil porosity and water retention: The increased organic matter content provided by wastewater enhances soil aggregation, which may improve water-holding capacity. Enhanced porosity facilitates improved water infiltration and retention in the upper soil layers. However, if wastewater contains high concentrations of salts (e.g., sodium and chloride), these ions can replace calcium and magnesium in the soil colloids, leading to dispersion of clay aggregates and a reduction in soil permeability. This can eventually result in waterlogging and poor drainage, particularly in fine-textured soils (Chen *et al*., 2024).

Effects on soil bulk density and compaction: Frequent application of wastewater, particularly with manual irrigation systems, can lead to variations in soil bulk density. While organic matter inputs generally decrease bulk density by improving soil structure, high salt concentrations and continuous wetting and drying cycles may increase soil compaction. Such compaction reduces the movement of air and water, negatively affecting root growth and overall soil health (Akter *et al*., 2025).

Effects on soil chemical properties

Nutrient enrichment and imbalances: One of the most notable benefits of wastewater irrigation is the influx of nutrients. Wastewater is typically rich in nitrogen, phosphorus, potassium and micronutrients, which can enhance soil fertility and crop productivity. However, the continuous accumulation of these nutrients may lead to imbalances. For example, excessive phosphorus may cause eutrophication in adjacent water bodies, while high levels of nitrogen can alter the carbon-to-nitrogen ratio, affecting soil organic matter decomposition rates and microbial activity (Chauhan *et al*., 2025).

Changes in soil pH and electrical conductivity: Wastewater irrigation can influence soil pH in multiple ways. Nutrient transformations, such as nitrification, can release protons and lower soil pH, whereas the presence of basic cations in wastewater might raise soil pH. The net effect depends on wastewater composition, soil buffering capacity and irrigation frequency. In parallel, wastewater irrigation often increases soil electrical conductivity (EC) due to the higher concentration of dissolved salts. Elevated EC values can impair plant water uptake and signal the onset of secondary salinization, which is particularly problematic in arid regions (Abou *et al*., 2025).

Accumulation of salts and heavy metals: Saline constituents in wastewater, including sodium, chloride and other dissolved ions, can accumulate in

the soil, particularly in the surface layers. This salt buildup not only affects soil structure and permeability but also poses risks of phytotoxicity. In addition, wastewater may contain trace amounts of heavy metals such as copper, zinc, cadmium and lead that can gradually accumulate in the soil over time. Although concentrations might initially remain below regulatory limits, long-term use without proper management can lead to toxic levels, affecting both soil biota and human health through crop uptake (Al-Karablieh *et al*., 2025).

Organic matter dynamics and carbon cycling: Wastewater irrigation typically increases the soil's organic matter content by adding dissolved and particulate organic carbon. Enhanced organic matter can improve soil fertility and water-holding capacity. However, this input also stimulates microbial activity, which accelerates the mineralization of organic matter. In some cases, this "priming effect" can lead to a reduction in the stable soil organic carbon pool over time, especially in subsoil layers, thus affecting long-term carbon sequestration and soil fertility (Chauhan *et al*., 2025).

Effects on soil biological properties

Shifts in microbial community composition: Wastewater irrigation introduces a diverse array of organic substrates and nutrients that can stimulate soil microbial activity. Increased nutrient availability often results in a shift in the microbial community structure, favouring fast-growing copiotrophic organisms. While this can enhance short-term decomposition and nutrient cycling, the long-term impacts may include a decline in microbial diversity and an imbalance between beneficial and pathogenic microorganisms. Furthermore, contaminants and heavy metals present in wastewater may exert selective pressure, potentially reducing the abundance of sensitive species (Akter *et al*., 2025).

Changes in enzyme activities and nutrient mineralization: Soil enzymes, which are critical for nutrient cycling and organic matter decomposition, are typically affected by wastewater inputs. Enhanced organic matter can increase enzyme activities, such as dehydrogenase, phosphatase and urease, thus promoting the breakdown of organic compounds and the release of plant-available nutrients. However, elevated salt concentrations and heavy metals may inhibit enzyme activity, leading to reduced nutrient mineralization rates and altered soil biochemical processes (Wang *et al*., 2025).

Impact on soil fauna and biodiversity: The addition of wastewater can influence the abundance and diversity of soil fauna, including earthworms, nematodes and arthropods. On one hand, increased organic matter and improved moisture conditions can support a higher density of soil organisms. On the other hand, high salinity, heavy metal accumulation and the presence of potentially harmful contaminants may adversely affect soil fauna, thus reducing biodiversity and disrupting soil ecosystem functions. The balance between these contrasting effects often depends on wastewater quality, treatment level and the specific characteristics of the soil ecosystem (Mola *et al*., 2025).

Additional effects and considerations

Long-term soil health and sustainability: The cumulative impact of wastewater irrigation on soil health is complex. While short-term benefits include improved nutrient availability and increased organic matter, long-term use may result in the gradual accumulation of salts and heavy metals, soil acidification or alkalinization and changes in soil structure. Monitoring these changes is essential to prevent soil degradation and ensure sustainable agricultural practices (Akter *et al*., 2025).

Interactions with plant growth and crop quality: Wastewater irrigation not only influences soil properties but also affects crop performance. Improved nutrient inputs can lead to increased crop yields and better fruit quality; however, adverse effects such as increased salt stress and contaminant uptake may compromise plant health and food safety. The interplay between soil properties and plant responses necessitates integrated management practices that optimize water quality, irrigation methods and soil amendments (Surdyk *et al*., 2025).

Mitigation strategies and management practices

To balance the benefits and risks associated with wastewater irrigation, several management strategies are recommended:

Regular soil monitoring: Continuous assessment of soil pH, EC, nutrient content and heavy metal concentrations is critical for early detection of adverse changes.

Soil amendments: The use of gypsum, organic compost or biochar can help counteract salinity buildup, improve soil structure and enhance nutrient retention.

Optimized irrigation techniques: Drip irrigation systems can help minimize salt accumulation in the root zone compared with surface irrigation methods.

Integrated fertilizer management: Adjusting fertilizer inputs based on nutrient contributions from wastewater can prevent nutrient imbalances and reduce the risk of eutrophication.

Phytoremediation: Plant species known for their ability to uptake and sequester heavy metals may be incorporated into crop rotations to mitigate contaminant accumulation.

Conclusion

Wastewater irrigation presents a promising alternative for agricultural water use in regions facing freshwater scarcity. Although it offers significant nutrient inputs and can enhance short-term crop productivity, its long-term application leads to multifaceted impacts on soil physical, chemical and biological properties. Changes in soil structure, increased salt accumulation, alterations in nutrient cycling and shifts in microbial communities are among the critical effects. Sustainable management practices-including regular soil monitoring, the use of soil amendments and optimized irrigation techniques-are essential to harness the benefits of wastewater irrigation while mitigating its potential adverse impacts. Continued research and adaptive management strategies are vital to ensuring that wastewater irrigation contributes to long-term soil health and sustainable agricultural production.

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Nano-Fertilizers: A New Era in Sustainable Agriculture

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Abstract

Modern agriculture faces the challenge of increasing crop productivity while minimizing environmental damage. Conventional fertilizers often suffer from low nutrient use efficiency due to losses through leaching, volatilization and fixation in the soil. Nano-fertilizers, developed using nanotechnology, have emerged as an innovative solution to enhance nutrient use efficiency and reduce environmental pollution. These fertilizers contain nutrients in nano-scale particles that allow controlled and targeted release of nutrients to plants. Nano-fertilizers improve nutrient uptake, enhance crop growth and reduce the quantity of fertilizer required. Their application also helps in improving soil health and reducing the environmental footprint of agricultural practices.

Introduction

Agriculture plays a vital role in ensuring food security for the rapidly growing global population. To achieve higher crop yields, farmers have traditionally relied on chemical fertilizers. However, the excessive and imbalanced use of these fertilizers has resulted in several environmental problems such as soil degradation, water pollution and greenhouse gas emissions. Moreover, only a small proportion of applied nutrients is utilized by plants, while the rest is lost through different pathways. In recent years, nanotechnology has opened new opportunities in agriculture. Nano-fertilizers are one of the most promising innovations developed to improve nutrient management in crop production. These fertilizers are engineered at the nano scale (1-100 nanometers), which enhances their surface area, reactivity and nutrient delivery efficiency. Due to their unique properties, nano-fertilizers can provide nutrients in a slow and controlled manner, ensuring better absorption by plants and minimizing nutrient losses. The use of nano-fertilizers has the potential to revolutionize nutrient management and contribute to sustainable agricultural development.

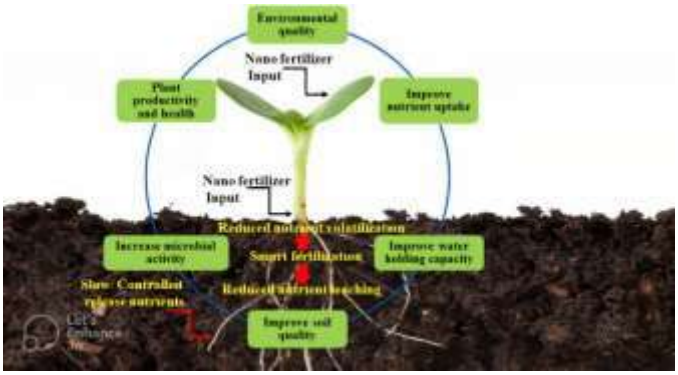

Fig. 1. Nano-fertilizers: A sustainable technology for improving crop nutrition and food security

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Content of Topic

Nano-Fertilizers: Concept and Types

Concept of Nano-Fertilizers

Nano-fertilizers are nutrient formulations that contain particles in the nano size range or nutrients coated with nano materials. They are designed to deliver nutrients more efficiently to crops through controlled release mechanisms. Their small particle size increases the surface area and enhances interaction with plant roots and leaves, resulting in improved nutrient uptake.

Types of Nano-Fertilizers

Nano-fertilizers can be classified into three main types:

Nano-scale fertilizers: These fertilizers contain nutrients directly in nano-particle form. Examples include nano nitrogen, nano zinc and nano iron fertilizers.

Nano-coated fertilizers: In these fertilizers, conventional fertilizer granules are coated with nano materials that regulate the release of nutrients over time.

Nano-encapsulated fertilizers: Nutrients are enclosed within nano-structured materials that protect them from losses and release them slowly according to plant requirements.

Role of Nano-Fertilizers in Sustainable Agriculture

Improved Nutrient Use Efficiency: Nano-fertilizers increase the efficiency of nutrient uptake by plants due to their small particle size and higher reactivity. They ensure better availability of nutrients in the root zone.

Reduced Nutrient Losses: Traditional fertilizers often lose nutrients through leaching, volatilization and fixation. Nano-fertilizers release nutrients gradually, which significantly reduces these losses.

Enhanced Crop Growth and Yield: Application of nano-fertilizers improves seed germination, root development, photosynthesis and overall plant growth, leading to higher crop productivity.

Environmental Protection: Reduced fertilizer application and minimized nutrient losses help prevent soil and water pollution. This makes nano-fertilizers an environmentally friendly alternative to conventional fertilizers.

Improved Soil Health: Nano-fertilizers help maintain soil fertility by reducing chemical load and promoting balanced nutrient availability.

Examples of Nano-Fertilizers in Agriculture

Nano Urea: Improves nitrogen use efficiency and reduces nitrogen losses.

Nano DAP (Di-ammonium phosphate): Provides phosphorus and nitrogen efficiently to crops.

Nano Zinc: Corrects zinc deficiency and improves crop growth and yield.

These nano-fertilizers are increasingly being promoted in several countries to support sustainable crop production.

Conclusion

Nano-fertilizers represent a promising advancement in modern agriculture. By improving nutrient use efficiency and reducing environmental pollution, they offer an effective solution for sustainable crop

production. Their ability to deliver nutrients in a controlled and targeted manner can significantly reduce fertilizer consumption while maintaining high crop yields. With continued research, proper regulation and increased farmer awareness, nano-fertilizers can play a crucial role in ensuring food security and environmental sustainability in the future.

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Beneficial Effects of Fly Ash Application on Soil Fertility and Crop Productivity

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Abstract

Fly ash is a by-product generated during the combustion of coal in thermal power plants and its disposal has become a major environmental concern. However, fly ash contains several plant nutrients such as calcium, magnesium, potassium, iron and other micronutrients that may improve soil fertility when applied in suitable quantities. In recent years, the utilization of fly ash in agriculture has gained attention as a potential soil amendment for improving soil properties and crop productivity. The application of fly ash can improve soil physical properties such as soil structure, porosity and water-holding capacity. It can also influence soil chemical properties by supplying certain nutrients and improving soil pH, particularly in acidic soils. Several studies have reported that the combined application of fly ash with organic manures or chemical fertilizers enhances crop growth and yield in crops such as wheat, rice, maize and vegetables. However, excessive application may lead to the accumulation of heavy metals in soil and plants. Therefore, the safe and effective use of fly ash requires appropriate management practices and recommended application rates. The beneficial use of fly ash in agriculture not only improves soil fertility and crop productivity but also provides an environmentally sustainable approach for the disposal of industrial waste.

Introduction

Fly ash is one of the major industrial by-products generated from coal-based thermal power plants. With the increasing demand for electricity, the generation of fly ash has increased significantly in many countries including India. The disposal of fly ash has become a serious environmental challenge because large quantities accumulate in ash ponds and landfills. In recent years, considerable attention has been given to the beneficial utilization of fly ash in agriculture because it contains several mineral elements that are important for plant growth and soil fertility. Fly ash generally consists of elements such as silicon, aluminum, calcium, magnesium, potassium, iron and other trace elements. When applied in appropriate quantities, these elements can contribute to the improvement of soil nutrient status and support better plant growth and development. The use of fly ash as a soil amendment has been explored as a strategy to improve soil properties and crop productivity while simultaneously addressing the problem of fly ash disposal.

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Effect of Fly Ash on Soil Properties: The application of fly ash can significantly influence the physical, chemical and biological properties of soil. Due to its fine particle size, fly ash can improve soil structure and aggregation when incorporated into the soil. Improved aggregation enhances soil aeration and creates favourable conditions for root development. In sandy soils, the addition of fly ash can increase the water-holding capacity and reduce nutrient leaching. In contrast, in clay soils, fly ash improves soil porosity and aeration, which facilitates better root growth and enhances microbial activity in the soil. Fly ash may also influence soil chemical properties by increasing soil pH in acidic soils and supplying certain plant nutrients such as calcium, magnesium and potassium, which are essential for plant growth and development.

Effect of Fly Ash on Crop Growth: Several studies have reported beneficial effects of fly ash application on crop growth and yield. The improvement in soil physical and chemical properties, along with increased nutrient availability, contributes to better plant growth and higher crop productivity. Crops such as wheat, rice, maize, mustard and various vegetables have shown positive responses to the application of fly ash, particularly when used in combination with organic manures or chemical fertilizers. The integrated use of fly ash with farmyard manure or compost enhances soil microbial activity and improves nutrient availability, thereby supporting better plant growth and development.

Environmental Considerations: Although fly ash has considerable potential for agricultural use, its application must be carefully managed. Fly ash may contain trace amounts of heavy metals such as lead, cadmium and arsenic, which may pose environmental risks if applied in excessive quantities. Continuous or uncontrolled application of fly ash may lead to the accumulation of these metals in soil and plants. Therefore, the application of fly ash should be based on recommended rates and proper soil testing. The combined use of fly ash with organic amendments such as farmyard manure or compost can help reduce potential environmental risks and improve the safe utilization of fly ash in agricultural soils.

Conclusion

Fly ash has considerable potential as a soil amendment for improving soil fertility and crop productivity. Its application can improve soil physical and chemical properties and supply certain plant nutrients. When used in appropriate quantities and combined with organic amendments, fly ash can contribute to sustainable agricultural production. At the same time, the utilization of fly ash in agriculture provides an effective solution for the disposal of industrial waste.

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Effect of Moisture Stress in Crop Production and their Management Practices

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Moisture stress occurs when a crops water requirements are not met due to the lack of available soil moisture, leading to reduced plant growth, yield and quality. Moisture Stress is a condition in plants, where there is an imbalance between water absorption and water loss through transpiration, leading to a deficit of water in the plant cells. This can be caused by insufficient water in the soil, high transpiration rate due to heat or poor water absorption by the roots and it negatively affects the plant's growth, development and yield.

Category of moisture stress

Moisture Stress in crops is caused by a lack of Soil moisture (drought), which reduces water uptake and also be caused by an excesses of water (water logging). Both deficiencies and excesses lead to the plant stress by disrupting a plants ability to maintain a balance between water uptake and water loss through transpiration. Drought Stress results in wilting, reduced growth, and lower yield, while waterlogging stress can cause hypoxia (low oxygen) in the soil leading to the accumulation of toxic substances and potential plant death.

Moisture deficiency (Drought stress): Lack of rainfall, poor irrigation or high transpiration rates that excud the rate of water absorption by the roofs.

Effect on plants

- ✓ Reduced cell turger, leading to wilting and the reduction in leaf size and plant hight.
- ✓ Leads to decreased photosynthetic activity and Sugar production.
- ✓ Curled leaves, turn yellow and eventually die, if the stress is prolonged.
- ✓ Reduces crop yield, with the impact varying depending on the crops growth stage.

Moisture excesses / waterlogging stress: Soil pore spaces become filled with water, leading to either low oxygen levels (hypoxia) or a total lack of oxygen (anoxia) in the roots rhizosphere.

Effect on plants

- ✓ Inhibits oxygen uptake by the roots, effecting the plant quality to function.
- ✓ Forces plants to switch from aerobic respiration to anaerobic fermentation for produce energy.
- ✓ Prolonged waterlogging can lead to the accumulation of toxic metabolic by products like ethanol and lactic acid.
- ✓ Cell death and lead to plant failure.

Relation between water stress and moisture stress

Water stress: This is an environmental and physiological condition, whereas, moisture stress is the resulting condition of low moisture content within the plants own tissues. Moisture stress is the condition of low moisture in plant tissues, while

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water stress in the broader condition of a plant being unable to absorb enough water to meet, its need, which can be caused by factors like draught, high temperatures or soil conditions. Essentially, moisture stress is a specific outcome (Low moisture in the plant) and water stress in the cause that can lead to that outcome.

Causes of moisture stress

Insufficient soil moisture: When the soil does not have enough water for the roots to absorb a deficit occurs.

High transpiration rates: If the plant losses water through its leaves faster than its roots can absorb it, stress develops. This is common during hot and dry weather.

Poor water absorption: The roots may not be able to absorb water efficiency due to factors like high salt content in the soil or root damage.

Deficient soil moisture: Insufficient water in the soil to meet the crop needs.

High temperature: Increased temperatures raise transpiration rates leading to more water loss from the plants than it can absorb from the soil.

Imbalance between transpiration and absorption: Water loss through transpiration can temporarily excud the rate and which the roots can aborb water, especially during the hottest parts of the day.

Symptoms of moisture stress condition in plants

Symptoms of moisture stress include wilting, leaf rolling and discoloration such as yellowing, brown and crespy edges. In case of more severe moisture stress can lead to stunted growth, premature leaves and flowers drop. Ultimately reduced crop yield and increased susceptibility to insect pests and diseases.

Common symptoms appeared on plants

Wilting: Loss of turger pressure in plant cells causes drooping or wilting.

Leaf rolling: Leaves curl inwords to reduce the surface area and which exposed to the sun.

Leaf discoloration: Leaves may turn yellow or dark green / gray.

Scorching: Brown and crispy patches may appear on leaf edges.

Dullness: Leaves can loose their shine and appear dull.

Premature leaf / flower drop: Plant may shed their leaves or flowers to conserve water.

Stunted growth: The plant may grow slowly or stop growing altogether.

Persistent foot prints: In plants, foot prints may remain visible inseated of springing back up.

Moisture stress examination techniques

Observe leaf behaviour: If leaves are wilting or starting to roll in the morning hours or stay welting into the evening hours, it's a sign of serious moisture / water stress and not just midday heat.

Judge for damage: Check for scarched or brown edges, which indicate dehydration stress.

Check for life: If a plant looks dead scarp a small amount of the outer layers of a twig or bark. If a green layer is visible underneath, it is still alive and may recover with watering.

Characteristics of moisture stress

- ✓ Yellowing foliage.
- ✓ Drooping and / or curling of leaves.
- ✓ Leaves do not retain to an upright perky state when the temperature cools.
- ✓ Leaves eventually dropping off in extreme circumstances.

Effect of moisture stress on crops

Moisture stress negatively impact crop growth by reducing photosynthesis, causing stunted growth, wilting and lower yield. Physiologically, it leads to reduced water content increased leaf temperature and stomatal closure to conserve water. Morphologically, it results in deceased plant height, reduced leaf area and less fruit / grain production.

Physiological effects

Reduced photosynthesis: Plants cannot absorb sufficient carbon dioxide due to stomatal closure, which is essential for photosynthesis.

Altered water status: Leaf water potential and relative water content decrease, while leaf and canopy temperature increase.

Hormonal changes: Moisture stress affects hormone production and metabolism, leading to premature aging and leaf drop.

Morphological effects

Stunted growth: Plant height, root length, and number of leaves are reduced.

Reduced leaf area: Leaf size and overall leaf area index decrease significantly, especially with increasing moisture stress.

Wilting and leaf damage: Leaves may yellow, wilt, and develop scorched or dried edges.

Reduced yield: The number of fruits or grains decreases due to poor pollen viability and premature shedding.

Other Common effects

Increased sensitivity: Certain growth stages like pod formation are more sensitive to moisture stress.

Adaptation: Crop may develop adaptations like deeper roots, reduced leaf area or osmotic adjustment to crops with the stress.

Increased susceptibility: Plants experiencing waterstress are more vulnerable to insect pests and diseases.

Reduced growth and yield: Both drought and waterlogging negatively impact to overall plant growth and can significantly reduce crop yield.

Metabolic disrupton: The stress disrupts vital plant functions including photosynthesis, suger production and metabolism.

Factors responsible for moisture stress

Factors that influence these effect include climate, soil type, crop characteristics and the specific growth stage of the plant. Environmental factors like precipitation, temperature and humidity affict the availability of water, while soil characteristics such as depth, texture and salinity determine how well the soil hold water. The plant's genetic makeup and developmental stage also play a crucial role in its ability to withstand or adopt to drought conditions.

Environmental factors

Climate: Factors like temperature and humidity directly influence the amount of water available in

the soil and the rate of transpiration affecting moisture stress levels.

Wind: Dry and windy conditions increase it, leading to higher usage by drops.

Soil: Soil type, depth, texture and water holding capacity are critical for water availability. Soil characteristics like salinity can also impact the plants ability to absorb water and nutrients.

Waterlogging: Excess water can fill soil pores leading to a lack of oxygen (hypoxia or anoxia) which damage roots and prevent water uptake.

Soil radiation: Higher solar radiation contributes to higher temperature and increase plant water needs.

Precipitation and drought: Insufficient or infrequent rainfall in the most direct couse of moisture deficiency.

Plant specific factors

Genetics: The inheren characteristics of the crop, such as its root system, leaf area and ability to perform osmotic adjustment, determine its tolerance to moisture.

Biochemical Processes: Moisture stress disrupts photosynthesis, nutrient transport and enzymatic reactions, leading to a decrease in a plant overall effectiveness.

Physiological Effects: Moisture stress can lead to wilting, yellowing and scorching of leaves and can cause oxidative stress through the generation of reactive oxygen species (ROS).

Growth and development: Reduced photoeunthesis leads to suppressed growth, lower quality produce and diminished yield.

Nutrient imbalance: Moisture stress can impair the absorption of essential nutrients like calcium and lead to an imbalance in plant minerals.

Increased Susceptibility: Plants under moisture stress may become more vulverable to insect pets, diseases and nutrient leaching.

Agricultural practices

Irrigation efficiency: Inefficient irrigation methods can lead to water loss through runoff or evaporation.

Physical damage: Damage to roots or stems from events like transplanting can impair the plants ability to take up water.

Management practices

Crop selction: Choosing drought-tolerant crop or varieties with good root systems is a preventire measure.

Mulching: Using soil covering materials like mulch (straw, cutting grass etc) and crop residue can reduce evaporation from the soil surface.

Efficient irrigation: Where possible, providing irrigation is a direct way to alleviate stress. Techno-logies like drip irrigation are efficient ways to delivers water directly to the roots.

Plant adaptation: Some plants have envolved to cope with stress through mechanism like deep roots, reduced leaf size or opening stomata at night to store water.

Adaptation of short duration crops: Choose short duration crop / verities to reduce the period of potential moisture stress.

Soil improvement: Increase organic matter in the soil through compost or farm yard manure to impro-

ve its water holding capacity.

Conclusion

Moisture stress happens when the water in a plant cells is reduced to not exactly normal leaves. They can occurs because to lack of water in the plant root zone, higher transpiration rates than the moisture uptake rate by the roots. An inability to absorb water because of high salt substance in the soil or roots damage due to transplantation.

Effective moisture stress management in crops is crucial for food security and involves a multi-faceted approach. Combing plant and soil based strategies with technological advancements. The crucial conclusion includes the need to select drought-tolerant varieties, improvement of soil health and adoption of efficient irrigation methods such as drip irrigation and micro-sprinklers lastely the ultimate goal is to minimize the negative impact of moisture stress on plant growth, yield, and quality, to ensuring sustainable agriculture and food security.

Herbicide Residues: Estimation Methods and Management

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Introduction

Herbicide residues: Any specified substances in food, soil, agricultural commodities and animal feed resulting from the use of a herbicide are called herbicide residues. It includes any derivatives of a herbicide, such as conversion products, metabolites, reaction products and impurities with toxicological significance.

Herbicide Residues can be estimated by

- ✓ Biological (bioassay)
- ✓ Chemical (GLC, HPLC) methods.

Bioassay method

- ✓ It involves growing of sensitive plants in soil containing trace levels of herbicide.
- ✓ Not accurate as chemical method.
- ✓ The sensitivity of crops to the level of herbicide residues in soil is reflected through variable growth inhibition levels.
- ✓ It is qualitative as well as quantitative
- ✓ It is of two types: Laboratory/pot culture and Field bioassay
- ✓ Field bioassay involve treating field with herbicide and then planting a test crop at various time interval
- ✓ Taking a crop in rotation after treating a crop in the previous season is also a sort of field bioassay

Sensitive/indicator plants (bio-assay materials)

Using sensitive indicator plants low levels of herbicide residues (so-called safe limit) could be detected.

- ✓ Plant species which produce small and relatively weak seedlings are not useful.
- ✓ Basic assumptions taken into consideration whenever bioassay is opted are:
  - Bioassay species will show an injury symptoms in proportion to herbicide concent-ration.
  - Response obtained are reproducible

Chemical method

- ✓ Involves complex chemical procedures, requires trained man power
- ✓ Gives very accurate estimation (up to nanogram level)
- ✓ Estimate herbicide residues in soil, water and even in the plant
- ✓ Costly and sophisticated equipment's are required.
- ✓ Exclusively laboratory method.

Herbicide Residue Management

Deactivation of herbicides: Deactivation is the process of chemically binding herbicides with organic amendments, such as compost or manure, to make them inactive and stop plants from absorbing them.

Reducing the availability of herbicides in soil: This technique limits the mobility and bioavailability

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of herbicides to crops and the environment by adsorbing them using soil additives like clay or activated charcoal.

Removal from site of contamination: To physically remove herbicide residues from the area, contaminated soil is either treated off-site or dug and disposed of at facilities with a license.

Cultural and mechanical management practices: Crop rotation, tillage, mulching, and cover crops are examples of techniques that interfere with weed cycles and encourage microbial activity that degrades pesticide residues.

Enhancing herbicide degradation: Microbial degradation is boosted by adding water, oxygen through tilling, and organic matter to stimulate soil microbes that metabolize herbicides faster.

Physiology of Fruit Development and Ripening in Vegetable Crops

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Introduction

Fruit development is a fundamental physiological process in vegetable crops and begins with the transformation of a fully matured ovary into a fruit after successful pollination and fertilization. This process involves a series of coordinated physiological, genetic, biochemical, and hormonal changes that regulate the growth, development, and maturation of the fruit. Fruit formation ensures the protection of developing seeds and aids in their dispersal while also contributing significantly to crop yield and quality in vegetable production. Fruit development generally occurs through four major phases. The first phase is fruit set, which takes place after successful pollination and fertilization, leading to the initiation of ovary growth. This is followed by a period of rapid cell division, where the number of cells in the developing fruit increases. The next stage involves cell enlargement or expansion, which contributes significantly to the increase in fruit size and weight. Finally, the fruit undergoes maturation and ripening, during which several physiological and biochemical changes occur, including alterations in color, texture, flavor, aroma and chemical composition. These processes are regulated by plant hormones such as auxins, gibberellins, cytokinins, ethylene and abscisic acid, along with environmental factors like temperature, light and nutrient availability. Understanding the physiology of fruit development and ripening is essential for improving fruit quality, yield, storage life, and post-harvest management in vegetable crops.

Fruit Set: Fruit set is the process in which a flower develops into a fruit after successful pollination and fertilization, which leads to the production of hormones such as gibberellins and auxins. These hormones signal the ovary to grow and develop into a fruit. In some plants, the fertilization process is bypassed, resulting in the formation of seedless fruits, a phenomenon known as parthenocarpy.

Model for Regulating Fruit Set: There are two main models explaining fruit set: the sugar signalling model and the multihormonal model. In the sugar signalling model, two conditions are involved. Under optimal conditions, sucrose is converted into glucose by the enzyme invertase, which promotes cell division and fruit set. However, under stressful conditions, sucrose is still converted into glucose by invertase, but this leads to programmed cell death and fruit abortion. In the multihormonal model, pollination and fertilization result in increased levels of the hormones auxin and gibberellin. These hormones stimulate cell division and cell expansion, thereby promoting fruit growth. Application of auxin results in a higher number of pericarp cells, whereas application of gibberellin (GA) leads to fewer but

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larger pericarp cells.

Gene Involved in Fruit Development: The FUL (Fruitfull) gene helps in the development of the fruit valves, which are the outer walls of the siliqua. It also suppresses the activity of other genes such as SHP1 and SHP2. The SHP1/2 (Shatterproof 1 and 2) genes are involved in forming the valve margins, which are the edges of the fruit valves. The RPL (Replumless) gene is responsible for the development of the replum, the central tissue that connects the two valves of the fruit. It also regulates and limits the activity of the SHP1/2 genes. The IND (Indehiscent) and ALC (Alcatraz) genes help in the formation of the dehiscence zone, a specialized region where the fruit opens to release seeds, such as in seed pod splitting. These genes are activated by SHP1/2. Together, these genes coordinate to regulate the structure and proper development of the siliqua fruit.

Cell Division and Cell Expansion

Cell Division: Cell division increases the number of cells in the developing fruit, contributing to fruit growth. This process is mainly regulated by plant hormones such as auxin, cytokinin, and gibberellins.

Cell Expansion: Cell expansion is a rapid, multi-stage process that occurs after pollination and fertilization, leading to an increase in cell size and contributing significantly to overall fruit growth.

Hormones Controlled in Fruit Growth

Auxin: Auxin plays an important role in initiating and promoting fruit set, cell division, and cell expansion, thereby signaling the ovary to develop into a fruit.

Cytokinin: Cytokinins enhance fruit size and fruit weight and promote shoot growth. They also delay senescence, and in some cases, cytokinins can induce parthenocarpic (seedless) fruit development.

Gibberellin: Gibberellins work together with auxins to stimulate cell expansion and promote fruit set and fruit development.

Fruit Growth

Early Stage: The fruit grows rapidly through cell division in the ovary wall and seed tissues.

Later Stage: After cell division, the cells enlarge through water uptake and accumulation of nutrients, which increases the overall size of the fruit.

Correlation between the Seed and Fruit Development

Seeds produce hormones such as cytokinins, which promote cell division during fruit growth. A higher number of seeds in a fruit generally results in larger fruit size due to increased hormone production.

Fruit Maturation: This is the phase in which the fruit reaches its maximum size and stops growing, followed by the formation of the abscission layer. During this stage, phenolic content decreases, while flavonoids such as epicatechin, catechin, quercetin, rutin, and myricetin remain predominant throughout fruit maturation. Anthocyanin content gradually increases during the maturation process. In addition, ethylene triggers the breakdown of chlorophyll and promotes the synthesis of pigments such as anthocyanins and carotenoids, leading to color development in the fruit.

Fruit Ripening: During fruit ripening, respiration and ethylene production are major physiological and biochemical changes. The respiration rate increases, leading to higher production of carbon dioxide (CO_2) and ethylene (C_2H_4).

Changes during Fruit Ripening Process

Colour Change: Before ripening, fruits contain a high concentration of chlorophyll a and b, which gives them a green color. As the fruit reaches the maturation stage, metabolic processes lead to the degradation of chlorophyll and the accumulation of pigments such as carotenoids and anthocyanins, resulting in characteristic fruit coloration.

Breakdown of Pectin and Cellulose: During ripening the cell wall structure undergoes modification, including cell wall thinning, pectin disassembly, and dissolution of the middle lamella. Enzymes such as polygalacturonase break down pectin, causing the fruit tissue to soften and the skin to become less rigid.

Starch Conversion: In the early stages of fruit development, starch is stored as a reserve carbohydrate. During ripening, the enzyme amylase converts starch into simple sugars such as glucose, fructose, and sucrose. At the same time, organic acids break down, reducing sourness and increasing sweetness, which improves fruit taste.

Flavour Development: Characteristic fruit flavour develops as acidity decreases during ripening. Organic acids such as citric acid and tartaric acid, which serve as energy sources, gradually decline during respiration. This reduction in acidity enhances the pleasant and balanced flavour of the fruit.

Aroma Formation: During ripening, fruits produce volatile aroma compounds that give them their distinct smell. These compounds mainly belong to chemical groups such as esters, aldehydes, alcohols, terpenoids, lactones and sulfur-containing compounds, which contribute to the sweet and fruity fragrance of ripe fruits.

Climacteric and Non-Climacteric Fruits

Fruits can be classified into two categories based on their ripening behavior:

Climacteric fruits: These fruits show a significant increase in respiration rate and ethylene production during ripening. They continue to ripen even after harvest. Examples include tomato and brinjal.

Non-climacteric fruits: These fruits do not exhibit a sharp increase in respiration or ethylene production and generally do not ripen further after harvest. They usually ripen only while attached to the mother plant. Examples include orange and other citrus fruits.

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Micro-Irrigation Systems as a Solution to Global Water Scarcity in Agriculture

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Water scarcity has emerged as one of the most critical challenges facing global agriculture in the 21st century. With increasing population, changing climate patterns, and declining freshwater resources, the pressure on agricultural water use has intensified significantly. Agriculture alone accounts for nearly 70% of global freshwater withdrawals, making efficient water management not just an option but a necessity. In this context, micro-irrigation systems have gained prominence as a sustainable and efficient solution to address water scarcity while maintaining crop productivity. Micro-irrigation refers to the application of water directly to the root zone of plants in a controlled manner, minimizing losses due to evaporation, runoff, and deep percolation. The two most widely used types of micro-irrigation systems are drip irrigation and sprinkler irrigation. Drip irrigation delivers water drop by drop through a network of pipes and emitters, ensuring precise water application. Sprinkler systems, on the other hand, simulate natural rainfall by distributing water through pressurized nozzles. Both methods significantly enhance water-use efficiency compared to traditional flood irrigation. One of the primary advantages of micro-irrigation is its ability to reduce water wastage. Studies have shown that these systems can save up to 30-70% of water compared to conventional methods. This is particularly crucial in arid and semi-arid regions where water resources are limited. More-over, micro-irrigation improves crop yield and quality by providing consistent moisture levels, reducing plant stress, and enabling better nutrient management through fertigation the application of fertilizers along with irrigation water. In addition to water conservation, micro-irrigation contributes to sustainable agricultural practices. By minimizing soil erosion and nutrient leaching, it helps maintain soil health over time. It also reduces weed growth, as water is delivered only to the targeted plant zones rather than the entire field. Furthermore, the integration of modern technologies such as sensors, automation, and Internet of Things (IoT) systems has transformed traditional irrigation into smart irrigation, allowing farmers to monitor soil moisture, weather conditions, and crop requirements in real time. Despite its numerous benefits, the adoption of micro-irrigation systems faces certain challenges. High initial installation costs, lack of technical knowledge and maintenance issues often discourage small and marginal farmers from adopting these technologies.

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However, government initiatives, subsidies, and awareness programs can play a crucial role in overcoming these barriers. For instance, schemes promoting efficient irrigation practices have already demonstrated positive impacts in several developing countries. In conclusion, micro-irrigation systems offer a promising pathway to address global water scarcity in agriculture. By enhancing water-use efficiency, improving crop productivity and supporting sustainable farming practices, these systems align with the goals of food security and environmental conservation. As water resources continue to decline, the widespread adoption of micro-irrigation will be essential in ensuring a resilient and sustainable agricultural future.

Trichoderma: A Biological Fungicide

Vishal D. Pawar and Kishor T. Thakre

Introduction

In recent years, the use of biological control agents has gained significant importance as a sustainable alternative to chemical fungicides. Among them, *Trichoderma* has emerged as one of the most effective and widely used beneficial fungi for the management of plant diseases. It plays a crucial role in Integrated Disease Management (IDM) by reducing dependency on chemicals and promoting eco-friendly agriculture. Soil-borne fungal pathogens such as Fusarium, Rhizoctonia, Sclerotium, and Pythium are responsible for serious crop diseases like wilt, damping-off, and root rot. These pathogens cause heavy yield losses in many agricultural crops. *Trichoderma* provides an efficient and environmentally safe solution for managing these diseases. Some of the commonly used species of *Trichoderma* include *Trichoderma harzianum*, *Trichoderma viride* and *Trichoderma asperellum*. These formulations are readily available in agricultural universities, Krishi Vigyan Kendras (KVKs), and various agro-input markets in different carrier forms such as talc-based powder, liquid formulations, and granules.

Mode of Action of *Trichoderma*

Trichoderma controls plant pathogens through multiple mechanisms, making it a powerful biological control agent:

Mycoparasitism (Direct Attack): *Trichoderma* grows rapidly and coils around the hyphae of pathogenic fungi. It penetrates and destroys them by secreting cell wall-degrading enzymes, ultimately absorbing nutrients from the host fungi.

Competition for Nutrients and Space: Being a fast-growing organism, *Trichoderma* competes aggressively with pathogenic fungi for essential nutrients such as carbon, nitrogen, and vitamins, thereby suppressing their growth and multiplication.

Antibiosis: It produces several antifungal secondary metabolites such as gliotoxin, viridin, and other antibiotic compounds that inhibit or kill pathogenic fungi.

Root Colonization and Protection: *Trichoderma* forms a protective barrier around plant roots by colonizing the rhizosphere. This prevents pathogen entry and enhances plant defense mechanisms.

Induced Resistance: It also stimulates the plant's natural defense system, helping the plant to resist future pathogen attacks more effectively.

Methods of Application of *Trichoderma*

Trichoderma can be effectively applied in different ways depending on the crop and disease

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condition:

Seed Treatment

- ✓ This is the most common and economical method.
- ✓ Mix 4-10 grams of *Trichoderma* powder per kg of seeds.
- ✓ Coat seeds uniformly and dry them in shade before sowing.
- ✓ This improves germination and protects seedlings from soil-borne pathogens.

Soil Treatment

- ✓ Mix 5 kg *Trichoderma* formulation with 500 kg well-decomposed farmyard manure (FYM) per hectare.
- ✓ Broadcast uniformly in the field and incorporate into the soil.
- ✓ Irrigation after application enhances its effectiveness.

Root Dipping

- ✓ Prepare a suspension using 500 grams *Trichoderma* in 5 liters of water.
- ✓ Dip seedlings for 5-10 minutes before transplanting.
- ✓ For fruit plants, apply a solution of 10-15 g per liter of water around the root zone.

Organic Manure Enrichment (Composting)

- ✓ Prepare compost using crop residues, leaves, dung, and farm waste.
- ✓ Add 1 kg *Trichoderma* per ton of organic material layer by layer.
- ✓ Maintain moisture and cover the pit properly for better decomposition.
- ✓ This accelerates decomposition and improves manure quality.

Foliar and Field Application: In some cases, liquid formulations are sprayed on crops or applied near the plant base to enhance disease suppression.

Benefits of *Trichoderma*: *Trichoderma* offers multiple agronomic and environmental benefits:

- ✓ Eco-friendly and safe for the environment
- ✓ No harmful residues in soil or crops
- ✓ Reduces development of resistance in pathogens
- ✓ Improves soil health and organic matter decomp-ostion

- ✓ Enhances seed germination and seedling vigor
- ✓ Provides long-term protection against soil-borne diseases
- ✓ Reduces input costs and increases crop yield
- ✓ Produces plant growth-promoting substances
- ✓ Supports sustainable and organic farming practices

Important Guidelines for Effective Use

- ✓ Store *Trichoderma* in a cool, dry place away from direct sunlight.
- ✓ Avoid mixing with strong chemical fungicides unless necessary; if used, increase dosage accordingly.
- ✓ Can be combined with biofertilizers like *Rhizobium*, *Azotobacter*, *Azospirillum* and PSB for better results.
- ✓ Ensure sufficient organic matter in soil for better colonization and activity.

- ✓ Avoid excessive chemical fungicide use to maintain microbial balance in soil.

Conclusion

Trichoderma is a highly effective biological control agent that plays a vital role in sustainable agriculture. Its ability to suppress soil-borne pathogens, improve soil fertility, and promote plant growth makes it an essential component of Integrated Disease Management (IDM). The use of *Trichoderma* not only enhances crop productivity but also contributes to environmental safety and long-term soil health. Therefore, its adoption should be encouraged among farmers as a reliable and eco-friendly plant protection strategy.