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Advanced Imaging and Sensor-Based Technologies for Early Identification of Post-Harvest Damage in Fruits, Vegetables, and Grains

Abstract

Over the past two decades, food scientists have attempted to develop new methods for detecting insect infestation in postharvest fruits and vegetables through various non-destructive techniques. With time, expectations for higher nutritional value and improved taste in fresh produce have increased. In addition, due to the strict quarantine regulations being implemented by regulatory agencies for the commercial import and export of fresh produce, there is an increasing need for advanced technologies that can provide rapid, accurate, and reliable detection of insect infestation before fruits and vegetables are commercialized. For these reasons, the food industry is seeking alternative, safe, and non-destructive methods to enhance and maintain food quality. Many studies have focused on the development of rapid, accurate, and reliable insect-infestation monitoring systems in order to replace conventional invasive and subjective methods, which often prove to be ineffective. Although significant progress has been achieved in in-field and postharvest online monitoring systems, several important limitations still remain in their practical applications.This article presents a comprehensive overview of the non-destructive techniques currently used to detect insect-induced damage in fruits and vegetables and discusses the fundamental principles and applications of sensor-based monitoring systems. It provides a detailed description of specific methods for detecting postharvest insect infestation in fruits, including their underlying principles, protocols, specific application examples, characteristics, and limitations.

1. Introduction

According to data provided by the United Nations, the world's human population has reached 8 billion, and it is projected to increase to approximately 9.8 billion by the year 2050. As the population continues to grow, the demand for sustainable and affordable food sources is also increasing, thereby further emphasizing the importance of agriculture in the context of sustainable development. From the perspective of food production and quality control, agricultural challenges can generally be divided into three main stages: pre-harvest, harvest, and post-harvest. Each stage involves numerous factors that must be carefully considered in order to minimize food waste.

The factors affecting shelf life during the post-harvest stage vary for each crop, and all of them must be properly taken into account. Neglecting any one of these factors, or errors occurring during storage or transportation, may result in post-harvest food losses. Examples of post-harvest losses in stored fruits and vegetables include decay and spoiled areas, which are often caused by improper handling, lack of hygiene, inadequate humidity control, improper temperature management, and mechanical damage. All of these factors contribute to quality deterioration and loss in stored produce.

Traditionally, the detection of pests and quality assessment in horticultural products have been carried out using manual and destructive methods, based on external symptoms as well as protein and DNA analysis. These methods are time-consuming, labor-intensive, expensive, and subjective. Furthermore, they are not suitable for the packaging industry because they cause damage to fruit tissues.

In contrast, non-destructive methods are more effective and advantageous, as they can assess the internal structure and quality of fruits and vegetables without causing damage. These methods can be implemented in online systems to examine all fruits and separate high- and low-quality products, thereby ensuring overall quality. Commonly used non-destructive methods to prevent post-harvest losses include RGB video cameras and sensors, Near-Infrared (NIR) data, gas-sensing spectroscopy, fluorescence spectroscopy, Magnetic Resonance Imaging (MRI), and Electronic Nose systems. Despite these advancements, post-harvest food losses are still estimated to range between approximately 40–50%.

Artificial Intelligence (AI) and its subfields—Machine Learning (ML) and Deep Learning (DL)—have been successfully applied across numerous domains by integrating them with recent advancements in Computer Vision (CV), remote sensing, wireless sensing technologies, and the Internet of Things (IoT). These applications span a wide range of fields, including space science, medicine, electrical engineering, agriculture, and the food supply chain. For example, farmers use computer vision–based technologies for crop quality management, such as plant growth monitoring, fruit detection, disease detection, and weed detection. These technologies are essential for improving food quality across all three stages: pre-harvest, harvest, and post-harvest. In addition, several computer vision–based methods are available for estimating and assessing post-harvest losses in stored crops.

Several techniques have been reported for the non-destructive detection of insect infestation, including Near-Infrared (NIR) spectroscopy, acoustic methods—such as sound, noise, and vibration imaging—visible light sensing, hyperspectral imaging, nuclear magnetic resonance, X-ray imaging, volatile emission analysis, and other digital imaging techniques.Further non-destructivre methods explained in detail .

2. Non-Destructive Methods

2.1 Spectroscopic Techniques

Near-Infrared Spectroscopy (NIR Spectroscopy) is a highly effective non-destructive technique for detecting insect infestation in fruits and vegetables. This technique utilizes the Near-Infrared (NIR) region of the electromagnetic spectrum (780–2500 nm), which is sensitive to chemical bonds such as C–H, O–H, and N–H, enabling the evaluation of the chemical and physical properties of food materials.

It detects infestation in two ways: either directly by identifying the presence of insects or larvae, or indirectly through changes in spectral properties caused by alterations in color, firmness, dehydration, and microbial activity in infected tissues. Research findings indicate that the interactive mode (permeation) provides better classification accuracy compared to reflectance and transmittance modes. Additionally, short NIR wavelengths (850–1888 nm) have been found to be more effective for smaller fruits.For example, studies have reported an accuracy of 82–87% in detecting plum insect infestation in tart cherries, only a 4.2% error rate in detecting fruit fly eggs/larvae in green mangoes, and a 90.6% classification rate in identifying carob moth larvae in pomegranates.

The major advantages of NIR spectroscopy include that it does not damage fruit tissues, provides rapid results, and has the capability to measure multiple quality attributes simultaneously. Therefore, NIR spectroscopy represents a highly effective approach for the rapid, accurate, and non-destructive detection of insect infestation in fruits and vegetables.

2.2. Visible Light Sensing

Over the past four decades, the use of machine vision systems in agricultural products has increased, including applications such as sorting fruits and vegetables, and detecting defects and diseases. Visible (RGB) cameras, operating within the wavelength range of 380–750 nm, are useful for identifying external surface defects.

For example, Blasco et al. used RGB and other optical sensors to detect deterioration caused by thrips, scales, and Mediterranean fruit fly (medfly) eggs in citrus fruits. Simple classification based on RGB and color spaces (HSI, CIE Lab*, Luv*) achieved an accuracy of 43–78%, whereas the use of a Region-Oriented Segmentation Algorithm (ROSA) increased classification accuracy to 93–100%. By employing multivariate image analysis and techniques such as Principal Component Analysis (PCA) along with a Bayesian discriminant classifier, the identification of defective samples reached an accuracy of 92–93%. However, visible color image systems are effective only for detecting surface defects. For internal defects or hidden infestations, wavelength-based techniques such as hyperspectral or multispectral imaging are more accurate.

3. Imaging Techniques

3.1. Hyperspectral Imaging System

Hyperspectral Imaging (HSI) systems are widely used in agricultural products and food processing for non-invasive quality evaluation and for detecting insect infestation in fruits and vegetables. The HSI technique generates a hypercube dataset from the scanned sample, which includes x and y spatial coordinates along with the λ (wavelength) coordinate. This data can be correlated with the physical and chemical properties of fruits and vegetables, enabling accurate detection of infestation. A major advantage of the HSI system is its ability to detect hidden internal damage, thereby reducing reliance on random sampling, lowering the risk of infestation during transportation, and decreasing processing costs within the supply chain.

An HSI system consists of light sources operating in the visible and NIR ranges, a spectrograph, and a CCD/CMOS camera. Data acquisition is performed using different scanning modes, including line (push-broom), point, area, and single-shot modes. During scanning, reflectance, transmittance, or interactance modes are selected depending on the application. Relative reflectance is normalized to minimize errors caused by variations in light source intensity. To simplify the analysis of large hypercube datasets and the decision-making process, mathematical and machine learning approaches such as Partial Least Squares (PLS), Stepwise Discriminant Analysis (SDA), Genetic Algorithm (GA), Sequential Forward Selection/Sequential Backward Selection (SFS/SBS), and Soft Independent Modeling of Class Analogy (SIMCA) are employed, enabling the development of multispectral models.

The application of HSI technology has achieved high accuracy in detecting insect infestation in various fruits and vegetables. For example, classification rates of up to 99% have been reported for detecting fruit fly larvae in mangoes, 98% and 94% classification rates for external insect infestation in jujubes, and 97–100% classification rates for infestation in soybeans. However, HSI is not yet fully adopted in commercial applications, primarily due to the requirement for near-perfect accuracy and the complexities involved in algorithm selection. In the future, advanced analytical techniques such as deep learning, bagging, and boosting can further enhance the accuracy of HSI measurements.

The HSI system involves processes such as data acquisition, preprocessing, calibration, validation, dimensionality reduction, and recalibration, and the selection of the most suitable algorithm is often based on trial-and-error approaches.

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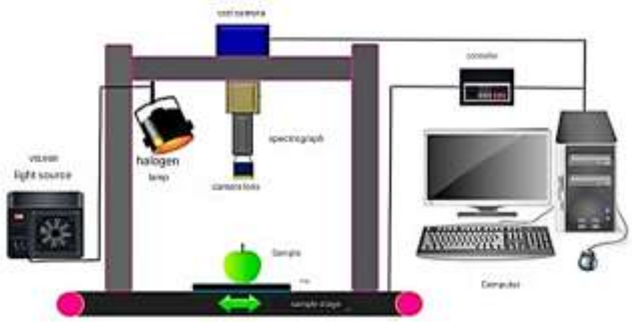

Figure 1. Components of a push-broom hyperspectral imaging system (Source: Adedeji et al., 2020)

3.2. X-ray Imaging

The X-ray imaging system is based on the principle of transmission imaging, in which X-ray rays pass through an object and are attenuated according to its density and thickness. Based on this attenuation, differences in internal structure (contrast) are produced, allowing the detection of hidden insect infestations or internal defects in fruits and vegetables. In the agricultural sector, X-ray imaging has been used as a non-destructive technique for seed quality inspection, evaluation of low-moisture products, and detection of concealed insect infestations.

Various studies have reported good accuracy in identifying insect infestations using X-ray imaging. For example, classification rates ranging from 90–100% have been reported for detecting fruit flies, seed weevils, and other insects in fruits such as mangoes, apples, cherries, olives, and dates. However, accuracy decreases in cases of early-stage or low-level infestation. For the analysis of X-ray images, grayscale intensity, texture features, and various classification algorithms (such as Linear Discriminant Analysis (LDA) and Bayesian classifiers) have been utilized.

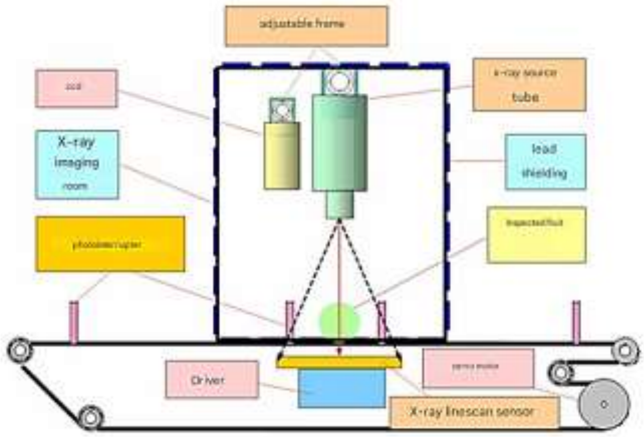

Figure 2. Layout of the X-ray quarantine scanning system (Source: Adedeji et al., 2020)

3.3. Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging (MRI), unlike X-ray or CT imaging, is a non-ionizing technique, meaning that it does not use harmful radiation. This technique was first applied in the medical field. The fundamental principle of MRI is that when the hydrogen nuclei (primarily found in water) within an object are subjected to a strong and uniform magnetic field, high-quality internal images can be obtained with the help of radiofrequency waves. Since different tissues contain varying amounts of water, contrast is generated in the image, allowing the internal structure to be clearly visualized.

The use of MRI in food quality inspection is still limited because the equipment is very expensive and complex to operate. Some studies have applied MRI to detect hidden insects inside fruits. For example, Torres used a low-field MRI system to detect fruit flies in peaches, achieving identification accuracies of 58% for healthy fruits and 71% for infected fruits. Similarly, Haishi and colleagues employed an MRI system with a 0.2 Tesla magnetic field to detect peach fruit moth infestation in apples. They demonstrated that larvae inside the fruit could be detected using a single-slice method in only 6.4 seconds, while the multi-slice method could cover a larger area within a few minutes.

3.4. Thermal Imaging

Thermal imaging is a sensing technique that was initially developed for military purposes. Later, its applications were extended to agricultural and food processing monitoring. A typical thermal imaging system consists of a thermal camera that includes an infrared detector, a signal processing unit, and an image acquisition unit. This technique operates by measuring the thermal energy emitted from the surface of an object. The differences in temperature across various parts of the object form the basis for generating a thermal image. These thermal values are first converted into electrical signals and then processed by the signal processing unit to produce the final image. Similar to X-ray imaging, image segmentation techniques are used in thermal imaging to identify infected regions.

Several studies have employed thermal imaging to detect insect infestation in fruits and crops. For example, Hansen and colleagues used an infrared camera sensitive to wavelengths of 7.5–15 micrometers to detect codling moth infestation in apples. Their study found that infected fruits appeared slightly cooler in thermal images compared to healthy fruits. This temperature difference was not affected by storage temperature or infestation conditions. Similarly, Chen and co-researchers used an Android-based thermal imaging system to detect powdery mildew disease in maize, enabling precise pesticide application. In another study, Chelladurai and other researchers utilized thermal imaging combined with machine learning techniques to detect cowpea seed beetle infestation in mung beans, achieving approximately 80% accuracy.

Although thermal imaging is a non-destructive and useful technique that can be applied for insect detection both in the field and during the post-harvest stage, it has certain limitations. Therefore, combining thermal imaging with another non-invasive technique, such as color vision, may further improve its reliability and effectiveness.

Figure 3: Thermal imaging setup (Source: Elmasry et al., (2020)).

4. Sensor-Based Monitoring in Crop Storage Facilities

Modern crop storage facilities are increasingly relying on sensor-based systems designed to maintain optimal storage conditions and prevent spoilage, insect infestation, and microbial contamination. Based on the technological possibilities described earlier, these systems continuously monitor temperature, relative humidity, and gas concentrations, and provide real-time feedback to automated control systems.

Rather than reiterating environmental challenges, this section focuses on how sensors function, how they perform measurements, how they respond to environmental changes, and how data-driven automated management optimizes storage systems.

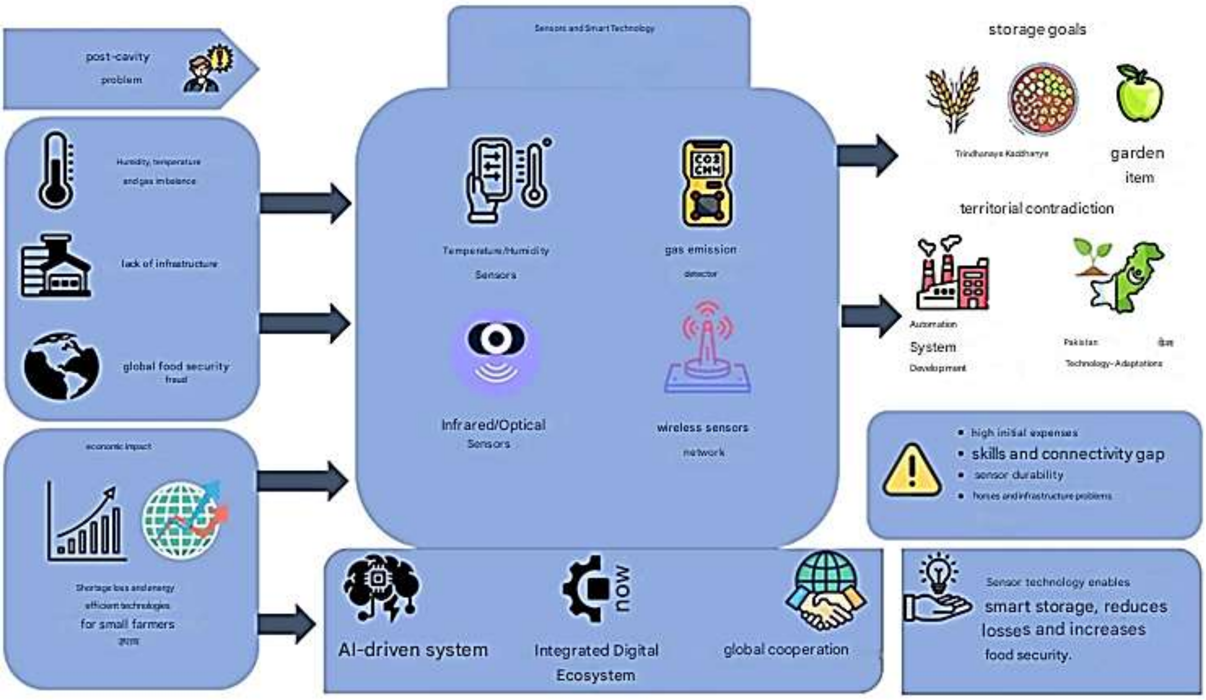

Figure 4: Sensor technology for disease detection in agricultural products

4.1 Environmental Condition Monitoring

4.1.1 Temperature Variation and Control

Temperature sensors such as thermocouples, Resistance Temperature Detectors (RTDs), and infrared sensors measure temperature variations at different locations within storage facilities. The data obtained from these sensors are transmitted to automated climate control systems, which operate ventilation systems, aeration fans, and cooling units to maintain temperature within a safe range (typically 10–15 °C for grains).

Advanced systems incorporate localized sensor networks capable of detecting temperature increases in specific zones, enabling corrective actions such as targeted cooling or increased airflow. In large grain silos, sensors installed at different depths help identify areas at higher risk of spoilage due to moisture accumulation and heat generation. This allows managers to focus only on affected zones rather than cooling the entire storage facility, thereby saving energy. Through IoT platforms, remote monitoring and control are also possible, and historical temperature data can be used to predict future risks.

4.1.2 Relative Humidity and Moisture Detection

Capacitive and resistive humidity sensors continuously monitor relative humidity inside grain storage units, while moisture sensors directly measure the moisture content of grain kernels. This information supports the dynamic control of aeration systems to maintain moisture balance.

Moisture monitoring is particularly critical immediately after harvest during drying and throughout long-term storage. Sensors ensure that grains are dried below safe moisture levels (typically 12–14%). Additionally, these sensors can detect condensation within storage walls or packaging, providing early warnings of potential spoilage. In recent years, the use of wireless sensor nodes has increased; these can be installed directly within grain piles to obtain real-time moisture profiles without disturbing the stored product.

4.1.3 Gas Emissions and Spoilage Indicators

Changes in gas composition within storage facilities often serve as early indicators of spoilage. Sensors capable of detecting gases such as carbon dioxide (CO_2), ammonia (NH_3), and volatile organic compounds (VOCs) help identify biological activity associated with fungal growth, insect respiration, or grain deterioration. Elevated CO_2 levels, for example, may indicate increased metabolic activity due to insect infestation or microbial growth. Continuous gas monitoring enables early intervention through aeration, fumigation, or environmental adjustments before significant damage occurs.

Early detection of fungal, insect, and rodent infestations in stored grains relies on advanced sensing technologies that identify subtle changes before visible damage occurs. In the case of fungal detection, biosensors and optical sensors monitor variations in temperature, humidity, and gas emissions, as well as directly detect fungal spores or mycotoxins, allowing timely aeration or treatment to maintain food safety. For insect detection, acoustic sensors capture sounds from insect movement and feeding within grain masses, enabling identification of infestations at an early stage; when combined with pheromone traps, this approach supports targeted pest control and reduces excessive chemical use. Similarly, rodent detection utilizes motion sensors, infrared cameras, and ultrasonic sensors to identify activity in storage areas, while smart traps provide real-time alerts to facility managers, ensuring quick intervention and minimizing contamination risks.

Figure 5: a) Temperature and humidity sensors b) Gas sensors, insect and fungal detectors and d) Rodent detectors (infrared cameras) (Source: Ahmed et al., 2023)

5. Conclusion

Post-harvest losses in fruits and vegetables—driven by insect infestation, fungal growth, decay, and internal quality deterioration—remain a major challenge to global food security, economic stability, and sustainable agriculture, further intensified by population growth, rising consumer expectations, and strict international quarantine regulations. Traditional inspection methods are often slow, labor-intensive, costly, and subjective, making them unsuitable for modern supply chains, whereas non-destructive imaging and sensor-based technologies offer efficient alternatives for assessing both internal and external quality without causing damage. Techniques such as Near-Infrared (NIR) spectroscopy, visible and hyperspectral imaging, X-ray imaging, Magnetic Resonance Imaging (MRI), thermal imaging, acoustic sensing, and gas and chemical sensors enable early, rapid, and accurate detection of insect infestation and quality deterioration, with hyperspectral and NIR methods excelling at identifying hidden internal defects and visible imaging better suited for surface issues. Furthermore, sensor-based storage monitoring systems play a crucial role in early-stage detection of fungal, insect, and rodent infestations by continuously tracking temperature, humidity, moisture, and gas emissions in real time, thereby reducing reliance on chemical treatments and enhancing overall storage management efficiency.

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NATURAL FARMING AS A CLIMATE-RESILIENT APPROACH TO SUSTAINABLE AGRICULTURE

ABSTRACT

Natural farming is an agricultural approach in which crops are cultivated in harmony with the natural environment, without the application of insecticides, pesticides, herbicides or other synthetic chemicals. This system functions by aligning farming practices with the inherent biodiversity of each region, thereby promoting ecological balance and enhancing the complexity of living organisms. Instead of relying on toxic inputs, natural farming emphasizes the use of light, alcohol, aroma, and other natural substances to improve soil fertility. Nutrient requirements are fulfilled through natural sources of nitrogen, phosphorus, and potash. According to Masanobu Fukuoka, natural farming adopts traditional methods that reduce labour requirements, minimize disturbance to nature, and maintain soil properties. Similarly, Yoshikazu Kawaguchi built upon Fukuoka's principles, focusing on minimal human intervention in natural processes. Cho Han Kyu introduced Korean Natural Farming, which emphasizes shifting away from chemical-based practices through the use of indigenous microorganisms, fermented plant juice and the nutritional cycle theory. Zero-budget natural farming represents another approach, where no external inputs are used and all resources are derived from within the farm. Additionally, the concept of effective microorganisms involves introducing beneficial microbes into the soil to enhance plant growth, soil health, and overall agricultural sustainability.

Keywords: Natural farming, Sustainable agriculture, rishi krishi, zero budget natural farming, microorganisms

INTRODUCTION

In a natural farming system, agricultural practices are carried out in accordance with the laws of nature. This approach enhances the natural biodiversity of each farm by encouraging the development of complex living systems, including both plant and animal components of the ecosystem. Soil microorganisms play a crucial role in regulating soil processes and significantly contribute to improving soil health (Bonanomi et al., 2016). Natural farming emphasizes reducing dependence on external inputs while promoting the natural regeneration and nourishment of soil. Practices such as zero tillage help preserve soil structure, whereas mulching aids in conserving soil moisture and reducing irrigation requirements. The system relies on site-specific biodiversity, giving importance to the interaction between crops, flora and fauna present within the farming environment. Unlike conventional farming, natural farming also incorporates aesthetic and spiritual values alongside productivity. Natural farming represents a philosophy that views humans as an integral part of nature rather than separate from it. It is often referred to as "the natural way of farming," "the Fukuoka Method," or "do-nothing farming" (Nene, 2017).

The term "do-nothing" does not imply inactivity, but rather the avoidance of unnecessary inputs, interventions, and machinery. While natural farming shares similarities with systems such as agroecology, agroforestry, eco-agriculture, fertility farming, organic farming, permaculture, and sustainable agriculture, it remains distinct from biodynamic agriculture.

MASANOBU FUKUOKA

Masanobu Fukuoka, a renowned Japanese farmer and philosopher, was the pioneer of natural farming. He successfully restored degraded and desertified land into fertile, biologically active ecosystems through his innovative approach. Fukuoka advocated grain production systems based on no-tillage and the complete avoidance of herbicides, reflecting practices traditionally followed in many indigenous farming cultures. He developed a distinctive method known as "Natural Farming" or "Do-nothing farming" (Nene, 2017). Fukuoka's Principles: According to Fukuoka, there are five principles in natural farming: (i) No fertilizer (ii) No herbicides or pesticides (iii) No pruning (iv) No-tillage and (v) No weeding. These principles emphasize minimal human intervention in natural processes. Soil cultivation through ploughing or tillage is considered unnecessary, as the soil maintains its structure and fertility naturally. The use of chemical fertilizers is avoided due to their negative impacts on the environment and human health. Similarly, herbicides and pesticides are excluded, allowing ecological balance to regulate pests and weeds. Weed management is limited to minimal disturbance practices, ensuring natural suppression without harming the soil.

FORMS OF NATURAL FARMING

Fertility Farming

Soil fertility refers to the capacity of soil to provide essential nutrients and favourable conditions required for optimal plant growth. It results from the combined action of physical, chemical, and biological processes that ensure adequate nutrient supply, water availability, aeration, structural stability, and the absence of harmful substances. In 1951, Newman Turner proposed the concept of "Fertility Farming," which emphasizes a system with no tillage, no weeding, no synthetic fertilizers, no composting, and no pesticides, while relying on the use of cover crops to maintain soil health (Thakur *et al.*, 2020).

Rishi Krishi

Rishi Krishi focuses on maintaining soil vitality through the utilization of cosmic energy, which is considered the fundamental driver of plant growth and development. This approach assumes that plants can interact with soil microorganisms and that external inputs, whether organic or inorganic, are not required. Instead, cosmic energy in its natural forms is believed to support high crop productivity (Ram and Pathak, 2016). The system is rooted in traditional knowledge and highlights the importance of 'Angara' (rhizosphere soil collected from the banyan tree, Ficus benghalensis) and 'Amrit Pani' for enhancing soil biological activity. Amrit Pani is a bio-enhancer prepared by fermenting cow dung with cow ghee and honey (Garg and Ram, 2017).

Zero Budget Natural Farming (ZBNF)

ZBNF was pioneered by Subhash Palekar is regarded as the "Father of Zero Budget Natural Farming" all over the country. It is a method of farming that emphasizes on the natural development of crops without any addition of fertilizer, pesticides, or any other foreign elements. The word 'Zero Budget' in agriculture, indicates to the zero-net cost of production of all crops (Korav *et al*., 2020). A farmer practicing Zero Budget Natural Farming has a lower cost of input and thus has a better capacity to increase income. The crops cultivated under ZBNF help in retaining soil fertility. Cow dung and cow urine are considered the best inputs for seed treatments and other inoculations. ZBNF has four pillars Jivamrita, Bijamrita, Acchadana (Mulching) and Whapasa (moisture). Other key concepts include intercropping, contour and bund systems, and native earthworm species. Additionally, Palekar provides formulas for pest management, Agniastra, Brahmastra, and Neemastra (Bishnoi and Bhati, 2017).

Organic mulching

Mulching is an important natural farming practice that involves covering the soil surface with organic materials such as leaves, straw, and plant residues. This technique helps prevent soil erosion and nutrient loss, improves soil fertility, and enhances water-holding capacity. It also creates a favourable habitat for soil microorganisms and promotes humus formation. Additionally, mulching suppresses weed growth and supports the proliferation of beneficial organisms such as earthworms, thereby improving overall soil quality (Ranjan *et al*., 2017).

FUTURE PERSPECTIVE AND CHALLENGES IN NATURAL FARMING

Natural farming, which emphasizes harmony with ecological processes and minimal external inputs, presents a sustainable pathway for agriculture. However, its large-scale adoption faces several technical, socio-economic, and environmental challenges that must be addressed for long-term success.

One of the major constraints is yield variability, as natural farming systems depend heavily on biological processes and environmental conditions. In the absence of synthetic inputs, crop performance becomes more sensitive to fluctuations in weather, soil fertility, and pest incidence, leading to inconsistent productivity (Kumar *et al*., 2020). Weed and pest management also remains a critical challenge. Although practices such as crop rotation, companion planting, and biological control are integral to natural farming, they are often less immediate in effect and may require greater labour and ecological understanding compared to chemical methods (Bana *et al*., 2022). Effective management therefore depends on continuous monitoring and a deep understanding of agroecosystems (El-Zik and Frisbie, 2018). Another important limitation is the lack of knowledge and awareness among farmers. Adoption of natural farming requires specialized skills, including understanding of ecological interactions, soil biology, and alternative crop management practices. Limited access to training, extension services, and awareness programs can hinder its widespread acceptance (Sumane *et al*., 2018). In terms of infrastructure and technology, natural farming is often labour-intensive and may lack adequate mechanization and modern tools suited for organic systems. The absence of data-driven technologies further restricts precision management and scalability (Roy *et al*., 2024). Climatic variability poses an additional risk, as natural farming systems are more exposed to irregular rainfall, extreme temperatures, and changing pest dynamics. These factors can significantly influence crop growth and productivity, necessitating resilient and adaptive farming strategies (Singh and Reddy, 2013). Lastly, consumer awareness and market support remain limited. Misconceptions about productivity and benefits can reduce demand, highlighting the need for better awareness of the environmental and health advantages of natural farming (Nuttavuthisit and Thogersen, 2017).

FUTURE PERSPECTIVE

Despite these challenges, natural farming holds strong potential for sustainable agriculture by improving soil health, conserving biodiversity, and reducing environmental degradation. Its future success depends on integrating traditional knowledge with modern scientific approaches, strengthening research and extension systems, promoting supportive policies, and enhancing market linkages. A collaborative effort among farmers, researchers, policymakers, and consumers will be essential to scale up natural farming as a viable and resilient agricultural system.

CONCLUSION

Natural farming offers strong potential to mitigate climate change by enhancing soil carbon sequestration, reducing dependence on chemical inputs, and promoting biodiversity-based farming systems. Rooted in the principles of Masanobu Fukuoka, it supports low-emission agriculture while improving soil health and ecosystem resilience. By integrating ecological processes with sustainable practices, natural farming emerges as a viable pathway for climate-resilient and environmentally sustainable agriculture.

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ARTICLE ID: 03

CROP DIVERSIFICATION AS A STRATEGY FOR LONG-TERM AGRICULTURAL SUSTAINABILITY

Abstract

Crop diversification has emerged as a key strategy to ensure long-term agricultural sustainability, particularly in regions dominated by monocropping systems such as the rice–wheat system in Punjab. Continuous cultivation of limited crops has led to ecological imbalances, declining soil fertility, groundwater depletion, and increased vulnerability to pests and diseases. Crop diversification involves the inclusion of a variety of crops such as pulses, oilseeds, fruits, vegetables, and fodder crops to improve system productivity, resource-use efficiency, and environmental sustainability. This review paper discusses the concept, importance, benefits, challenges, and future prospects of crop diversification in achieving sustainable agriculture. The paper highlights that diversification not only enhances soil health and biodiversity but also improves farmers' income and resilience to climate variability. However, its adoption requires strong policy support, infrastructure development, and farmer awareness.

Introduction

Agriculture plays a crucial role in ensuring food security, livelihood generation, and economic stability in developing countries like India. However, the intensive cultivation of cereal-based cropping systems, particularly the rice–wheat system in Punjab and other parts of the Indo-Gangetic Plains, has resulted in severe ecological and economic challenges. Over-exploitation of natural resources, especially groundwater, declining soil fertility, and increasing pest and disease incidence have threatened the sustainability of these systems.

Crop diversification is considered a viable solution to these problems. It involves the introduction of alternative crops into existing cropping systems to reduce dependency on a single crop or a narrow range of crops. Diversification enhances system resilience, improves resource utilization, and contributes to environmental conservation. In recent years, there has been growing recognition of the need to shift from monoculture to diversified farming systems to achieve long-term sustainability.

Figure1 Diagram representing crop diversification

Concept of Crop Diversification

Crop diversification refers to the practice of cultivating a variety of crops in a given area over time and space. It includes strategies such as crop rotation, intercropping, mixed cropping, and multiple cropping. The main objective is to optimize the use of available resources and reduce risks associated with crop failure.

Diversification can be horizontal (increasing the number of crops grown) or vertical (adding value through processing and marketing). It may also involve shifting from low-value to high-value crops such as fruits, vegetables, and medicinal plants. The selection of crops depends on factors such as climate, soil type, water availability, and market demand.

Need for Crop Diversification

The need for crop diversification arises due to several constraints associated with monocropping systems. Continuous cultivation of rice and wheat has led to the depletion of groundwater resources, especially in Punjab and Haryana. The excessive use of chemical fertilizers and pesticides has degraded soil health and caused environmental pollution.

Moreover, monocropping systems are highly vulnerable to climate variability, pests, and diseases. Farmers also face economic risks due to price fluctuations and limited income sources. Crop diversification helps in addressing these challenges by improving system stability, reducing input costs, and enhancing profitability.

Role of Crop Diversification in Agricultural Sustainability

Soil Health Improvement

Diversified cropping systems improve soil structure, increase organic matter content, and enhance microbial activity. Inclusion of leguminous crops helps in biological nitrogen fixation, reducing the need for synthetic fertilizers.

Pest and Disease Management

Crop diversification disrupts pest and disease cycles, thereby reducing their incidence. It also minimizes the reliance on chemical pesticides, promoting eco-friendly farming practices.

Climate Change Mitigation and Adaptation

Diversified systems are more resilient to climate variability. They help in carbon sequestration, reduce greenhouse gas emissions, and enhance the adaptive capacity of farming systems.

Challenges in Crop Diversification

Despite its benefits, the adoption of crop diversification faces several challenges. These include lack of assured markets for alternative crops, inadequate infrastructure for storage and processing, limited access to quality seeds, and insufficient policy support. Farmers are often reluctant to shift from traditional cropping systems due to risk aversion and lack of awareness.

Policy Support and Government Initiatives

The government has introduced several initiatives to promote crop diversification, such as the National Food Security Mission (NFSM), Rashtriya Krishi Vikas Yojana (RKVY), and schemes promoting pulses and oilseeds cultivation. In Punjab, policies encouraging the cultivation of maize and pulses instead of paddy are being implemented to conserve water resources.

Future Prospects

The future of sustainable agriculture depends on the successful implementation of crop diversification strategies. Integration of modern technologies, improved crop varieties, precision farming, and digital agriculture can enhance the effectiveness of diversification. Strengthening market linkages, providing price support, and promoting agro-processing industries are essential for encouraging farmers to adopt diversified cropping systems.

Conclusion

Crop diversification is a holistic approach to achieving long-term agricultural sustainability. It addresses ecological, economic, and social challenges associated with monocropping systems. By improving soil health, conserving water, enhancing biodiversity, and increasing farmers' income, diversification contributes significantly to sustainable development. However, its success depends on coordinated efforts involving policy support, research, extension services, and farmer participation.

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ARTICLE ID: 04

MECHANISM OF PHOSPHATE SOLUBILIZATION AND PHOSPHATE MOBILIZATION

Abstract

Phosphorus (P) is an essential macronutrient required for critical physiological and biochemical functions in plants, yet its availability in soil is often limited due to fixation, precipitation, and immobilization processes. Although abundant in the Earth's crust, phosphorus primarily exists in insoluble inorganic and organic forms that are not directly accessible to plants. Soil microorganisms play a pivotal role in enhancing phosphorus availability through various biochemical and physiological mechanisms. Phosphate-solubilizing microorganisms (PSMs), including bacterial genera such as Pseudomonas and Bacillus, and fungal genera such as Aspergillus and Penicillium, facilitate the conversion of insoluble phosphates into plant-available forms ($H_2PO_4^-$ and HPO_4^{2-}) via organic acid production, proton extrusion, siderophore secretion, exopolysaccharide formation, and enzymatic mineralization. Additionally, arbuscular mycorrhizal fungi (AMF) significantly contribute to phosphorus mobilization by extending the root absorption zone through their hyphal networks and enhancing both inorganic solubilization and organic phosphorus mineralization. The synergistic interactions between PSMs and AMF improve phosphorus use efficiency and promote sustainable nutrient management. The application of such biofertilizers represents an eco-friendly and effective strategy to enhance soil fertility and crop productivity in phosphorus-deficient soils.

Key words: Phosphate solubilization, Phosphate mobilization, organic acids, siderophores.

Introduction

Plants require essential nutrients for their proper growth and development. Phosphorus (P) is one of the major macronutrients required for various physiological and biochemical processes in plants, including energy transfer, root development, and cell division. The primary source of phosphorus in nature is phosphate rocks and P-bearing minerals present in the Earth's crust. However, plants cannot directly absorb phosphorus from these mineral forms. Plants can only take up phosphorus in soluble ionic forms, primarily dihydrogen phosphate ($H_2PO_4^-$) and hydrogen phosphate (HPO_4^{2-}).

In soil, phosphorus exists in both inorganic and organic forms, but most of it remains unavailable to plants. The conversion of these unavailable forms into plant-available forms is a crucial step in the soil phosphorus cycle. Due to its highly reactive nature, phosphorus is rapidly fixed in the soil through processes such as adsorption on soil minerals and precipitation with calcium, iron, and aluminium. In addition, microorganisms can immobilize inorganic phosphorus into organic forms within their biomass, further reducing its immediate availability to plants. These processes are the main reasons for the low fertilizer use efficiency of phosphatic fertilizers.

In contrast, processes such as desorption, solubilization, and mineralization help in releasing phosphorus back into the soil solution, making it available for plant uptake. Soil microorganisms have evolved several mechanisms to mobilize and mineralize occluded, insoluble, and organic phosphorus, thereby enhancing plant growth in terrestrial ecosystems. A diverse group of soil microorganisms plays a vital role in transforming unavailable phosphorus into plant-available forms.

Biofertilizers are formulations containing effective strains of beneficial microorganisms that improve nutrient availability to plants and often produce plant growth–promoting substances. Since phosphorus is immobile in soil, it must be mobilized in the rhizosphere to become accessible to plant roots. Based on their mode of action, phosphate solubilizers and phosphate mobilizers are widely used biofertilizers and are important components of integrated nutrient management and sustainable agriculture.

Microorganisms convert unavailable inorganic phosphorus into soluble forms through a process known as phosphate solubilisation. Phosphate-solubilising microorganisms (PSMs) include bacteria and fungi that play a key role in the soil phosphorus cycle. Common phosphate-solubilising bacteria include Pseudomonas and Bacillus, while fungi include Aspergillus and Penicillium. Organic phosphorus compounds are mineralised through enzymatic activity, whereas inorganic phosphorus compounds such as iron phosphate, aluminium phosphate, and calcium phosphate are solubilised through various microbial mechanisms, including organic acid production, proton extrusion, siderophore secretion, and exopolysaccharide production. Additionally, arbuscular mycorrhizal fungi (AMF) are highly effective at enhancing phosphorus uptake by plants. The use of PSM inoculants as biofertilizers has shown great potential for improving soil phosphorus availability.

Mechanisms of Phosphate Solubilization by Microorganisms

1. Secretion of organic acids

PSMs solubilize inorganic phosphorus compounds such as Fe–P, Al–P, and Ca–P mainly through the secretion of organic acids like citric, lactic, and gluconic acids. These acids lower the pH around microbial cells, which helps dissolve insoluble phosphate compounds. Organic acids also chelate metal ions such as calcium, iron, and aluminium, releasing phosphate ions into the soil solution. These acids are produced during microbial metabolism, particularly during respiration and fermentation of organic carbon sources.

2. Proton extrusion

Microorganisms release hydrogen ions (H^+) into the soil, which reduces the pH and enhances the dissolution of insoluble phosphorus compounds into soluble forms such as $H_2PO_4^-$ and HPO_4^{2-}. Proton release occurs mainly during ammonium assimilation, carbonic acid formation during respiration, and the release of organic acid anions. The reduction in pH is generally greater when ammonium is the nitrogen source compared to nitrate.

3. Siderophore production

Some PSMs produce siderophores, which are organic compounds with a strong affinity for iron (Fe^{3+}). These siderophores bind iron from Fe–P complexes, disrupting the complex and releasing phosphate ions into the soil solution. This mechanism is particularly important in soils where both iron and phosphorus are limiting. Microorganisms such as Pseudomonas, Bacillus, Azotobacter, Aspergillus, and Penicillium are known to solubilize phosphorus through siderophore production.

4. Exopolysaccharide (EPS) production

Microbial exopolysaccharides are high-molecular-weight carbohydrates secreted during stress conditions or biofilm formation. EPS contain functional groups that can bind metal ions such as Ca^{2+}, Fe^{3+}, and Al^{3+}. By binding these metals, EPS disrupt phosphate–metal complexes, indirectly enhancing the release of soluble phosphorus into the soil.

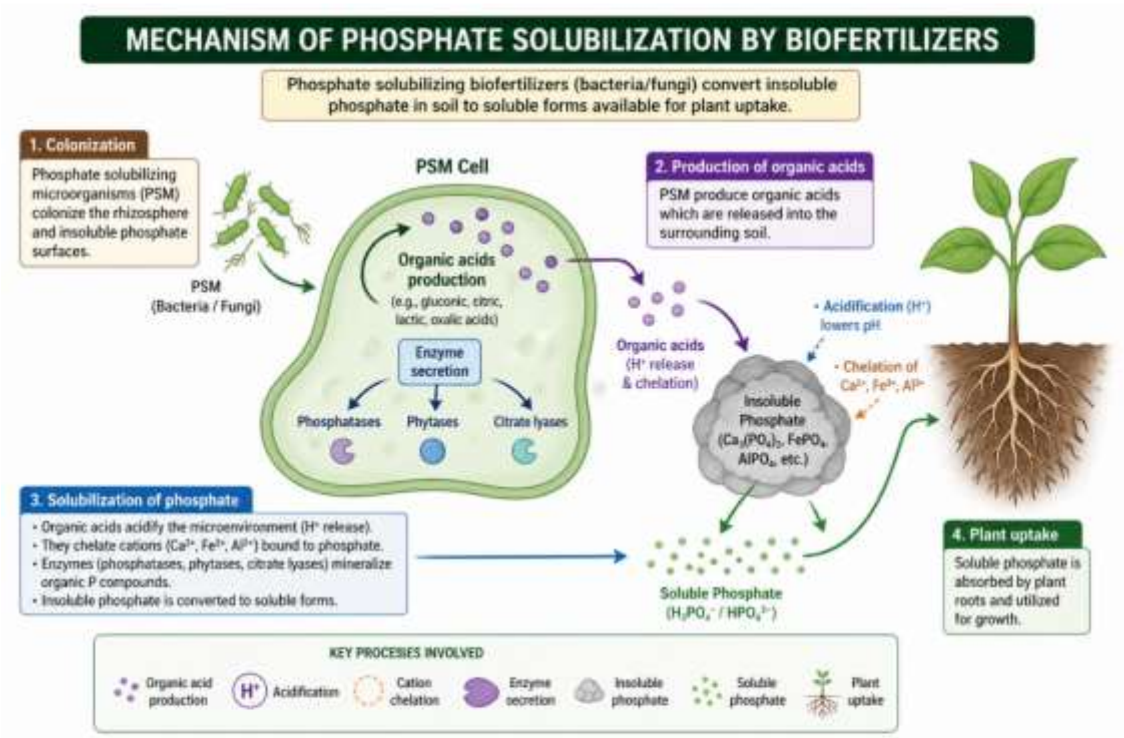

Figure: Schematic representation of the mechanism of phosphate solubilization by microorganisms

5. Enzymatic mineralization of organic phosphorus

The solubilization of organic phosphorus depends on the type of chemical bonds present. Organophosphate compounds (C–O–P bonds) are mineralized by enzymes such as acid phosphatases, alkaline phosphatases, and phytases. Acid phosphatases are released by both plant roots and microorganisms, while alkaline phosphatases are mainly of microbial origin. Phytases specifically hydrolyse phytate, a major organic phosphorus compound in soil, releasing inorganic phosphate. In contrast, organophosphonates (C–P bonds) require specialized phosphonate-degrading enzymes for mineralization.

Phosphate Mobilization by Mycorrhizal Fungi

Phosphate mobilization refers to the process by which fixed or unavailable phosphorus in soil is made accessible to plant roots through biological, chemical, and physical mechanisms. Arbuscular mycorrhizal fungi (AMF) play a crucial role in this process, especially in soils with low phosphorus availability.

AMF form symbiotic associations with plant roots and develop extensive extraradical hyphal networks that extend far beyond the root depletion zone. These hyphae explore a much larger volume of soil than roots alone, allowing plants to access sparingly soluble phosphorus pools. AMF mobilize phosphorus bound to calcium, iron, and aluminium minerals through organic acid secretion, proton release, and localized acidification of the hyphosphere, which leads to the dissolution of insoluble phosphates.

AMF also contribute to the enzymatic mineralization of organic phosphorus by producing or stimulating enzymes such as acid phosphatase, alkaline phosphatase, and phytase. These enzymes hydrolyze organic phosphorus compounds and release plant-available inorganic phosphate. The absorbed phosphate is taken up by fungal hyphae through high-affinity phosphate transporters, stored temporarily as polyphosphate granules, and efficiently transported to plant root cortical cells, where it is released at arbuscules for plant uptake.

In addition, AMF colonization improves root architecture, increases root surface area, enhances interactions with phosphate-solubilizing bacteria, and creates a synergistic rhizosphere environment for phosphorus mobilization. Phosphorus is also temporarily immobilized in fungal biomass and is released back into the soil upon hyphal death and decomposition, acting as a temporary phosphorus reservoir.

Conclusion

Phosphorus availability remains a major constraint in agricultural soils due to its complex chemistry and strong fixation reactions. Microorganisms play an indispensable role in overcoming this limitation by transforming unavailable phosphorus into plant-accessible forms through multiple mechanisms, including acidification, chelation, enzymatic activity, and biological mobilization. Phosphate-solubilizing microorganisms enhance nutrient cycling by solubilizing inorganic phosphates and mineralizing organic phosphorus, while arbuscular mycorrhizal fungi improve phosphorus uptake efficiency through extensive hyphal networks and symbiotic associations with plant roots. The combined action of these microbial groups not only increases phosphorus availability but also improves soil health, root development, and overall plant growth. Therefore, the integration of PSMs and AMF as biofertilizers offers a sustainable and environmentally sound approach to improving phosphorus use efficiency and reducing dependence on chemical fertilizers, contributing to long-term soil fertility and agricultural sustainability.

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EMERGENCE OF RUGOSE SPIRALLING WHITEFLY AS A MAJOR THREAT TO COCONUT PLANTATIONS AND HORTICULTURAL CROPS

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Abstract: A new invasive pest, Rugose Spiralling Whitefly (RSW), *Aleurodicus rugioperculatus* Martin (Hemiptera: Aleyrodidae) is wide spread in central and south America. Its invasiveness in India was recorded by the ICAR-National Bureau of Agricultural Insect Resources, Bengaluru's scientists on coconut plantations at pollachi, Tamil Nadu (Sundararaj and Selvaraj, 2017) and subsequently, it has spread to different districts of Karnataka, Kerala, Andhra Pradesh, Goa, Assam and West Bengal (Selvaraj et al., 2017 & 2019) and it was recently observed in Lakshadweep islands, coastal districts of Maharashtra, Gujarat, Telangana, Odisha, Chhattisgarh and few districts of Meghalaya and Assam. The incidence and infestation of the RSW was recorded on many other Horticultural crops including oil palm, banana, guava, sapota, cashew nut etc. RSW is a small sap sucking insect belonging to Order Hemiptera which is taxonomically related to mealybugs and aphids. RSW developmental stages includes egg stage, four nymphal stages and adult stage. Both nymphs and adults suck the sap from the leaves by feeding especially on underside of the leaves. Adults produce the large quantities of honey dew excretion which in turn completely darken by sooty mould development on the upper surface of leaves. Field sanitation, removal of alternate hosts, spraying of NSKE 5% and use of yellow sticky traps are the management practices of Rugose Spiralling Whitefly.
Key words: Invasive pest, Rugose Spiralling Whitefly, *Aleurodicus rugioperculatus*, RSW, Coconut, Horticultural crops**.**

Introduction: Coconut, *Cocos nucifera* L. (Arecaceae) is an important plantation crop grown mainly in the tropical and subtropical areas of the world and most of the farmers depend on coconut both directly or indirectly for their livelihood. India is one of the leaders in coconut farming and stands third biggest coconut producing country worldwide. Amongst coconut producing states, Tamil Nadu, Kerala, Karnataka and Andhra Pradesh are the leading coconut producing states which account for more than 90% of coconut production.

Pest infestation is one of the main constraints for attaining better production and productivity in coconut. Coconut Eriophyid mite, *Aceria guerreronis* Keifer (Eriophyidae: Acarina), rhinoceros beetle, *Oryctes rhinoceros* L (Coleoptera: Scarabaieidae), pink palm weevil, *Rhynchophorus ferrugineus* Olivier (Coleoptera: Curculionidae), black headed caterpillar, *Opisina arenosella* Walker (Lepidoptera: Oecophoridae) and white-grub, *Leucopholis coneophora* Burmeister (Coleoptera: Scarabaieidae) are considered as major pests of coconut. Rugose Spiralling Whitefly (RSW), *Aleurodicus rugioperculatus* Martin (Hemiptera: Aleyrodidae) a new invasive pest was identified in India. It has become potential threat to Arecaceae family crops attacking more than 120 crops like ornamentals, palms, weeds, native and invasive plant species (stocks and Hodges, 2012).

Host plants: RSW is a polyphagous pest, in India it was reported to feed approximately 44 host plants especially coconut, oil palm, banana, mango, sapota, guava, cashew, ramphal, maize, Indian almond, water apple, jack fruit and ornamental plants *viz*., bottle palm, Indian shot, false fowl of paradise and butterfly palm.

Biology:

Egg stage: Adult female lays eggs in concentric circular or loose spiral pattern on the ventral surface of the leaves, on leaf petioles, stems and fruits. Eggs are elliptical and yellowish in colour, 0.3 mm long, translucent with a short stalk and are associated with abnormal spiralling deposits of white flocculent wax surrounding each egg in a semi-circular spiralling manner.

Nymph stage: The first instar nymphs are known as crawlers, which are only mobile stage with functional legs and these are transparent mild to golden yellowish in colour devoid of wax. second instar nymphs are immobile, fringed with marginal wax along the transverse grooves on their dorsum and the compound pores produce glassy wax filaments. They are transparent light to golden yellowish and bigger in size compared to first instar.

Third instar nymphs have numerous evenly spread short, glass rods like waxy filaments along the sides of body. Fourth instar nymphs are protected with copious quantity of opaque white waxy material dorsally as tufts.

Adult stage: Adults are about 3 times larger than the present invasive spiralling whitefly, *Aleurodicus dispersus* and are lethargic by nature. Adults can be distinguished by the presence of a pair of irregular light brown bands across the wings. Males have long pincer-like structures at the distal ends of the abdomen.

Nature of damage and economic significance: Both nymphs and adults suck the sap by using their piercing and sucking type of mouth parts from the abaxial surface of the coconut leaflets. De-sapping by RSW reduces the plant growth due to removal of water and vitamins. Massive feeding of the insect also leads in excretion of honey dew which subsequently gets deposited on the upper surface, lower surface of the leaves and on other feeding areas. Honey dew excrement, encourages the development of the fungus, *Capnodium ramosum* as a black encrustation, which causes the disfigurement of leaves, affecting the photosynthetic performance of the plant. Severe infestation causes stunted growth, premature leaf drying, dropping of fronds, immature nutfall and malformed nuts. White mealy waxy flocculent material produced by nymphs and adults causes nuisance to humans in severely infested areas.

IPM practices for the management of Rugose Spiralling Whitefly

Cultural practices:

- Field sanitation removal of weeds and other alternate host plants.
- Prevent transportation of infected planting materials.
- Provide balanced N:P:K fertilisers.
- Avoid high density planting.
- Intercropping with banana, pearl millet, cocoa and nutmeg to boost parasitoid activity in infected fields.
- Grow marigold as a intercrop to suppress the whitefly population. The limonene present in marigold flowers may repel the whiteflies. (Anon,

2019).

Mechanical practices:

- Spray water forcibly on the underneath surface of the fronds or on infected leaves to distort the whitefly population.
- Installation of yellow sticky traps.
- Periodically burn the badly infected leaves.

Biological practices:

- Field release of *Encarsia guadeloupae* parasitoids by stapling the leaf with RSW puparia parasitized with *E. guadeloupae*. To encourage the colonisation and multiplication of *E. guadeloupae* in Indian shot, banana and annona flowers can be grown as intercrop.
- Release predator lace wing, *Chrysoperla spp*. or *Apertochrysa astur* @ 400 eggs/acre.
- Release sooty mildew feeding scavenging beetles, *Leiochrinus nilgirianus* Kaszab 1946 (Tenebrionidae: Coleoptera).
- Spraying of Entomopathogenic fungus, *Isaria fumosorosea* on the RSW causes yellow muscardine disease leading to mortality of the pest (Sandhu *et al*., 2012).

Chemical practices:

- Apply of neem oil @10000 ppm by combining with washing powder to reduce RSW population (stocks & Hodges, 2012).

Conclusion and Future prospects

Rugose spiralling whitefly emerging as a severe threat to wide range of host plants, specifically coconut, oil palm, banana, citrus, and ornamental species. Its rapid reproduction, wide host range, and quick spread make it hard to control once established. While RSW is a significant threat, the pest is effectively managed through timely biological interventions and ecological monitoring. Several parasitoids like *Encarsia guadeloupae* and *Chrysoperla*, Coccinellid predators have already shown effective control potential towards RSW. In areas, where these natural enemies establish well, RSW populations often drop significantly. Future pest infestation and damage will likely depend on how efficiently those biological controls are conserved and deployed.

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CIRCULAR RNA: HIDDEN REGULATORS OF PLANT TRAITS

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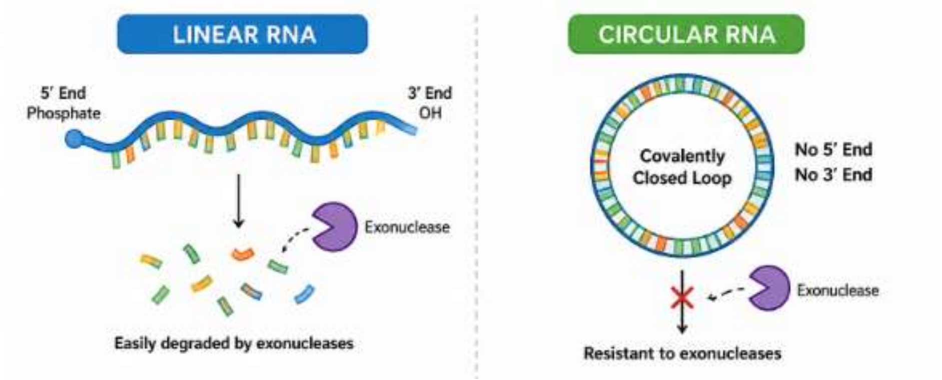
Abstract

Circular RNAs (circRNAs) are an emerging class of non-coding RNAs that have gained significant attention due to their unique structure and diverse biological functions. Unlike linear RNAs, circRNAs form covalently closed loops, which make them highly stable and resistant to degradation. Once considered mere by-products of RNA splicing, they are now recognized as important regulators of gene expression, protein interactions, and cellular processes. Recent studies suggest that circRNAs play a crucial role in stress response, development, and productivity in plants. This article provides a simplified and comprehensive overview of circRNAs, their formation, functions, and potential applications in agriculture, particularly in crop improvement.

Introduction

In the past, it was widely believed that only protein-coding genes were functionally important in living organisms. However, advances in molecular biology have revealed that a large portion of the genome produces non-coding RNAs that play vital regulatory roles. Among these, circular RNAs (circRNAs) have emerged as an exciting and rapidly growing area of research. Unlike conventional linear RNAs, circRNAs possess a unique circular structure in which the 3′ and 5′ ends are covalently linked, forming a continuous loop. This structural feature makes them highly stable and resistant to degradation within the cell. Although circRNAs were first discovered in plant viroids in 1976, they were long considered insignificant and were often dismissed as splicing errors. With the development of advanced sequencing technologies, circRNAs are now recognized as abundant, conserved, and functionally important molecules that regulate gene expression. Their potential role in plant systems has opened new possibilities for improving crop performance and resilience.

Figure 1. Difference Between Linear RNA and Circular RNA



Structure and Characteristics of circRNA

Circular RNAs possess distinct structural and functional features that differentiate them from linear RNA molecules.

- Closed-loop structure: circRNAs are single-stranded RNA molecules that form a covalently closed loop, lacking free 5′ and 3′ ends.
- High stability: the absence of free ends makes circRNAs resistant to exonuclease degradation, resulting in greater stability compared to linear RNAs.
- Size range: circRNAs typically vary in length from approximately 100 to 4000 base pairs.
- Cellular localization: they are found in different cellular compartments, including the nucleus and cytoplasm, with some specialized forms present in mitochondria.
- Tissue-specific expression: circRNAs exhibit cell- and tissue-specific expression patterns, indicating regulated and functional roles rather than random occurrence.
- Functional significance: these characteristics make circRNAs stable and versatile molecules involved in various biological processes.

Types of circRNA

Circular RNAs are classified into different types based on their origin and composition, and each type performs distinct biological functions.

Exonic circRNAs (ecircRNAs)

Exonic circRNAs are formed entirely from exon sequences and represent the most abundant class of circRNAs. They are primarily located in the cytoplasm, where they play significant roles in gene regulation, particularly through mechanisms such as microRNA sponging.

Circular Intronic RNAs (ciRNAs)

Circular intronic RNAs originate from intronic sequences that escape normal degradation during RNA splicing. These circRNAs are mainly found in the nucleus, where they are involved in regulating the transcription of their parent genes.

Exon–Intron circRNAs (EIciRNAs)

Exon–intron circRNAs consist of both exon and intron sequences. Similar to intronic circRNAs, they are predominantly localized in the nucleus and contribute to the regulation of gene expression, often by enhancing transcriptional activity.

tricRNAs

tricRNAs are specialized circRNAs derived from tRNA introns during the process of tRNA maturation. Although their functions are still being explored, they are believed to play roles in gene regulation and cellular processes.

Mitochondria-encoded circRNAs (mecciRNAs)

Mitochondria-encoded circRNAs originate from mitochondrial genes and are involved in mitochondrial function. They play important roles in protein transport and cellular energy regulation, highlighting their significance in maintaining cellular homeostasis. Some important examples include mecciND1, mecciND5, mc-COX2, and circRNA SCAR.

Table 1. Types of Circular RNAs and Their Functions

Type	Origin	Function
Exonic circRNA	Exons	Gene regulation, miRNA sponge
Intronic circRNA	Introns	Transcription regulation
Exon–intron circRNA	Exons + introns	Enhances gene expression
tricRNA	tRNA introns	Regulatory roles
mecciRNA	Mitochondria	Protein transport

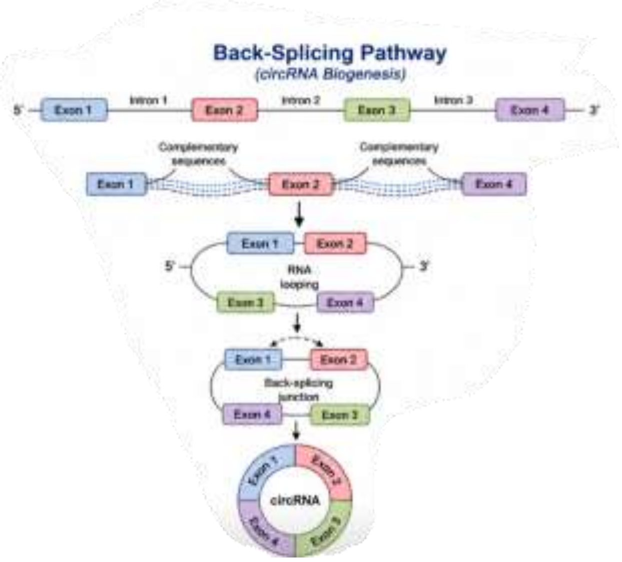
Biogenesis of Circular RNAs

The formation of circular RNAs (circRNAs) is a unique and highly regulated process that differs significantly from the conventional linear RNA splicing pathway. Unlike linear RNAs, which are produced through canonical splicing, circRNAs are generated through non-canonical splicing events that result in a covalently closed loop structure. Broadly, circRNA biogenesis occurs through two major pathways: back-splicing and lariat-driven circularization. These pathways involve intricate interactions between RNA sequences, splicing machinery, and regulatory proteins, ensuring the precise formation of circRNAs.

Back-Splicing Pathway

Back-splicing is the primary and most widely studied mechanism responsible for circRNA formation. In this process, a downstream 5′ splice donor site is joined to an upstream 3′ splice acceptor site, resulting in the formation of a circular RNA molecule. This reverse order of splicing distinguishes back-splicing from canonical linear splicing and leads to the production of exonic circRNAs (ecircRNAs) and exon–intron circRNAs (EIciRNAs).

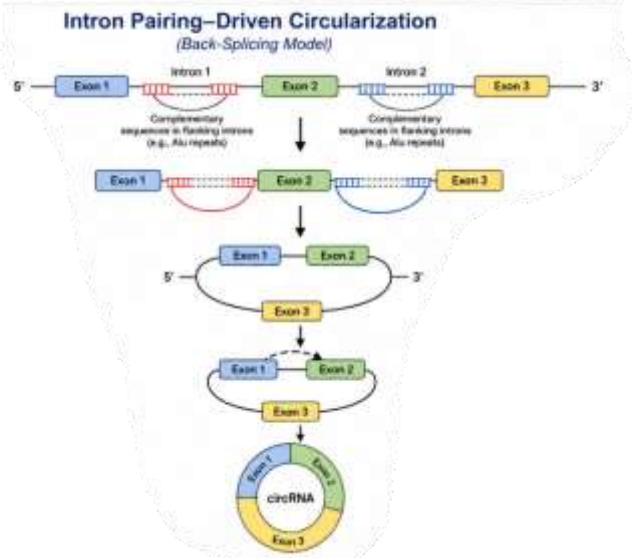
The efficiency and occurrence of back-splicing depend on the spatial proximity of splice sites, which is achieved through specific molecular mechanisms. Two major mechanisms that facilitate back-splicing are intron pairing-driven circularization and RNA-binding protein (RBP)-mediated circularization.



Intron Pairing–Driven Circularization

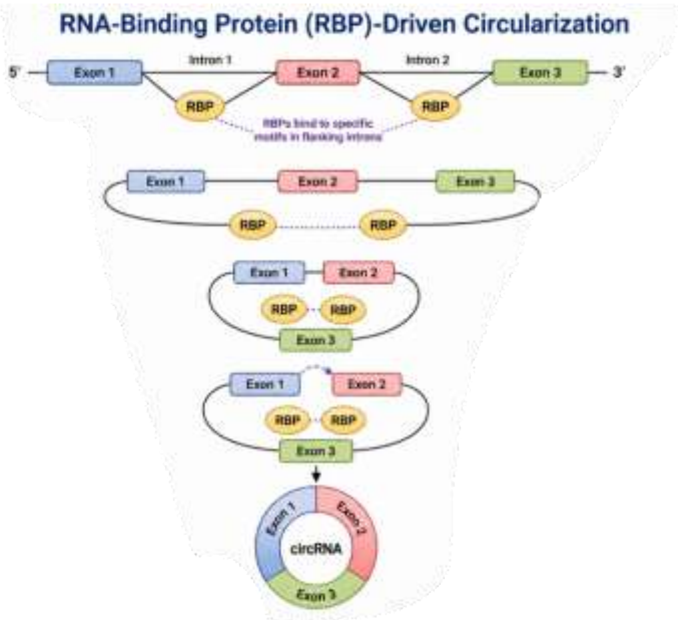
Intron pairing-driven circularization is one of the key mechanisms that promote back-splicing. In this process, complementary sequences present within the flanking introns base-pair with each other. These complementary sequences, such as Alu repeats in humans, bring the splice donor and acceptor sites into close proximity. This spatial arrangement facilitates the back-splicing reaction, allowing the exons to be joined in a circular configuration.

Following the circularization event, the intronic sequences are typically removed, and the exons are ligated to form a stable circRNA molecule. This mechanism highlights the importance of intronic sequence complementarity in regulating circRNA formation and suggests that longer introns with repetitive elements may favor circularization.



RNA-Binding Protein (RBP)-Driven Circularization

Another important mechanism involved in circRNA biogenesis is mediated by RNA-binding proteins (RBPs). In this process, RBPs bind to specific sequence motifs located in the flanking introns or exons of a precursor mRNA. These proteins can dimerize, meaning that two RBP molecules interact with each other, effectively bringing the intronic regions closer together.



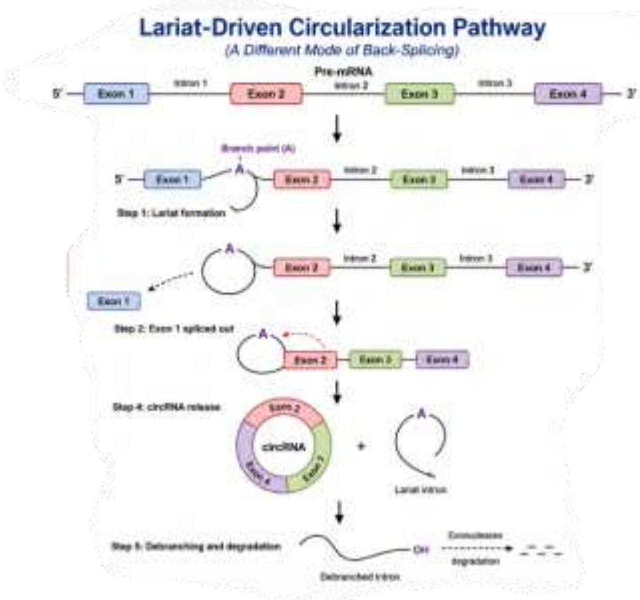
This reduction in distance between splice sites promotes the back-splicing event and enhances the efficiency of circRNA formation. RBPs therefore act as molecular bridges that facilitate and regulate circularization. A well-known example is the Muscleblind (MBL) protein in *Drosophila*, which binds to its own pre-mRNA and promotes the production of circRNA from that gene. This demonstrates how proteins can exert precise control over circRNA biogenesis.

Lariat-Driven Circularization Pathway

In addition to back-splicing, circRNAs can also be generated through the lariat-driven circularization pathway. During normal RNA splicing or exon skipping events, an intermediate loop-like structure known as a lariat is formed. This lariat may contain intronic sequences or even skipped exons.

Under typical conditions, lariat structures are rapidly degraded by cellular enzymes. However, in certain cases, these lariats escape degradation and undergo further processing. During this process, introns may be removed or retained, resulting in the formation of circular RNA molecules. This pathway is particularly important for the generation of circular intronic RNAs (ciRNAs) and some exonic circRNAs.

The lariat-driven mechanism highlights the role of splicing intermediates as precursors for circRNA formation and underscores the complexity of RNA processing within the cell.



Regulation of circRNA Biogenesis

Cis-Regulatory Elements

Cis-regulatory elements are sequences present within the same pre-mRNA, mainly in the flanking introns, that influence circRNA formation. These include complementary sequences such as Alu repeats, which can pair with each other and bring splice donor and acceptor sites closer together. This proximity facilitates back-splicing and promotes the formation of circular RNAs.

Trans-Acting Factors (RNA-Binding Proteins)

RNA-binding proteins (RBPs) are important trans-acting factors that regulate circRNA biogenesis. They bind to specific regions on the RNA and influence splicing decisions. Some RBPs, such as NF90/NF110, QKI, and MBL, enhance circularization by bringing splice sites together, while others like ADAR1 inhibit circRNA formation by disrupting RNA pairing.

Spliceosome Machinery

The spliceosome plays a central role in RNA processing and affects circRNA formation. Since both linear mRNA and circRNA are produced from the same pre-mRNA, they compete for the same splice sites. When spliceosome activity favors linear splicing, fewer circRNAs are formed. Conversely, reduced spliceosome activity can increase circRNA production.

Intron Features

The characteristics of introns, such as their length and sequence composition, also influence circRNA formation. Longer introns often contain more complementary sequences and protein-binding sites, which help in bringing splice sites closer and promoting circularization.

RNA Modifications (m6A Methylation)

RNA modifications, particularly m6A methylation, play a role in regulating circRNA biogenesis. These modifications can alter RNA structure and affect how proteins bind to RNA or how splice sites are recognized. Depending on the context, m6A can either promote or inhibit circRNA formation.

Functions of Circular RNA (circRNA)

miRNA Sponge Activity

One of the major functions of circRNAs is their ability to act as microRNA (miRNA) sponges. They bind to miRNAs through complementary sequences and prevent them from interacting with their target mRNAs. As a result, gene expression is enhanced due to the release of mRNA from miRNA-mediated suppression. A well-known example is ciRS-7.

Interaction with Proteins

CircRNAs can interact with proteins and regulate their activity. They may act as protein sponges by sequestering proteins, or as scaffolds by bringing multiple proteins together to form functional complexes. In some cases, circRNAs also influence protein stability, thereby affecting cellular processes.

Protein Coding Potential

Although circRNAs lack a 5′ cap and poly-A tail, some of them can be translated into proteins. This occurs through cap-independent mechanisms such as internal ribosome entry sites (IRES), m6A modification, and Kozak sequences, which enable translation initiation.

Regulation of Gene Expression

Certain circRNAs regulate gene expression at the transcriptional level. These circRNAs, mainly located in the nucleus, interact with transcription machinery such as U1 snRNP or form RNA–DNA hybrid structures (R-loops), thereby influencing transcription of their parent genes.

Role in Cellular Processes

CircRNAs are involved in various biological processes, including tumor progression, chromatin organization, and immune regulation. They influence cell proliferation, maintain chromatin structure, and participate in antiviral responses, highlighting their importance in cellular function.

Importance of circRNA in Agriculture

The discovery of circRNAs has opened new avenues in agricultural research, particularly in the field of crop improvement. CircRNAs are involved in regulating gene expression related to important agronomic traits such as growth, development, and stress tolerance. They play a role in helping plants respond to environmental stresses such as drought, salinity, and temperature extremes, which are major challenges in modern agriculture. Additionally, circRNAs may contribute to disease resistance by regulating plant defense mechanisms. Their stability and specific expression patterns make them promising candidates for use in molecular breeding programs. By understanding and manipulating circRNAs, scientists may be able to develop crop varieties that are more resilient, productive, and adaptable to changing environmental conditions.

Advantages of Circular RNA (circRNA)

Circular RNAs possess several unique features that make them highly important in biological systems and potential applications.

- High stability: circRNAs are highly stable because their circular structure lacks free 5′ and 3′ ends, making them resistant to degradation by exonucleases.
- Tissue-specific expression: they exhibit cell- and tissue-specific expression patterns, which makes them useful for targeted biological and functional studies.
- Efficient gene regulation: circRNAs act as powerful regulators of gene expression by functioning as miRNA sponges, interacting with proteins, and modulating gene activity at multiple levels.
- Protein-coding potential: some circRNAs have the ability to encode proteins through alternative translation mechanisms, expanding their functional significance.
- Biomarker potential: due to their stability and specific expression, circRNAs are promising candidates as biomarkers for disease diagnosis and prognosis.
- Therapeutic applications: circRNAs are being explored for use in gene therapy and RNA-based treatments, offering new possibilities in medical and biotechnological research.

Limitations of Circular RNA (circRNA)

Despite their promising roles, circRNAs also have several limitations that restrict their full utilization in research and applications.

- **Difficult detection and identification:** circRNAs are challenging to detect due to their low expression levels and the need for specialized techniques.
- **Distinguishing from linear RNA:** it is often difficult to differentiate circRNAs from linear

RNAs, which complicates analysis and accurate characterization.

- **Incomplete understanding:** the mechanisms underlying circRNA biogenesis and functions are not yet fully understood, limiting their effective application.
- **Complex experimental validation:** studying and validating the functional roles of circRNAs requires complex and time-consuming experimental approaches.
- **Low translation efficiency:** although some circRNAs can be translated into proteins, their translation efficiency is generally low.
- **Challenges in therapeutic use:** the application of circRNAs in therapeutics faces issues such as efficient delivery, targeting specificity, and safety concerns.

Conclusion

Circular RNAs represent a promising new frontier in molecular biology and agricultural science. Their unique structure, stability, and diverse functions make them important regulators of gene expression and cellular processes. Although research on circRNAs is still in its early stages, their potential applications in crop improvement and stress management are significant. With continued research and technological advancements, circRNAs may play a key role in developing sustainable and high-performing crop varieties in the future.

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Spirituality as a Source of Inner Peace in Modern Life

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Introduction

Modern life is characterized by rapid changes, technological dependence, work pressure, social competition and rising expectations. While these developments have improved living standards, they have also increased stress, anxiety, emotional exhaustion and feelings of emptiness among many individuals. In such circumstances, people often seek ways to restore balance and calmness in their lives. One of the most meaningful paths toward this goal is spirituality.

Spirituality refers to the search for meaning, purpose, connection and harmony within oneself and with the world. It may be connected with religion, but it can also exist independently through personal values, meditation, mindfulness, gratitude, compassion and self-reflection. Spirituality helps individuals develop inner peace by creating emotional stability, mental clarity and a sense of fulfilment.

Meaning of Spirituality

Spirituality is a broad concept that focuses on the inner life of an individual. It involves understanding oneself and connecting with something greater than personal desires or material success.

Key Features of Spirituality

- Search for meaning and purpose in life
- Self-awareness and inner growth
- Compassion and kindness toward others
- Gratitude and acceptance
- Sense of connection with nature, humanity or divine power
- Peaceful and ethical living

Meaning of Inner Peace

Inner peace is a state of calmness, balance and emotional stability. It does not mean the absence of problems, but the ability to remain steady and positive during difficulties.

Signs of Inner Peace

- Reduced anxiety and fear
- Emotional control
- Positive thinking
- Acceptance of life situations
- Healthy relationships
- Satisfaction and happiness

Why Inner Peace is Difficult in Modern Life

Today's lifestyle creates many obstacles to peace of mind.

Major Challenges

- Busy schedules and workload
- Financial pressure
- Social comparison through social media
- Family conflicts
- Lack of time for self-care
- Fear of failure and uncertainty
- Overdependence on technology

These factors often disturb mental health and emotional balance.

How Spirituality Promotes Inner Peace

Spirituality provides practical and emotional support to maintain peace in daily life.

1. Gives Meaning and Purpose

- Helps people understand the value of life
- Reduces feelings of emptiness
- Encourages goal-oriented living

2. Reduces Stress and Anxiety

- Prayer, meditation and mindfulness calm the mind
- Helps manage tension and worries
- Improves emotional regulation

3. Builds Acceptance

- Teaches people to accept what cannot be changed
- Reduces frustration and anger
- Encourages patience during difficult times

4. Strengthens Hope and Resilience

- Gives courage during failure, loss or crisis
- Promotes positive thinking
- Helps individuals recover emotionally

5. Encourages Positive Relationships

- Develops empathy and forgiveness
- Reduces conflicts
- Improves family and social harmony

Spiritual Practices for Inner Peace

Many spiritual activities can be practiced in everyday life.

Common Practices

- Meditation
- Yoga
- Prayer
- Deep breathing exercises
- Gratitude journaling
- Reading inspirational literature
- Spending time in nature
- Helping others through service
- Self-reflection and silence

Benefits of Spirituality in Modern Life

1. Psychological Benefits

- Better mental health
- Reduced depression and stress
- Improved concentration
- Emotional balance

2. Social Benefits

- Stronger relationships
- Better communication
- Greater compassion and cooperation

3. Physical Benefits

- Improved sleep
- Lower blood pressure
- Better immunity through reduced stress

4. Personal Growth Benefits

- Self-confidence
- Moral values
- Sense of fulfilment
- Better decision-making

Spirituality among Youth

Young people today face academic competition, career pressure and digital distractions. Spirituality can help youth by:

- Improving focus and discipline
- Reducing stress and confusion
- Building confidence
- Encouraging responsible behaviour
- Helping discover life purpose

Spirituality among Older Adults

Older adults may face loneliness, health concerns, and life transitions. Spirituality supports them through:

- Emotional comfort
- Sense of hope
- Acceptance of aging
- Better coping with loss
- Stronger life satisfaction

Challenges in Practicing Spirituality Today

Although spirituality is valuable, some barriers exist.

Common Barriers

- Lack of time
- Materialistic lifestyle
- Misunderstanding spirituality as superstition
- Digital distractions
- Stressful routine
- Lack of guidance

Ways to Develop Spirituality in Daily Life

- Begin the day with silence or prayer
- Practice gratitude daily
- Spend time away from screens
- Meditate for 10–15 minutes
- Read uplifting books
- Help others regularly
- Maintain honesty and kindness
- Reflect on personal values

Conclusion

Spirituality is an important source of inner peace in modern life. It helps individuals manage stress, find purpose, improve relationships and maintain emotional balance. In a world full of distractions and pressures, spirituality offers a path toward calmness, fulfilment and harmony. By adopting simple spiritual practices, people can create a healthier and more peaceful life for themselves and society.

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Evolving Scientific Feeding Standards for Indian Cattle: A Comparative Analysis of ICAR (2013) and ICAR (2024)

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Abstract

Scientific feeding standards are central to optimizing productivity, efficiency, and sustainability in dairy production systems. In India, the Indian Council of Agricultural Research (ICAR) has periodically revised nutrient requirement frameworks to incorporate advances in animal nutrition science. The ICAR (2013) standards represent a consolidation of classical feeding systems integrated with emerging concepts in ruminant nutrition, whereas ICAR (2024) reflects a transition toward predictive, data-driven methodologies grounded in meta-analysis of Indian feeding trials. This review critically evaluates the evolution of feeding standards with emphasis on dry matter intake (DMI), energy systems, protein evaluation, and mineral nutrition. ICAR (2024) introduces regression-based intake prediction, improved digestibility estimates, and explicit adoption of metabolizable protein systems, enhancing biological precision. However, mineral nutrition remains relatively unchanged due to limited empirical evidence. The transition signifies a paradigm shift from empirical to predictive nutrition, with implications for precision feeding and ration optimization under Indian conditions.

1. Introduction

Feeding standards constitute the scientific foundation for ration formulation, enabling alignment between nutrient supply and physiological demand. In India, ICAR has played a pivotal role in contextualizing global nutritional frameworks to indigenous production systems. The ICAR (2013) publication marked a significant advancement by integrating classical digestibility-based systems with concepts of energy partitioning and rumen protein dynamics. In contrast, ICAR (2024) advances this framework through incorporation of regression modelling, meta-analytical datasets, and system-based approaches derived largely from Indian experimental conditions.

Understanding this transition is critical for evaluating the robustness, applicability, and limitations of contemporary feeding standards.

2. Evolution of Feeding Standards: From Empirical to Predictive Systems

Early feeding systems were rooted in empirical observations and digestibility trials, relying on proximate principles and digestible nutrient fractions. These approaches assumed constant efficiencies of nutrient utilization, limiting their biological realism.

Subsequent developments in animal energetics introduced hierarchical energy partitioning (gross, digestible, metabolizable, and net energy), enabling more physiologically meaningful evaluation. Parallel advances in rumen microbiology led to improved understanding of fiber digestion and microbial protein synthesis.

ICAR (2013) reflects this integrative stage, combining classical nutrient systems with emerging biological insights. ICAR (2024), however, represents a methodological shift toward predictive modelling, wherein nutrient requirements are estimated using statistical relationships derived from large datasets.

This transition enhances adaptability and precision, particularly under variable production and physical conditions.

3. Dry Matter Intake (DMI): From Descriptive to Predictive Modelling

Dry matter intake governs total nutrient supply and is influenced by both physical (rumen fill) and metabolic (energy demand) mechanisms. ICAR (2013) treats DMI as a multifactorial outcome influenced by diet composition, palatability, and environmental conditions; however, it does not provide explicit predictive equations. In contrast, ICAR (2024) adopts a quantitative approach by employing regression-based models that incorporate metabolic body weight and production parameters such as fat-corrected milk (FCM) yield. This allows for more precise estimation of intake under varying physiological and production conditions.

$$\mathbf{DMI} = \mathbf{a} + \mathbf{b_1 W^{\{0.75\}}} + \mathbf{b_2 FCM} \qquad (\mathbf{i})$$

where:

- $W^{\{0.75\}}$ = metabolic body weight (kg)
- FCM = fat-corrected milk yield (kg/day)
- a, b_1, b_2 = regression coefficients

This shift from descriptive to predictive modelling enables quantitative estimation of feed intake, thereby facilitating precision ration formulation and dynamic adjustment to production levels.

4. Energy Evaluation: Refinement of TDN and ME Systems

Energy evaluation has evolved from crude digestibility measures to more refined partitioning systems. ICAR (2013) employs both total digestible nutrients (TDN) and metabolizable energy (ME), with TDN widely used due to its operational simplicity, although its dependence on digestibility coefficients introduces inherent variability.

ICAR (2024) adopts a more precise approach by refining the quantitative relationship between TDN and ME:

$$\mathbf{1\ kg\ TDN} \approx \mathbf{3.615\ Mcal\ ME} \qquad (\mathbf{2})$$

In addition, ICAR (2024) provides specific efficiency coefficients for the utilization of metabolizable energy:

Efficiency of ME utilization for maintenance: $\mathbf{k_m} = \frac{\mathbf{ME_m}}{\mathbf{ME\ intake}} \qquad (\mathbf{iii})$

Efficiency of ME utilization for lactation: $\mathbf{k_l} = \frac{\mathbf{ME_l}}{\mathbf{ME\ intake}} \qquad (\mathbf{iv})$

These coefficients improve the partitioning of energy for maintenance (**:** k_m) and lactation (k_l), as they are adjusted based on the metabolizability of the diet:

Metabolizability: $\mathbf{q_m} = \frac{\mathbf{ME}}{\mathbf{GE}} \qquad (\mathbf{v})$

This level of refinement was less granular in the ICAR (2013) system. The updated estimates are derived from meta-analysis of Indian feeding trials, thereby improving the reliability of energy evaluation. Furthermore, greater emphasis is placed on ME as a biologically meaningful unit for partitioning energy requirements into maintenance and production functions.

This dual refinement enhances both field applicability and scientific accuracy.

5. Protein Evaluation: Transition to Metabolizable Protein Systems

Protein nutrition in ruminants is governed by the interaction between rumen microbial synthesis and post-ruminal digestion. ICAR (2013) incorporates crude protein (CP), Rumen Degradable Protein (RDP), and Rumen Undegradable Protein (UDP) to describe protein supply; however, this system does not directly quantify the metabolizable amino acids available to the animal.

In contrast, ICAR (2024) advances protein evaluation through improved estimation of microbial protein synthesis. A key relationship used for estimating Microbial Crude Protein (MCP) is:

$$\mathbf{MCP}\left(\frac{\mathbf{g}}{\mathbf{day}}\right) = \mathbf{130} \times \mathbf{TDN\ intake}\left(\frac{\mathbf{kg}}{\mathbf{day}}\right) \qquad (\mathbf{vi})$$

This coefficient is specifically tuned to Indian tropical feed conditions, where fiber content is higher, thereby providing a more realistic estimate of microbial protein synthesis under typical feeding systems.

Furthermore, ICAR (2024) adopts the metabolizable protein (MP) framework, which represents the true absorbable protein available to the animal:

$$\mathbf{MP} = \mathbf{Digestible\ Microbial\ Protein} + \mathbf{Digestible\ UDP}$$

This framework allows for more accurate estimation of amino acid supply at the tissue level. Consequently, it improves nitrogen utilization efficiency, reduces excess protein feeding, and aligns with the principles of sustainable livestock production.

The adoption of the metabolizable protein system represents a major conceptual advancement in Indian feeding standards.

6. Mineral Nutrition: Persistence of Knowledge Gaps

Mineral requirements—particularly for calcium (Ca) and phosphorus (P)—are estimated using a factorial approach that integrates the needs for maintenance, growth, and lactation. This approach can be generalized as:

$$\boldsymbol{Mineral\ Requirement} = \boldsymbol{Maintenance} + \boldsymbol{Growth} + \boldsymbol{Lactation} + \boldsymbol{Gestation}$$

More specifically, for individual minerals:

$$\mathbf{Requirement} = \frac{\mathbf{Net\ Requirement}}{\mathbf{Absorption\ Efficiency}} \qquad (\mathbf{vi})$$

where net requirement accounts for endogenous losses, tissue accretion, and secretion in milk.

While substantial advancements have been achieved in other nutritional domains, ICAR (2024) largely retains the mineral recommendations established in ICAR (2013), reflecting the limited availability of new experimental data under Indian production systems. This reliance indicates that mineral nutrition has not progressed at the same pace as energy and protein evaluation.

However, the 2024 revision introduces updated tabulations for trace minerals such as zinc (Zn), copper (Cu), and manganese (Mn), with particular emphasis on high-yielding crossbred cattle that were inadequately represented in earlier datasets. These refinements improve the applicability of mineral recommendations under evolving production systems. Despite these updates, the overall framework remains largely unchanged, underscoring a persistent research gap in mineral nutrition. This is noteworthy given the critical role of minerals in influencing productivity, reproductive efficiency, immune function, and overall animal health.

7. Conclusion

The progression from ICAR (2013) to ICAR (2024) reflects a substantive paradigm shift in cattle nutrition—from empirically derived feeding standards to predictive, data-driven systems. Key advancements include quantitative prediction of dry matter intake, refinement of energy evaluation, and adoption of metabolizable protein frameworks. These developments enhance the precision, efficiency, and applicability of ration formulation under Indian conditions. However, the limited advancement in mineral nutrition underscores the need for targeted research. Future revisions should aim to integrate mineral metabolism with predictive modelling frameworks to achieve a fully comprehensive nutritional system.

In conclusion, ICAR (2024) represents a critical step toward precision livestock nutrition, aligning scientific rigor with practical applicability.

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Sustainable Pest and Disease Control in Cauliflower

Abstract

An Integrated Pest Management (IPM) approach for cauliflower (*Brassica oleracea* var. *botrytis*) focuses on reducing the excessive use of chemical pesticides traditionally applied to control pests like mustard aphid (*Lipaphis erysimi*) and diseases such as damping-off and Alternaria leaf spot. Instead of relying only on chemicals, IPM combines cultural, biological, and need-based chemical methods for effective control. This approach helps in improving crop yield, with production reaching around 24 t/ha, which is about 10% higher compared to conventional practices. It also provides better economic returns, with higher net income and benefit-cost ratio. At the same time, IPM significantly reduces pesticide use by about 63.8% and cuts down the number of spray applications by more than half. Safer bio-pesticides and low-risk chemicals are preferred over harmful pesticides, making the method more environmentally friendly. Overall, IPM is a cost-effective and sustainable way to manage pests and diseases in cauliflower.

Introduction

Cauliflower is an important vegetable crop widely grown for its nutritional value and economic importance. However, its production is greatly affected by various insect pests and diseases that damage leaves and curds, leading to reduced yield and quality. Excessive use of chemical pesticides can cause environmental pollution, health risks, and pest resistance. Therefore, Integrated Pest and Disease Management (IPDM) has become essential in modern agriculture. IPDM focuses on combining different methods such as cultural practices, biological control, mechanical methods, and limited chemical use to manage pests and diseases effectively. This approach aims to maintain pest populations below harmful levels while protecting the environment and ensuring sustainable crop production.

Different Pests and Diseases in Cauliflower:

Pests:

Diamondback moth (*Plutella xylostella*) is the most serious pest. Its small green caterpillars feed on leaves and make tiny holes, giving a net-like or skeleton appearance.

Cabbage butterfly (*Pieris brassicae*) larvae are big caterpillars that eat leaves heavily, leaving large holes. In severe cases, only the veins remain.

Aphids (*Brevicoryne brassicae*) are small insects that suck sap from leaves and curds. They cause yellowing, curling, and sticky surfaces due to honeydew.

Cutworms are soil pests that cut young seedlings at the base, usually at night. Plants suddenly fall and die.

Leaf Webber (*Crocidolomia binotalis*) tie leaves together with silk and feeds inside, which reduces plant growth and affects curd formation.

Cabbage head borer (*Hellula undalis*) bores into the curd and shoots, making the cauliflower unfit for market.

Flea beetles are tiny jumping insects that make small holes in leaves, especially in young plants.

Cabbage looper (*Trichoplusia ni*) is a green caterpillar that moves in a looping manner and feeds on leaves, making large irregular holes.

Thrips are very small insects that suck sap from leaves, causing silvery patches and poor growth.

Diseases:

Damping-off affects young seedlings in the nursery. The base of the plant becomes weak, rots, and the seedling falls over and dies.

Black rot is a serious bacterial disease. Leaves develop yellow "V-shaped" patches from the edges, and the veins turn black.

Clubroot causes swelling and deformation of roots. Because roots are damaged, the plant cannot absorb nutrients properly and becomes weak and stunted.

Downy mildew shows yellow spots on the upper side of leaves and a grey or whitish growth on the underside, especially in cool and moist conditions.

Alternaria leaf spot causes dark brown or black circular spots on leaves, sometimes with ring patterns. It can spread quickly in humid weather.

Powdery mildew appears as a white powdery coating on leaves, which reduces plant growth.

Black leg causes dark, sunken lesions on stems and may lead to wilting and plant death.

Soft rot makes the plant tissues soft, watery, and foul-smelling, especially in wet conditions.

Fusarium yellow leads to yellowing of leaves, stunted growth, and wilting of plants.

Mosaic disease (viral) causes light and dark green patches on leaves, along with distortion and poor growth.

Preventive measures:

Use of Healthy Seeds

Always use certified, high-quality, and disease-free seeds. Seeds should be free from pathogens to avoid introducing diseases into the field. Choosing resistant or tolerant varieties helps in reducing the chances of infection and pest attack from the beginning.

Seed Treatment

Before sowing, seeds should be treated with fungicides like thiram or carbendazim to control seed-borne diseases. Alternatively, bioagents such as *Trichoderma* can be used for eco-friendly protection. This step is especially important to prevent diseases like damping-off in the early stages.

Proper Nursery Management

Seedlings should be raised on raised nursery beds to ensure good drainage and prevent water stagnation. The nursery area should be clean and free from weeds and old plant debris. Avoid overcrowding of seedlings, as it increases humidity and promotes disease development.

Crop Rotation

Cauliflower should not be grown repeatedly in the same field. Rotating with non-cruciferous crops like cereals or pulses for 2–3 years helps break the life cycle of soil-borne pathogens and pests, especially clubroot and black rot.

Field Sanitation

Maintain a clean field by removing weeds, infected plants, and crop residues regularly. These can act as sources of infection and shelter for pests. Destroying them helps in preventing the spread of diseases and pests.

Proper Spacing and Aeration

Maintain recommended spacing between plants to allow proper air circulation and sunlight penetration. This reduces humidity around plants and helps prevent fungal diseases such as downy mildew and Alternaria leaf spot.

Balanced Fertilization

Apply fertilizers in balanced amounts based on crop requirements. Excess nitrogen should be avoided as it promotes soft and tender growth, which attracts pests like aphids and increases disease susceptibility. Proper nutrition helps plants grow strong and resist infections.

Irrigation and Drainage Management

Provide adequate irrigation without overwatering. Excess moisture creates favorable conditions for diseases like damping-off, root rot, and soft rot. Proper drainage should be ensured so that water does not accumulate in the field.

Use of Traps

Install pheromone traps to monitor pests like diamondback moth and detect their presence early. Yellow sticky traps are useful for controlling aphids and other small insects. These traps help in early warning and reduce pest population.

Encourage Natural Enemies

Promote beneficial insects such as ladybird beetles, lacewings, and parasitoids that naturally feed on harmful pests. Conserving these natural enemies helps maintain ecological balance and reduces the need for chemical pesticides.

Use of Biopesticides

Apply neem-based products like neem oil or neem seed kernel extract (NSKE), and microbial pesticides like *Bacillus thuringiensis (Bt)*. These are safe for the environment and effective in controlling pests at early stages.

Regular Field Monitoring (Scouting)

Inspect the crop regularly to identify early symptoms of pests and diseases. Early detection allows timely action, preventing the problem from becoming severe and reducing crop losses.

Conclusion

Integrated Pest and Disease Management in cauliflower is an effective and sustainable strategy for controlling pests and diseases while minimizing environmental harm. By adopting preventive measures, maintaining field sanitation, encouraging natural enemies, and using chemicals only when necessary, farmers can reduce crop losses and improve productivity. Regular monitoring and timely management play a key role in successful implementation. Overall, IPDM helps in achieving higher yield, better quality produce, and long-term agricultural sustainability.

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ARTICLE ID: 10

Advanced Steering Systems for Agriculture

Summary

This article presents an overview of advanced steering systems used in modern agriculture and their role in improving operational efficiency, maneuverability, and field accuracy. Various steering technologies including GPS/GNSS-based auto-steering, machine vision guidance, electro-hydraulic steering, crawler steering, dog clutch-based steering, and ECU-controlled intelligent steering systems are discussed. Commercially available steering solutions such as John Deere AutoTrac™, Trimble Autopilot, zero-turn steering, crab steering, and four-wheel steering systems are also highlighted. In addition, the article examines the specific need for advanced steering technologies in Indian agriculture, where fragmented land holdings, wetland cultivation, labour shortages, and irregular field conditions demand improved machine guidance, precision operation, and efficient machinery management.

Keywords: *Agricultural mechanization, Precision agriculture, Steering systems, Autonomous tractors, Smart farming*

Introduction

Agriculture is experiencing a major transformation driven by mechanization, precision technologies, automation, and digital integration. Modern farming is no longer limited to increasing machine power alone; greater emphasis is now placed on operational precision, efficiency, and intelligent control. Among the many components of agricultural machinery, the steering system plays a crucial role in ensuring accurate field operations, although it often receives less attention compared to engines and implements. Traditionally, steering in farm vehicles was entirely mechanical and depended heavily on the experience, physical effort, and endurance of the operator. Farmers had to manually guide tractors across fields, maintain row alignment, and maneuver through uneven terrains under varying field conditions.

With the increasing adoption of precision agriculture, the role of steering systems has changed significantly. Present-day agricultural operations such as sowing, spraying, fertilizer application, and harvesting require high levels of positional accuracy. Even minor steering deviations can lead to overlaps, skipped areas, increased input consumption, and reduced operational efficiency. At the same time, the emergence of autonomous and semi-autonomous farm machinery has transformed steering from a simple directional control mechanism into an intelligent decision-making system capable of automatic navigation and adaptive response.

Advanced research in farm vehicle steering systems has therefore become essential to improve operational precision, safety, maneuverability, and operator comfort. Modern steering technologies are being designed not only to reduce steering effort and fatigue but also to integrate with GPS, sensors, machine vision, and artificial intelligence systems for autonomous field operations. These developments are playing a vital role in the advancement of smart farming and sustainable agricultural mechanization.

Steering Technologies

Different types of advanced steering systems are currently being adopted in agriculture to improve precision, reduce operator fatigue, and enhance machine efficiency during field operations. Among these, GPS/GNSS-based auto-steering systems are the most widely used. These systems utilize satellite positioning along with RTK correction signals to guide tractors accurately along predefined paths with minimal human intervention. Such technologies help reduce overlaps and misses during field operations, thereby saving fuel, seeds, fertilizers, and time.

Camera-based steering systems are another important development, where machine vision technologies are used to detect crop rows and maintain alignment automatically. These systems are particularly useful in row crops and precision cultivation practices. Similarly, laser-guided steering systems use laser transmitters and receivers to achieve accurate navigation in applications such as land levelling and controlled-environment agriculture. Ultrasonic sensor-based steering systems also assist in directional control by detecting crop rows or nearby obstacles through sound-wave sensing techniques.

Recent advancements in machine vision and artificial intelligence have further improved autonomous steering capabilities. AI-assisted steering systems combine cameras, sensors, and intelligent algorithms to perform path planning, obstacle detection, and autonomous navigation under varying field conditions. Electro-hydraulic steering systems use electronic controllers and hydraulic actuators to automatically control steering movement, while Electric Power Steering (EPS) systems use electric motors to provide energy-efficient steering assistance with improved responsiveness.

Modern autonomous tractors increasingly rely on sensor fusion technologies, integrating GPS, inertial measurement units (IMU), LiDAR, cameras, and steering angle sensors to achieve high-precision navigation. These systems enable accurate steering even under difficult field conditions such as low visibility, uneven terrain, or slippery soils.

Apart from wheel-based steering systems, several advanced mechanical steering concepts are also gaining importance in agricultural machinery. Dog clutch-based steering systems selectively engage or disengage drive transmission to individual wheels or tracks to achieve directional control with minimal power loss. These systems are particularly useful in compact utility vehicles and robotic agricultural platforms.

Crawler tractor steering is another important technology used in tracked tractors operating in wetlands and low-bearing-capacity soils. Unlike conventional wheel steering, crawler tractors achieve turning through differential track speed control, where one track slows down or stops while the other continues moving. This mechanism enables smooth maneuverability in muddy and slippery field conditions while minimizing soil compaction. Advanced crawler steering systems now incorporate hydrostatic drives and electronic control units for improved steering response and operational stability.

ECU-based steering systems have emerged as one of the most advanced developments in precision agriculture. These systems integrate Electronic Control Units (ECU) with sensors such as GPS, IMU, steering angle sensors, and wheel speed sensors to automatically regulate steering operations. ECU-controlled steering enables functions such as auto-guidance, adaptive steering response, automated headland turning, and autonomous navigation. By combining real-time data processing with intelligent control algorithms, these steering systems significantly improve field efficiency, safety, operational accuracy, and compatibility with next-generation smart agricultural machinery.

Many of these advanced steering technologies have now moved beyond research laboratories and are commercially available in modern agricultural machinery worldwide.

Commercial Systems

Several advanced steering systems are now commercially available and are widely used in agriculture both in India and internationally. These systems are helping farmers improve operational precision, reduce manual effort, and move toward autonomous farming practices. One of the most popular commercial systems is John Deere AutoTrac™, which provides GPS-based hands-free steering with centimeter-level accuracy. The system has already been introduced in India for precision farming applications and is widely recognized for improving operational efficiency and reducing operator fatigue.

Fig.1 John Deere AutoTrac™

Fig.2 Trimble Autopilot

Trimble Autopilot is another globally accepted steering technology known for its high-accuracy RTK guidance and compatibility with multiple tractor brands and machinery platforms. Similarly, Topcon offers advanced steering solutions such as the AES-35 Electric Steering System and other auto-steering technologies compatible with tractors, sprayers, combines and various farm equipment.

Fig.3 Zero turn lawn mower

Apart from satellite-guided steering systems, several specialized steering concepts are also commercially used in agricultural machinery. Zero-turn steering systems, commonly seen in riding lawn mowers and compact agricultural vehicles, allow machines to rotate within their own turning radius, thereby improving maneuverability in confined spaces. Crab steering systems, where all wheels move in the same direction simultaneously, are used in high-clearance sprayers and specialty agricultural vehicles to reduce crop damage and facilitate sideward movement across fields.

Four-wheel steering systems are increasingly being adopted in large tractors and telehandlers to reduce turning radius, improve stability, and enhance maneuverability under field conditions. Modern agricultural machinery manufacturers such as John Deere, Trimble, Topcon, Kubota, CLAAS, and AGCO are continuously integrating autonomous steering, sensor fusion, and AI-assisted navigation technologies into their smart farming platforms. These developments indicate the growing importance of intelligent steering systems in the future of agricultural mechanization.

Indian-Specific Needs

Indian agriculture is dominated by small and fragmented land holdings, irregular field shapes, narrow bunds, and diverse cropping systems, which make accurate maneuvering of farm machinery difficult. In addition, increasing labour shortages and the declining availability of skilled tractor operators are creating a greater demand for intelligent and operator-friendly steering technologies. Precision steering can help reduce overlaps and misses during sowing, spraying, and fertilizer application, thereby minimizing wastage of costly inputs such as fuel, seeds, fertilizers, and pesticides. Wetland cultivation, especially paddy farming in many regions of India, also requires improved steering control under muddy and slippery conditions where wheel slip is high. Advanced steering systems integrated with GPS, sensors, and electronic controllers can improve operational accuracy, reduce operator fatigue, support night-time operations, and enhance the efficiency of custom hiring centres that manage multiple machines across different farms. Furthermore, the development of affordable indigenous steering technologies using Indian navigation systems such as NavIC could play a major role in promoting smart and sustainable agricultural mechanization in the country.

Personal opinion

Indian farmers focus on maximum yields and are unlikely to accept losses caused by mechanization. Headland and turning space play a major role in losses due to mechanization under most field conditions. Hence, steering systems offering zero or very little headland/turning space are highly desirable for farm machinery. Research and development efforts must focus on the development of such steering systems while also taking automation and robotics into account.

Conclusion

Advanced steering systems are playing an increasingly important role in modern agricultural mechanization by improving operational accuracy, reducing operator fatigue, and supporting precision farming practices. Technologies such as GPS-guided auto-steering, AI-based navigation, crawler steering, and ECU-controlled systems are transforming conventional farm machinery into intelligent and efficient machines.

In the Indian context, these technologies can help address challenges such as labour shortages, fragmented land holdings, and wetland cultivation conditions. With continuous advancements in automation, sensors, and digital agriculture, advanced steering systems are expected to become a key component of future smart and sustainable farming systems.

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ARTICLE ID: 11

THE OCEAN'S ANTACID: ACCELERATING NATURE'S SLOWEST PROCESS TO COOL THE PLANET

Abstract

As global climate mitigation strategies shift from focusing solely on emission reduction to include carbon dioxide removal (CDR), Enhanced Rock Weathering (ERW) in aquatic environments has emerged as a high-potential intervention. Often termed Ocean Alkalinity Enhancement (OAE), this process accelerates the natural geological cycle of silicate weathering to sequester atmospheric CO_2 as stable oceanic bicarbonate. This approach offers dual benefits significant atmospheric carbon drawdown and the remediation of ocean acidification, which is vital for protecting calcifying marine organisms. The strategic selection of rock types remains critical, requiring a balance between the high carbon capture efficiency of minerals like olivine and the lower environmental risks associated with basalt. However, scaling this technology faces significant hurdles, including complex supply chain logistics, energy-intensive life cycles, and the technical difficulties of Monitoring, Reporting, and Verification (MRV) in dynamic marine systems. Ultimately, aquatic ERW represents a vital, scalable tool that requires immediate, rigorous field testing to ensure ecological safety and efficacy as part of a broader decarbonization effort.

Keywords: Enhanced Rock Weathering, Ocean Alkalinity Enhancement, Carbon Sequestration and Ocean Acidification.

Introduction

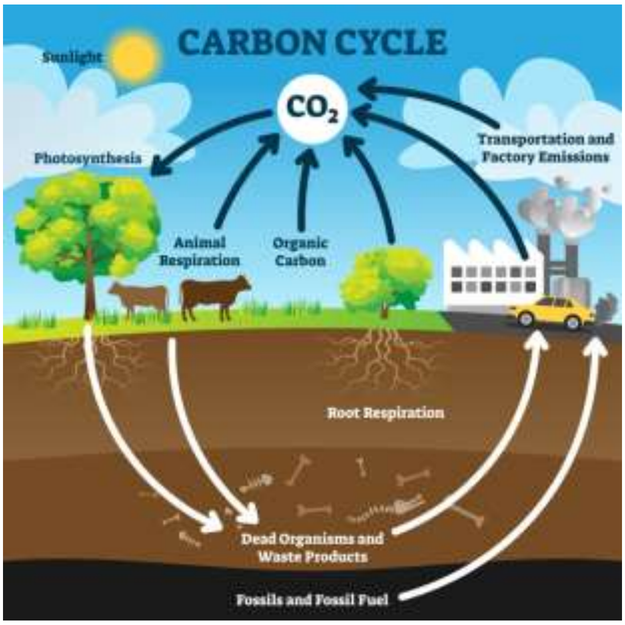
The climate crisis is effectively an energy crisis, but it is also a chemistry problem. For two centuries, humanity has dug up carbon buried deep underground and burned it, shifting it into the atmosphere as carbon dioxide (CO_2). To stabilize the planet's temperature, we know we must rapidly stop emitting new CO_2. However, scientists increasingly agree that emissions cuts alone are no longer enough; we also need to remove historic carbon from the atmosphere. While technological solutions like giant vacuums sucking CO_2 from the air get a lot of media attention, some of the most promising solutions involve partnering with Earth's own geology. One such method is Enhanced Rock Weathering (ERW), and its application in aquatic environments specifically the world's oceans is gaining significant traction as a potential game-changer.

To understand ERW, we first need to understand natural weathering. It is a process that has regulated Earth's climate over millions of years. Rain, which is slightly acidic due to atmospheric CO_2, falls on silicate rocks and slowly dissolves them. This chemical reaction consumes CO_2 and converts it into dissolved bicarbonate, which eventually washes into the ocean, where the carbon is locked away for hundreds of thousands of years.

The problem is that this natural thermostat is incredibly slow. Bach et al. (2019) describe the current effort in geoengineering as trying to speed up this geological clock. Enhanced Rock Weathering essentially involves mining specific types of rock usually basalts or olivine grinding them into a fine powder to increase their surface area, and spreading them. When applied to aquatic environments, this process is often referred to as Ocean Alkalinity Enhancement (OAE).

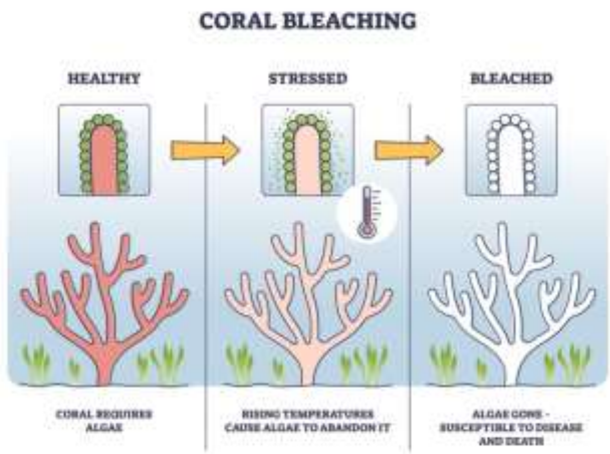
A Dual Benefit: Carbon Storage and Ocean Health

The ocean is already the primary regulator of



climate on Earth. It has absorbed roughly 90% of the excess heat trapped by greenhouse gases and about 30% of the CO_2 we have emitted since the Industrial Revolution. Without this massive buffer, climate change would already be far more catastrophic. However, this service has come at a steep cost to marine health. When CO_2 dissolves in seawater, it creates carbonic acid, leading to ocean acidification. This change in ocean chemistry is devastating for marine life, particularly organisms that build shells or skeletons out of calcium carbonate, such as corals, oysters, and certain plankton.

This is where aquatic ERW offers a unique, two-pronged benefit. By adding alkaline rock minerals to the ocean, we are effectively giving the seawater a giant dose of antacid. Renforth and Henderson (2017) explain that this process not only draws down



atmospheric CO_2 by converting it into stable bicarbonate ions but also simultaneously counteracts ocean acidification, potentially throwing a lifeline to threatened ecosystems like coral reefs.

Selection of Rock

The choice of rock is crucial for this process to work effectively and safely. Not just any stone will do. The focus is primarily on silicate rocks that are rich in magnesium and calcium. Basalt, a volcanic rock that makes up much of the ocean floor and many landmasses like Iceland/Hawaii, is a top contender. It is abundant, relatively fast-weathering, and generally considered safer in terms of trace elements. Another is olivine, a greenish mineral found deeper in the Earth's mantle. Olivine weathers even faster than basalt, theoretically absorbing CO_2 more quickly. However, it comes with caveats. Oelkers et al. (2022) note that while olivine has a higher carbon capture potential per ton, basalt is often preferred in proposed large-scale applications because it carries a lower risk of releasing toxic trace metals like nickel into the marine environment as it dissolves.

Implementation Strategies

Applying these rock dusts to the aquatic environment can take several forms. Some proposals involve spreading rock dust on high-energy coastal beaches, where the natural churning action of waves performs the mixing and speeds up the dissolving process. Others suggest adding rock minerals directly to the wake of ships crossing the open ocean. There are also hybrid approaches. For instance, applying rock dust to agricultural land is a major area of ERW research, and much of the dissolved bicarbonate from that process eventually runs off into rivers and makes its way to the ocean. Eisaman et al. (2023) highlight that marine applications of ERW have a distinct advantage over terrestrial methods because the ocean provides a virtually unlimited sink for the resulting bicarbonate, avoiding saturation issues that might occur in some soils.

Managing Operational and Ecological Risks

Although the underlying chemistry works well under controlled laboratory conditions, applying it in the vast and dynamic ocean environment is far more complex. Managing the extraction, crushing, and large-scale transport of enormous quantities of rock poses major practical hurdles. If these operations rely on fossil-fuel energy, the resulting emissions could cancel out the intended climate benefits. This means every stage of the process must operate on low-carbon energy sources. As highlighted by Fuss et al. (2018), thorough life-cycle assessments are essential to verify that the mining and transport emissions do not exceed the amount of carbon removed through enhanced weathering.

Furthermore, the environmental impacts on complex marine ecosystems are not fully understood. While reducing acidity is generally good, dumping massive amounts of ground rock could have unintended consequences. The dust could increase turbidity, blocking sunlight for photosynthetic algae. It could irritate the gills of fish or filter-feeders. There is also the aforementioned risk of trace metal contamination if the wrong rock source is used. Bach et al, (2019) emphasize the critical need for extensive biological impact studies on marine food webs before any massive deployment is attempted, arguing that we cannot risk trading one environmental disaster for another.

Confirmation and Challenges

A major challenge in this field is what researchers refer to as Monitoring, Reporting, and Verification (MRV). If a government or private company claims it has removed a million tons of CO_2 by dispersing finely ground minerals into the Atlantic, the real question is: how can we confirm that? The ocean is enormous, constantly shifting, and naturally variable, which makes detecting the small chemical changes produced by added rock extremely difficult. According to Chlela and Seloss, 2025 stated that creating reliable, scalable, and cost-effective MRV systems is likely the most critical technical requirement for expanding ocean alkalinity enhancement and establishing a transparent and credible carbon removal market.

Even with the obstacles, research activity is steadily increasing. Scientists around the world are running laboratory studies and limited field trials to examine how various minerals behave, how they should be applied, and how marine organisms respond. Many teams are using mesocosms large outdoor tank systems that mimic real ocean conditions to watch how corals, plankton, and other marine life react when rock dust is introduced. These controlled setups are crucial for identifying safe boundaries for future deployment. It is generally agree that enhanced rock weathering in aquatic environments is not a miracle solution that lets society continue relying on fossil fuels. Instead, it is one potential strategy among many. As emphasized by Gattuso et al. (2021), ocean-based climate interventions must go hand-in-hand with rapid and substantial emissions cuts, not replace them.

Conclusion

Enhancing rock weathering in aquatic environments represents a fascinating convergence of geology, chemistry, and oceanography aimed at solving the greatest challenge of our time. It seeks to utilize the earth's immense natural reserves of minerals and the ocean's vast capacity for carbon storage to tidy up the atmospheric mess humanity has created. While the potential scale of carbon removal is enormous, and the co-benefit of de-acidifying the ocean is highly attractive, the ecological risks and logistical hurdles are equally significant. Proceeding requires a delicate balance of urgency and caution. We must move fast to understand this technology, but we must also move smartly to ensure the cure isn't worse than the disease.

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ARTICLE ID: 12

A Historical Overview of Agricultural Drone Development and Its Impact on Modern Farming

Abstract

Agricultural drones, also known as unmanned aerial vehicles (UAVs), have revolutionized precision farming by enhancing efficiency, reducing costs, and enabling data-driven decisions. This paper explores the historical development of agricultural drones, from their military and hobbyist roots to their integration into modern agronomy. The study traces technological milestones, regulatory influences, and evolving use cases, highlighting key contributions from academia and industry. The article also discusses the challenges and opportunities associated with drone use in agriculture.

1. Introduction

Agriculture has consistently embraced technological advances to improve productivity. The use of drones represents one of the most significant developments in precision agriculture. These aerial tools have enabled farmers to monitor crop health, map fields, and optimize inputs with remarkable accuracy. This paper presents a historical account of agricultural drone development, its technological evolution, and its influence on farming practices.

2. Origins and Early Applications

The origin of drone's dates back to the early 20th century initially developed for military purposes. The first pilotless aircraft, such as the Radio plane OQ-2, was used during World War II for training anti-aircraft gunners (Austin, 2010). After the war, drone technology found applications in photography, mapping, and eventually, commercial sectors. The concept of drones in agriculture emerged in Japan during the 1980s, when Yamaha introduced the RMAX unmanned helicopter for spraying rice paddies (Yamaha Motor Co., 2020). This marked the first significant use of UAVs in a civilian agricultural context.

3. Technological Evolution (2000s–2010s)

In the early 2000s, drones equipped with GPS and remote sensing capabilities began entering Western agricultural markets. The adoption was initially slow due to high costs, limited battery life, and regulatory hurdles. However, with the advent of consumer-grade drones like those from DJI Technologies, and the integration of multispectral imaging, UAVs became more accessible and practical for farmers (Zhang & Kovacs, 2012).

The period from 2010 to 2015 saw rapid development:

- 2013: 3D Robotics and DJI launched programmable drones tailored for agricultural surveying.
- 2014: PrecisionHawk began developing AI-powered data analytics platforms to complement UAV data.

4. Regulatory Framework and Commercial Expansion

Governments across the globe, notably the Federal Aviation Administration (FAA) in the United States, began establishing drone usage guidelines around 2015, enabling legal commercial drone operations under Part 107 rules (FAA, 2016). This regulatory clarity led to increased investment and adoption in agriculture.

By the late 2010s, UAVs were used extensively for:

- Crop health monitoring
- Irrigation management
- Pest detection
- Livestock tracking
- Aerial planting and spraying (Tsouros et al., 2019)

5. Integration into Precision Agriculture

Modern agricultural drones are integrated into Internet of Things (IoT) systems and Artificial Intelligence (AI) platforms. These tools convert drone-collected imagery into actionable insights through algorithms and cloud computing. Companies like Trimble, John Deere, and senseFly have developed end-to-end platforms combining drone hardware with analytics software, promoting data-driven farming.

6. Challenges and Limitations

Despite significant advances, agricultural drones face several challenges:

- Limited flight time and payload capacity
- Data privacy and security concerns
- High initial investment
- Need for operator training and certification (Hunt et al., 2019)

Moreover, adoption remains low in developing regions due to lack of infrastructure and government support.

7. Conclusion

The journey of agricultural drones from military roots to modern precision farming tools illustrates their transformative potential. With continued innovation, improved regulations, and wider accessibility, drones are set to play a pivotal role in sustainable agriculture.

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ARTICLE ID: 13

Precision genome engineering via CRISPR-Cas9 for enhanced crop traits.

Abstract

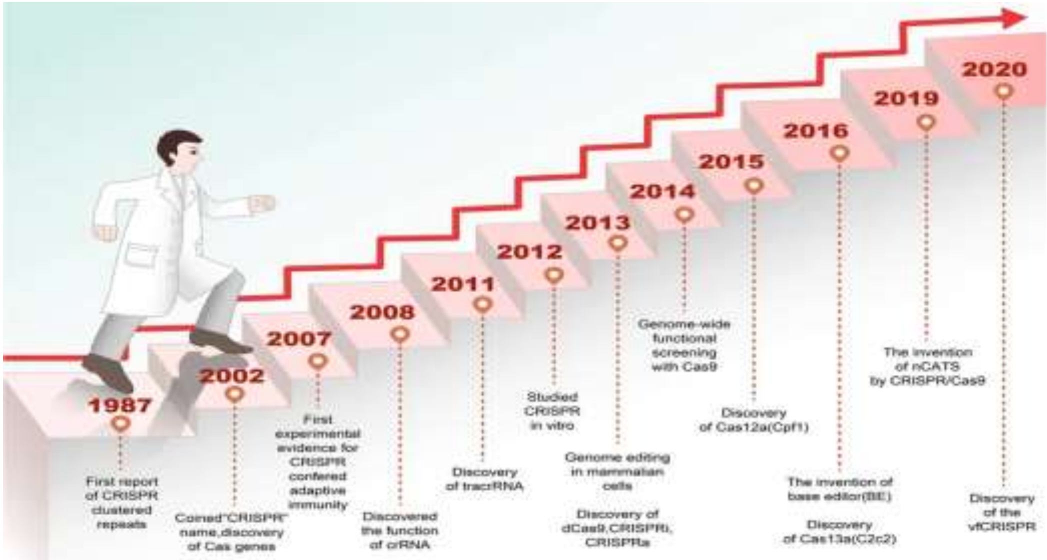
CRISPR–Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats — CRISPR-associated protein 9) has rapidly transformed genome engineering by providing a simple, programmable RNA-guided endonuclease for targeted DNA modification. Since its functional repurposing for genome editing in eukaryotic cells, CRISPR–Cas9-based methods have enabled efficient gene disruption, targeted corrections and the development of precision editing variants such as base editors and prime editors. In agriculture, these tools represent a significant leap over traditional transgenesis; by enabling precise 'DNA-free' edits within a plant's own genome, CRISPR produces varieties that are often indistinguishable from those developed through natural breeding. These edited crops avoid the random integration and 'foreign DNA' baggage of first-generation GMOs, offering superior precision, faster development timelines, and a more streamlined path to regulatory approval. While these technologies have accelerated fundamental research and produced promising clinical results, they continue to face technical and ethical challenges related to off-target effects, delivery and equitable global access.

CRISPR-Cas9; genome editing, crop improvement, gene therapy, plant biotechnology.

Introduction

CRISPR technology has surpassed ZFNs and TALENs as a popular method for genome editing, earning recognition from "methods of the year" in 2011 to "breakthrough of the year" in 2015. This bacterial technique is quickly adopted for genome editing in eukaryotic cells.

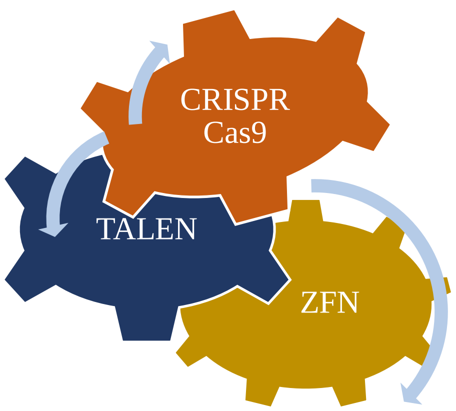
Development history of the CRISPR/Cas9-based gene editing tools



Sources: Zhang *et. al.*, Mol Cancer (2021) 20:126

The development of engineered endonucleases/mega-nucleases, zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs) and type II clustered regularly interspaced short palindromic repeat (CRISPR)/CRISPR-associated protein 9 (Cas9) has enabled single nucleotide excision mechanisms for crop improvement. Genome editing modifies a specific genome in a precise and predictable manner. There may be various genes that can be altered in different cell types and creatures using nucleases that provide specific changes. Sangamo Bio Sciences has one of the oldest gene editing technologies, ZFNs, which was created in the 1990s. ZFNs are restriction enzymes that bind to particular DNA sequences using zinc finger motifs and have a non-specific cleavage domain similar to Fok1 endonucleases. 4-6 binding modules make a single zinc finger unit. A ZFN pair detects a unique 18-24 bp DNA sequence, and Fok1 dimer creates double stranded breaks. FokI nucleases are naturally occurring type IIS restriction enzymes that cause single-stranded breaks in double-helical DNA. FokI acts as a dimer, with each catalytic monomer (nickase) cleaving a single DNA strand to form a staggered DSB with overhangs. (Pabo *et al.*, 2001). ZFNs have successfully modified the genomes of several plants, including tobacco, maize, and soybean. TALENs have a customisable DNA-binding domain coupled with a non-specific Fokl nuclease domain.

Genome editing tools



CRISPR/Cas9

CRISPR/Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats/CRISPR-associated protein 9) is a revolutionary genome-editing technology adapted from a natural adaptive immune system found in bacteria and archaea. It serves as a programmable "molecular scissor" that can be directed to specific DNA sequences to introduce precise modifications.

Zinc Finger Nucleases (ZFNs)

Zinc Finger Nucleases (ZFNs) were the first major breakthrough in programmable genome editing, predating the more famous CRISPR-Cas9 system (fig 1). When both ZFNs bind to their respective spots, the *FokI* domains are brought close enough to pair up and create a Double-Strand Break (DSB) in the DNA.

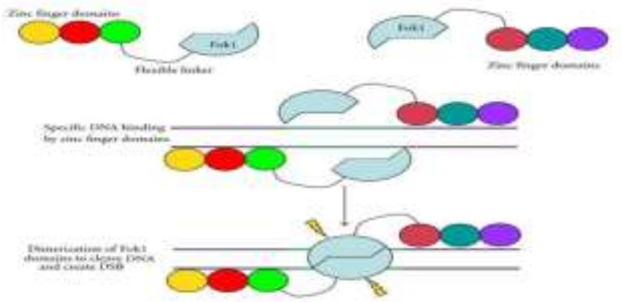


Figure1 : Mechanism of ZFN
Sources: Urnov, F. D., *et al*. (2010).

TALEN

TALENs (Transcription Activator-Like Effector Nucleases) are powerful tools used for precise genome editing. TALENs are always designed in pairs to bind on opposite sides of the target DNA (fig 2). The cell recognizes the break and tries to fix it using two main pathways: NHEJ (Non-Homologous End Joining): Often results in small errors (insertions or deletions), which can "knock out" or disable a gene. HDR (Homology-Directed Repair): If a "template" DNA is provided, the cell can use it to precisely rewrite or "knock in" a new sequence.

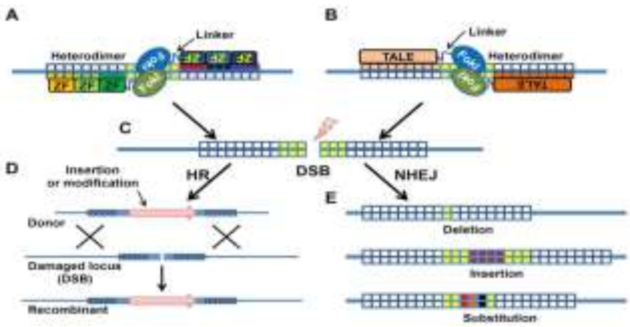


Figure2: The principles of ZFN-or TALEN-mediated gene targeting. (A) Zinc finger (ZF) motifs and (B) TALE modules are designed to detect specific sequences in an opposite direction. Previously developed, heterogeneous nuclease domains of FokI endonuclease can only form a heterodimer that is essential to exert endonuclease activity. (C) When connected to ZFs or TALEs through a linker, each pair of ZFNs or TALENs induces a double-strand break (DSB) at the spacer region between the binding sequences. DSBs are repaired through homologous recombination (HR) or non-homologous end joining (NHEJ). (D) If a donor DNA containing an additional sequence or modifications of the endogenous sequence, HR-mediated gene conversion can be achieved. (E) Without the template for HR-mediated DNA repair, DSB will be repaired through the error-prone NHEJ pathway,

frequently resulting in deletion, insertion, and substitution of the original sequence.

Sources: Large-scale mouse mutagenesis and ZFN/TALEN Young Hoon Sung, *et al.,* 2012.

CRISPR/Cas9 as a Tool for Crop Improvement

By 2026, CRISPR-Cas9 has shifted from an experimental laboratory tool to a cornerstone of precision breeding in agriculture. This technology allows for targeted genetic modifications in major staple crops like rice, wheat, and maize to address global challenges such as food insecurity and climate change. Unlike traditional genetic modification, CRISPR is often favored because it can create non-transgenic varieties—making precise alterations without introducing foreign DNA—which can help bypass certain GMO regulations.

Core Applications in Crop Improvement

1. Climate Resilience (Abiotic Stress)- CRISPR-Cas9 is used to engineer "climate-smart" crops capable of surviving extreme environmental hazards. Drought and Salinity: Researchers target specific genes to enhance water retention and salt tolerance, which is critical as climate change reduces arable land. For example, studies on the zmPP2C15 gene in maize have shown its role in improving drought tolerance.

2. Yield and Quality Enhancement- Grain Size and Weight: Scientists use CRISPR to selectively delete or "knock out" genes that regulate grain size to directly increase crop yields.

3. Nutritional Biofortification- Vitamin and Mineral Boosting: CRISPR is used to enhance the nutritional profile of staple foods, such as increasing provitamin A and iron content.

4. Biotic Stress Resistance- Disease and Pest Resistance: By knocking out "susceptibility genes" (*S-genes*), researchers create cultivars naturally resistant to bacterial blights, viruses, and fungal pathogens. Recent work has even extended this to managing post-harvest diseases in fruits like citrus.

Future aspects in crisper case/9

Agricultural CRISPR applications are moving beyond simple "GMO" traits toward climate resilience and biofortification. Climate-Adaptive Crops: Scientists are now using multiplex editing (editing multiple genes at once) to create crops that can survive extreme drought, high salinity, and rising temperatures simultaneously. Nutritional Biofortification: A major 2026 trend is the development of "functional foods," such as rice with increased zinc and iron or tomatoes with higher antioxidant levels, aimed at solving malnutrition in developing regions. Pest & Disease Resistance: CRISPR is being deployed to create wheat resistant to rust fungus and soy without common allergens, reducing the reliance on chemical pesticides Frontiers in Cell and Dev. Biology (2021/2026 updates).

The "Climate-Ready" Crop: CRISPR is being used to bypass the slow process of traditional breeding to address food security:vAbiotic Stress Tolerance: 2026 research highlights crops edited for "Multiplex Traits"—plants that are simultaneously resistant to drought, high salinity, and extreme heat. Pesticide Reduction: By knocking out "susceptibility genes," scientists have created wheat and rice that are naturally resistant to fungi and bacterial blight, aiming to cut chemical pesticide use by 20–50%.

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ARTICLE ID: 14

USE OF BIOETHANOL INDUSTRY BY-PRODUCT AS A LIVESTOCK FEED RESOURCES

ABSTRACT

The rapid growth of the livestock sector, coupled with the rising cost of conventional feed ingredients, has intensified the search for alternative and sustainable feed resources. In this context, the bioethanol industry has emerged as a significant source of valuable by-products such as distillers dried grains with solubles (DDGS), corn gluten feed (CGF), corn gluten meal (CGM), vinasse, and bagasse. These by-products are rich in protein, energy, fibers and essential nutrients, as the ethanol production process utilizes only the starch fraction of grains, leaving behind concentrated nutrients suitable for animal feeding (Popp *et al.*, 2016). Among these, DDGS is widely used due to its high protein content, digestible fiber, and residual yeast, which enhance palatability, rumen microbial activity, and overall animal performance. Similarly, CGF serves as an economical energy and fiber source for ruminants, while CGM is a high-protein ingredient commonly used in poultry diets. Other by-products such as vinasse and treated bagasse can be utilized in multi-nutrient blocks and as low-cost roughage sources, respectively, improving nutrient utilization in livestock systems (ICAR, 2023). The inclusion of these by-products in animal diets not only reduces feed costs and dependence on conventional ingredients like maize and soybean meal but also contributes to waste valorization, environmental sustainability, and the development of a circular bio-economy (Kim and Dale, 2005). However, challenges such as variability in nutrient composition, mycotoxin contamination, and amino acid imbalance require careful management for their efficient utilization (Liu, 2011). Continued research, technological advancements and regulatory collaboration in feed manufacturing technology will enhance its effectiveness as alternative feed resources.

1. INTRODUCTION

The livestock sector plays a vital role in food security and economic development. However, increasing feed costs and scarcity of conventional feed resources such as maize and soybean meal have created a need for alternative feed sources. In this context, agro-industrial by-products have gained importance (ICAR, 2023). Bioethanol is a renewable fuel produced mainly from crops such as maize, sugarcane, and other biomass sources. Globally, bioethanol production has increased significantly due to environmental concerns and fuel blending policies. According to the Renewable Energy Policy Network for the 21st Century (REN21, 2025), global production reached approximately 106–107 billion litres in 2023 and is expected to exceed 157 billion litres by 2030.The major feed stocks used worldwide include maize, sugarcane, wheat, and cassava. Countries like the United States and Brazil dominate global production, and the share of liquid biofuels is steadily increasing.

India's actual bioethanol production is projected to be around 10.5 billion litres in 2025, reflecting an average blending rate of about 20% during 2024–25.Chhattisgarh has an estimated production capacity of about 1.0 billion litres (≈102 crore litres), primarily from around 20 grain-based ethanol projects using feedstocks like rice and corn. This forms part of the central government's push toward grain-based ethanol production, with additional plants under development. *Chinimandi* (2025)

Contribution of Feedstocks and Regional Bioethanol Production

1. Contribution of Different Feedstocks for Bioethanol Production (Global Perspective) : Bioethanol production worldwide relies on a variety of feedstocks, primarily depending on regional agricultural availability and technological advancement. The major feedstocks include maize (corn), sugarcane, wheat, cassava, and other carbohydrate-rich crops.Globally, maize and sugarcane are the dominant feedstocks used for bioethanol production. The United States mainly utilizes maize, while Brazil predominantly uses sugarcane due to its high sucrose content and better ethanol yield efficiency. In Europe and parts of Asia, wheat and other cereals contribute significantly, whereas cassava is commonly used in Southeast Asian countries.According to International Energy Agency (IEA, 2024) and USDA (2024), maize contributes the largest share to global ethanol production, followed by sugarcane and wheat. The choice of feedstock affects not only ethanol yield but also the quantity and quality of by-products available for livestock feeding.

2. Global Feedstock Contribution: At the global level, bioethanol production reached approximately 106–107 billion litres in 2023, with projections to exceed 157 billion litres by 2030. The contribution of different feedstocks is distributed as follows:Maize (Corn): Major contributor, especially in the USA,Sugarcane: Dominant in Brazil and tropical regions ,Wheat and Barley: Used in Europe,Cassava: Used in Asian countries. The dominance of maize and sugarcane is due to their high fermentable sugar and starch content, which leads to higher ethanol yields and efficient processing (REN21, 2025; IEA, 2024).

3. Feedstock Contribution in India : In India, the bioethanol industry is primarily based on sugarcane molasses, followed by grain-based feedstocks such as rice, maize, and wheat. Traditionally, molasses was the main raw material; however, with the expansion of ethanol blending programmes, there has been a significant shift toward grain-based ethanol production. As per FAS USDA (2024) and Ministry of Petroleum and Natural Gas (2024):Sugarcane molasses contributes a major share. Grain-based ethanol (rice, maize, broken rice) is rapidly increasing. Surplus food grains are now being diverted for ethanol production. This diversification of feedstocks has increased ethanol production capacity and ensured better utilization of agricultural produce.

4. State-wise Bioethanol Production in India : Bioethanol production in India is unevenly distributed and largely depends on the availability of raw materials and industrial infrastructure. Major ethanol-producing states include: Uttar Pradesh: Leading producer due to abundant sugarcane ,Maharashtra: Strong sugar industry support ,Karnataka: Significant contribution from both sugarcane and grains ,Bihar and Gujarat: Emerging contributors. According to Ministry of Petroleum and Natural Gas (2024) and ICAR (2024), these states collectively contribute the majority of India's ethanol production, supporting the national ethanol blending programme.

5. Contribution of Chhattisgarh in Bioethanol Production : Chhattisgarh has emerged as an important state in India's grain-based ethanol production, particularly due to its high rice production. The state is actively promoting ethanol production using surplus and broken rice under government policies. As reported by *Chinimandi* (2025) The state has an estimated production capacity of around 1.0 billion litres (≈102 crore litres). Around 20 grain-based ethanol plants are operational or under development. This development aligns with the Government of India's initiative to enhance ethanol blending and utilize surplus food grains effectively.

6. Ethanol Yield Potential from Different Feedstocks: Different feedstocks vary in their ethanol yield potential. For example:Sugarcane and molasses provide high ethanol yield due to direct sugar

fermentation ,Maize and grains require starch conversion but still offer high output ,Broken rice is increasingly used due to its availability and efficiency. According to available data, broken rice shows a high ethanol yield potential, making it an important feedstock in India's ethanol expansion strategy (IEA, 2024; USDA, 2024).During ethanol production, a large quantity of by-products is generated. Approximately 2–3 kg of by-products are produced per litre of ethanol (FAS USDA, 2024). These by-products are rich in protein, fibre, and energy, making them valuable feed resources for livestock.Utilization of bioethanol by-products helps reduce feed costs, improves nutrient recycling, and supports sustainable livestock production systems (Popp *et al*., 2016).

BIOETHANOL PRODUCTION AND BY-PRODUCTS

Bioethanol is produced through fermentation of carbohydrates present in grains or sugar crops. The main steps include grinding, liquefaction, saccharification, fermentation by yeast, and distillation. Only starch is converted into ethanol, while other nutrients such as protein, fat, fibre, and minerals remain in the by-products (Popp *et al*., 2016).There are two main processes: Dry Milling (≈90%) → produces DDGSAnd Wet Milling (≈10%) → produces CGF and CGM. These by-products are concentrated sources of nutrients and are widely used in livestock feeding (Feedipedia, 2018).

TYPES OF BIOETHANOL BY-PRODUCTS

The bioethanol industry generates several valuable by-products during the conversion of biomass into ethanol. These by-products are rich in nutrients such as protein, fibre, fat, and minerals, making them suitable for use as livestock feed. The major types of bioethanol by-products include corn gluten feed, corn gluten meal, vinasse, sugarcane bagasse, and distillers dried grains with solubles (DDGS). Each of these has distinct characteristics and applications in animal nutrition.

1. Corn Gluten Feed (CGF) :Corn gluten feed is a by-product obtained during the wet milling process of maize. It consists of corn bran and steep liquor, which are combined and dried. CGF is a medium-protein feed ingredient containing approximately 20–25% crude protein and a relatively high fibre content. Due to its high digestible fibre and energy content, CGF is particularly suitable for ruminants such as cattle, sheep, and goats. It helps in maintaining rumen health by reducing the risk of acidosis, as it contains less starch compared to cereal grains. Additionally, CGF is palatable and can improve feed intake in livestock. However, care should be taken to ensure it is free from mycotoxins, especially aflatoxins, which may develop during improper storage. (Feedipedia, 2018).

2. Corn Gluten Meal (CGM) :Corn gluten meal is another product of the wet milling process of maize. It is the dried residue remaining after the removal of most of the starch, fibre, and germ. CGM is a highly concentrated protein source, typically containing around 60% crude protein.It is widely used in poultry diets due to its high protein content and digestibility. CGM is also rich in methionine, an essential amino acid for poultry, but it is relatively low in lysine. In addition to its nutritional value, CGM is often used as a natural pigment source in poultry feed, enhancing the yellow color of egg yolks and broiler skin. Its low fibre content makes it less suitable for ruminants compared to CGF (Feedipedia, 2018).

3. Vinasse :Vinasse is a liquid by-product generated during the distillation of fermented biomass in ethanol production. It is commonly derived from sugarcane, molasses, cassava, or other carbohydrate-rich materials.Vinasse contains significant amounts of organic matter, minerals, and small quantities of protein. Although it has low dry matter content, it can be used in livestock feeding after proper processing. It is often incorporated into multi-nutrient blocks or used as a liquid feed supplement, particularly in ruminant diets. Vinasse also improves palatability and provides a source of potassium and other minerals. However, its high moisture content makes transportation and storage challenging. (Feedipedia, 2018).(Kewalramani *et al*., 2018).

4. Sugarcane Bagasse : Sugarcane bagasse is the fibrous residue left after extracting juice from sugarcane during ethanol production. It is composed mainly of cellulose, hemicellulose, and lignin. (Cabello et al., 2018).Although bagasse is low in protein and has poor digestibility due to its high lignin

content, it can still be utilized as a roughage source for ruminants after appropriate treatment. Methods such as urea treatment, alkali treatment, or biological processing can improve its digestibility and nutritional value. Bagasse is particularly useful in regions where conventional fodder is scarce, helping to meet the fibre requirements of livestock.

5. Distillers Dried Grains with Solubles (DDGS) : Distillers dried grains with solubles (DDGS) is the most widely used and nutritionally important by-product of the bioethanol industry. It is produced during the dry milling process after fermentation and distillation of grains such as maize. DDGS is a highly nutritious feed ingredient containing about 28–32% crude protein, along with high levels of digestible fibre, fat, and energy. It also contains yeast cells from the fermentation process, which enhance palatability and support gut health in animals. DDGS has a high proportion of bypass protein, making it especially beneficial for high-producing dairy animals. However, DDGS is relatively low in lysine and may have variable nutrient composition depending on processing conditions. Therefore, proper diet formulation is essential when incorporating DDGS into animal feed (Shurson and Stein, 2020).

NUTRITIONAL COMPOSITION

Bioethanol by-products are nutritionally rich due to the concentration of nutrients after starch removal.DDGS contains approximately 30% crude protein, 10–12% fat, and 40% neutral detergent fiber (NDF) (Liu, 2019).It also contains high bypass protein (~55%) and low starch, making it safe for rumen fermentation (Shurson and Stein, 2020).Additionally, DDGS is rich in available phosphorus, which improves mineral nutrition in livestock (NRC, 2007).

5. DDGS AS LIVESTOCK FEED

DDGS is widely used in cattle, sheep, goats, and poultry due to its high nutrient value.It improves rumen microbial activity, enhances fiber digestion, and provides both energy and protein (Shurson and Stein, 2020).

Physical and Chemical Properties of DDGS (Distillers Dried Grains with Soluble) :DDGS is a major by-product of grain-based bioethanol production and is widely used as a nutrient-rich livestock feed ingredient. During ethanol production, starch from grains is fermented into ethanol, resulting in the concentration of other nutrients such as protein, fat, fiber, and minerals in DDGS. Its physical and chemical properties play a crucial role in determining its feeding value, handling characteristics, and storage stability.

Physical Properties of DDGS

The physical characteristics of DDGS influence its storage, transportation, and mixing in animal feed. DDGS generally appears as a yellow to golden-brown granular material. The color is an important quality indicator; a lighter color usually reflects proper processing and better nutrient availability, whereas darker color may indicate overheating during drying, which can reduce amino acid availability, particularly lysine. (NRC, 2007).In terms of texture, DDGS has a coarse and free-flowing structure, although particle size may vary depending on the grinding and drying process. Uniform particle size is desirable for better mixing in compound feeds and improved digestibility. The moisture content of DDGS is typically maintained between 8–12%, which ensures a longer shelf life and prevents microbial spoilage. However, if moisture increases during storage, it may lead to mold growth and nutrient deterioration. The bulk density of DDGS ranges from approximately 450 to 650 kg/m³, which is important for handling, packaging, and transportation efficiency. DDGS also possesses a characteristic slightly sweet, fermented odor, which enhances feed palatability. Any off-odor may indicate spoilage or poor storage conditions. Additionally, DDGS generally shows good flowability, although high fat content may sometimes cause caking or stickiness during prolonged storage. (Belyea *et al.*, 2018).

Chemical Properties of DDGS

The chemical composition of DDGS is highly concentrated due to the removal of starch during fermentation, making it a valuable source of nutrients.DDGS typically contains 25–30% crude protein, making it an important protein supplement in livestock diets. It is relatively rich in sulfur-containing amino acids such as methionine and cysteine but is deficient in lysine, which is further reduced during high-temperature drying.The fat content of DDGS ranges between 8–12%, contributing significantly to its high energy value. This fat provides essential fatty acids; however, it also increases the risk of oxidative rancidity if the product is stored improperly. The fiber content is relatively high, usually around 8–12% crude fiber, and includes components such as neutral detergent fiber (NDF) and acid detergent fiber (ADF). This fiber is beneficial for ruminants but less digestible for monogastric animals like poultry and pigs. DDGS contains about 4–6% ash, indicating its mineral content. It is particularly rich in phosphorus (0.6–1.0%), which is highly bioavailable. Other minerals include magnesium, potassium, and sulfur. However, excess sulfur content can pose health risks, especially in ruminants. In terms of energy, DDGS provides high metabolizable energy (ME) due to its fat and digestible fiber content, making it comparable to conventional energy sources like maize. The carbohydrate fraction in DDGS mainly consists of non-starch polysaccharides, as most starch is utilized during fermentation. These carbohydrates provide a slower and sustained release of energy. One important characteristic of DDGS is the variability in its chemical composition, which depends on the type of raw material used, processing techniques, and drying conditions. This variability can affect its nutritional value and requires careful consideration during feed formulation.(Liu, K. (2011).

Production Process of DDGS (Distillers Dried Grains with Solubles)

DDGS is a major by-product of bioethanol production, especially from grain-based feedstocks such as corn, wheat, and rice. The production process involves several sequential steps, starting from raw grain handling to final by-product recovery.

1. Cereal Storage :The process begins with the storage of cereal grains (such as corn, wheat, or rice) in silos. Proper storage conditions are maintained to prevent moisture buildup, fungal growth, and nutrient loss before processing.

2. Milling :Stored grains are finely ground in the milling process to increase the surface area for enzymatic action. During this stage: Water is added to form slurryEnzymes (like amylases) are added to begin the breakdown of starch. This step prepares the substrate for efficient conversion into fermentable sugars.

3. Saccharification and Fermentation - In this stage additional enzymes convert complex starch into simple sugars (glucose) — this is called saccharification. Yeast (*Saccharomyces cerevisiae*) is added to ferment sugars into ethanol and carbon dioxide. The result is a fermented mash known as beer in ethanol production.

4. Distillation and Rectification - The fermented mash is then subjected to distillation: Ethanol is separated and purified through distillation and rectification columns. The purified ethanol is collected as the main product (bioethanol). The remaining residue is called stillage, which contains unfermented solids and nutrients.

5. Separation of By-products -The stillage is processed further, it is separated into solid and liquid fractions using centrifugation. The solid fraction forms Wet Distillers Grains (WDG). The liquid fraction (thin stillage) contains dissolved nutrients

6. Production of DDGS -To produce DDGS: The liquid fraction is concentrated through evaporation to form “solubles”. These solubles are recombined with WDG. The mixture is then dried to produce Distillers Dried Grains with Solubles (DDGS)

7. Final Products- The process results in:Bioethanol (main product) ,WDG (Wet Distillers Grains) – used as animal feed (high moisture) ,DDGS – a dried, nutrient-rich feed ingredient widely used in livestock and poultry diets. Veljko Vic, V. B., *et al*. (2018).

ADVANTAGES OF BIOETHANOL BY-PRODUCTS

Bioethanol by-products are cost-effective feed ingredients with high nutrient density. They reduce dependency on conventional feeds and improve feed efficiency (Popp *et al.*, 2016).They also enhance animal performance and provide bypass protein, which is beneficial for high-producing animals (Shurson and Stein, 2020). By-products in livestock feeding offers numerous advantages from nutritional, economic, and environmental perspectives. These by-products, such as DDGS, corn gluten feed, corn gluten meal, and others, have emerged as valuable alternatives to conventional feed ingredients.

1. Cost-Effective Feed Resource- One of the major advantages of bioethanol by-products is their cost-effectiveness. Conventional feed ingredients like maize and soybean meal are expensive and subject to price fluctuations. Bioethanol by-products are generally available at lower cost, making them an economical option for livestock producers. Their use helps reduce the overall cost of feed formulation, which is a major component of livestock production expenses.

2. Rich Nutritional Value - Bioethanol by-products are nutritionally rich and provide essential nutrients required for animal growth and production. For example, DDGS contains high levels of crude protein, energy, digestible fibre, and fat. These nutrients are concentrated during ethanol production because starch is removed, enhancing the feed value of the by-products. Additionally, they contain important minerals like phosphorus and trace elements that support animal health.

3. Efficient Utilization of Agro-Industrial Waste - The use of bioethanol by-products promotes the efficient utilization of agro-industrial residues. Instead of being discarded as waste, these materials are recycled into valuable livestock feed. This approach reduces waste accumulation and contributes to a circular economy, where resources are used more efficiently.

4. Environmental Sustainability - Incorporating bioethanol by-products into animal diets helps reduce environmental pollution. Proper utilization of these by-products prevents issues such as water contamination and greenhouse gas emissions that may arise from improper disposal. Moreover, it reduces the pressure on land and resources required to produce conventional feed crops, thereby supporting sustainable agriculture.

5. Improved Animal Performance - Several studies have shown that the inclusion of bioethanol by-products in animal diets can improve feed intake, growth rate, feed efficiency, and milk production. In ruminants, the high digestible fiber content supports rumen function and microbial activity. In poultry and swine, they provide energy and protein that contribute to better performance when included at appropriate levels.

6. Availability and Consistent Supply - With the rapid expansion of the bioethanol industry, these by-products are becoming increasingly available. Ethanol plants operate throughout the year, ensuring a continuous and reliable supply of feed ingredients. This availability helps stabilize feed resources and reduces dependency on seasonal crops.

7. Source of Bypass Protein- Some bioethanol by-products, especially DDGS, contain a significant amount of bypass (undegradable) protein. This is particularly beneficial for high-producing dairy animals, as bypass protein escapes rumen degradation and is directly utilized in the small intestine, improving milk production and overall efficiency.

8. Better Feed Conversion Efficiency - The inclusion of bioethanol by-products in diets can enhance feed conversion efficiency. Animals are able to utilize nutrients more effectively, resulting in improved productivity per unit of feed consumed. This contributes to more efficient livestock production systems.

9. Reduction in Competition with Human Food - Using bioethanol by-products as animal feed reduces competition between livestock and humans for grains like maize. Since these by-products are derived after ethanol extraction, they represent a secondary use of the same raw material, promoting better resource allocation.

LIMITATIONS AND PRECAUTIONS

Limitations of Bioethanol By-Products : Although bioethanol industry by-products such as DDGS, corn gluten feed, corn gluten meal, vinasse, and bagasse are valuable feed resources, their use in livestock feeding is associated with certain limitations that must be carefully considered.

1. Variability in Nutrient Composition - One of the major limitations is the inconsistency in nutrient composition. The nutritional value of bioethanol by-products varies depending on the raw material used (maize, rice, sugarcane), processing methods, and drying conditions. This variability makes it difficult to maintain uniform feed quality and requires careful

analysis before formulation.

2. Low Levels of Essential Amino Acids - Some by-products, particularly DDGS, are deficient in essential amino acids such as lysine and tryptophan. This imbalance can limit animal growth and productivity if not corrected through proper supplementation. Therefore, diets containing DDGS often require the addition of synthetic amino acids or complementary protein sources.

3. Risk of Mycotoxin Contamination - Bioethanol by-products are susceptible to contamination with mycotoxins such as aflatoxins, especially when raw materials are of poor quality or storage conditions are inadequate. Mycotoxins can negatively affect animal health, immunity, and productivity, posing a significant risk in livestock feeding.

4. High Fiber Content - Many bioethanol by-products, particularly DDGS and corn gluten feed, contain high levels of fiber. While this is beneficial for ruminants, it can reduce digestibility and nutrient utilization in monogastric animals like poultry and swine when included at high levels.

5. High Phosphorus Content - DDGS contains relatively high levels of phosphorus, which, if fed in excess, can lead to environmental concerns such as phosphorus excretion and water pollution. It may also disturb the mineral balance in animal diets if not properly managed.

6. Storage and Shelf-Life Issues - Some bioethanol by-products, especially wet distillers grains (WDG) and vinasse, have high moisture content, making them prone to spoilage and microbial growth. This limits their storage life and makes transportation difficult.

7. Heat Damage During Processing - Excessive heat during drying can reduce the quality of DDGS by damaging amino acids, particularly lysine. This results in reduced digestibility and nutritional value of the feed.

8. Palatability Issues - Variations in color, odor, and texture due to processing conditions can affect the palatability of by-products. Animals may refuse feed if the product has a burnt smell or dark color.

Precautions While Using Bioethanol By-Products in Feed :

To ensure safe and effective utilization of bioethanol by-products in livestock diets, certain precautions must be followed:

1. Proper Quality Evaluation **:** Before inclusion in feed, by-products should be tested for nutrient composition, moisture content, and presence of toxins. Regular laboratory analysis helps in maintaining feed quality and consistency.

2. Controlled Inclusion Levels : Bioethanol by-products should be included in diets at recommended levels based on species and production stage. Excessive inclusion can negatively affect digestion, performance, and health.

3. Balanced Diet Formulation : Since some by-products are deficient in essential amino acids, diets should be properly balanced by adding supplements such as lysine, methionine, or other protein sources to meet nutritional requirements.

4. Prevention of Mycotoxin Contamination : Proper storage practices such as maintaining low moisture, good ventilation, and clean storage facilities are essential to prevent fungal growth. Use of mycotoxin binders may also be considered.

5. Monitoring Physical Quality : The physical characteristics of DDGS, such as color and smell, should be regularly checked. Light-colored DDGS with a pleasant smell is generally of better quality, whereas dark or burnt material should be avoided.

6. Proper Storage and Handling : By-products should be stored in dry, cool, and well-ventilated conditions to prevent spoilage. Wet by-products should be used quickly or preserved using appropriate methods.

7. Gradual Introduction in Diet : When introducing bioethanol by-products into animal diets, it should be done gradually to allow animals to adapt and avoid digestive disturbances.

8. Regular Monitoring of Animal Performance : Animal health, feed intake, and production performance should be closely monitored to assess the effectiveness of the feed and make necessary adjustments.

ENVIRONMENTAL AND ECONOMIC BENEFITS

The utilization of bioethanol industry by-products such as distillers dried grains with solubles (DDGS), corn gluten feed (CGF), corn gluten meal (CGM), vinasse, and bagasse in livestock feeding systems provides significant environmental and economic advantages. These benefits make them highly valuable components in sustainable animal production systems.

Environmental Benefits

1. Waste Reduction and Resource Recycling : Bioethanol production generates large quantities of by-products, which, if not properly utilized, can lead to environmental pollution. The incorporation of these by-products into livestock feed ensures efficient recycling of nutrients and minimizes waste disposal issues. This supports the concept of a circular economy in agriculture (Popp *et al*., 2016).

2. Reduction in Environmental Pollution : Improper disposal of bioethanol residues such as vinasse and stillage can lead to soil and water contamination. By using these materials as animal feed, the risk of environmental pollution is significantly reduced. This also decreases the biochemical oxygen demand (BOD) load on water bodies (Kalscheur *et al.*, 2012).

3. Lower Greenhouse Gas Emissions : The use of bioethanol by-products reduces dependence on conventional feed crops such as maize and soybean, which require extensive cultivation and contribute to greenhouse gas emissions. By replacing these feeds, bioethanol by-products help in lowering the carbon footprint of livestock production systems (Erickson *et al.*, 2005).

4. Efficient Utilization of Natural Resources : Feeding bioethanol by-products improves the efficiency of land, water, and energy use. Since these by-products are derived from already processed crops, they represent an additional output without requiring extra agricultural resources (FAO, 2012).

5. Improved Nutrient Management : By-products like DDGS contain higher levels of phosphorus and other minerals. When properly utilized, they enhance nutrient recycling within the production system. However, balanced feeding is necessary to prevent excess nutrient excretion (NRC, 2007).

Economic Benefits

1. Reduction in Feed Cost : Feed accounts for a major portion of livestock production costs. Bioethanol by-products are generally less expensive than conventional feed ingredients such as soybean meal and maize. Their inclusion in animal diets significantly reduces feed costs without compromising productivity (Kalscheur *et al.*, 2012).

2. Alternative to Expensive Feed Ingredients : Bioethanol by-products serve as effective substitutes for traditional feed ingredients. DDGS, for example, can partially replace both protein sources (soybean meal) and energy sources (maize), making feed formulation more economical (Schingoethe*et al*., 2009).

3. Increased Profitability for Farmers: By reducing feed costs and maintaining or improving animal performance, the use of bioethanol by-products increases overall farm profitability. Improved feed efficiency and productivity contribute to better economic returns (Shurson, 2017).

4. Value Addition to Agro-Industrial By-Products : The conversion of ethanol industry residues into valuable feed ingredients adds economic value to what would otherwise be waste materials. This creates additional revenue streams for both ethanol producers and livestock farmers (Popp *et al*., 2016).

5. Stability in Feed Supply : With the expansion of the bioethanol industry, the availability of by-products has increased, providing a consistent and reliable source of feed ingredients. This reduces dependence on seasonal feed resources and stabilizes feed supply throughout the year (USDA, 2024).

6. Support to Rural Economy : The integration of bioethanol by-products into livestock feeding systems supports rural economies by linking crop production, biofuel industries, and animal husbandry. It generates employment opportunities and promotes sustainable agricultural practices (FAO, 2012).

CONCLUSION

The bioethanol industry has emerged as a significant contributor not only to renewable energy production but also to the livestock sector through the generation of valuable by-products. These by-products, including distillers dried grains with soluble (DDGS), corn gluten feed (CGF), corn gluten meal (CGM), vinasse, and sugarcane bagasse, possess considerable nutritional potential and can effectively be utilized as alternative feed resources for livestock.Among these, DDGS is the most widely used and nutritionally important by-product due to its high protein, energy, and digestible fibre content. The process of ethanol production concentrates nutrients such as protein, fat, and minerals, making these by-products superior in certain aspects compared to conventional feed ingredients. As reported by Popp *et al*. (2016), nutrients in distillers grains are concentrated nearly threefold compared to the original grain, enhancing their feeding value.The inclusion of bioethanol by-products in animal diets has been shown to improve feed efficiency, growth performance, and milk production when used at appropriate levels. Studies by Kalscheur *et al.* (2012) and Shurson (2017) indicate that DDGS can partially replace costly feed ingredients like soybean meal and maize without adversely affecting animal performance, thereby reducing feed costs and improving profitability. In addition to their nutritional and economic advantages, these by-products contribute significantly to environmental sustainability. Their utilization helps in reducing agro-industrial waste, minimizing environmental pollution, and promoting efficient use of natural resources. According to Erickson *et al*. (2005), the use of ethanol co-products in livestock diets reduces the environmental burden associated with feed production and disposal of industrial residues.However, certain limitations such as variability in nutrient composition, low levels of essential amino acids (especially lysine), risk of mycotoxin contamination, and storage challenges must be carefully managed. Proper quality control, balanced diet formulation, and adherence to recommended inclusion levels are essential to maximize the benefits of these feed resources. The National Research Council (NRC, 2007) also emphasizes the importance of nutrient balancing when incorporating by-products like DDGS into livestock diets. Furthermore, there is a need for continued research to standardize the quality of bioethanol by-products, develop efficient processing and detoxification methods, and explore their use in non-ruminant and aquaculture systems. As highlighted by the FAO (2012), improving the utilization of biofuel co-products can significantly enhance global feed resource efficiency.In conclusion, bioethanol industry by-products represent a sustainable, economical, and nutritionally valuable alternative to conventional feed ingredients. Their effective utilization can reduce feed costs, improve livestock productivity, and contribute to environmental conservation. With proper management and scientific feeding strategies, these by-products have the potential to play a vital role in the future of livestock nutrition and sustainable agriculture.

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Impact of Thermal Stress on Growth and Milk Production of Bovines

Abstract

Thermal stress, particularly heat stress, is one of the major environmental constraints affecting growth, reproduction, and milk production of bovines in tropical and subtropical regions. High ambient temperature combined with humidity disrupts thermoregulation, reduces feed intake, alters hormonal balance, and impairs metabolic efficiency. The Temperature–Humidity Index (THI) is widely used to assess the severity of heat stress in dairy animals. When THI exceeds 72, productive and physiological functions begin to decline. Heat stress negatively affects growth rate, milk yield, milk composition, fertility, and overall animal welfare. This popular article highlights the physiological responses, production losses, hormonal changes, and practical strategies to mitigate thermal stress in bovines for sustainable dairy production.

Keywords: Heat stress, bovines, milk production, growth performance, THI, thermal stress management.

Introduction

Stress is characterised as an external condition that induces strain within a biological system. In dairy animals, environmental heat stress represents one of the most significant stressors impacting productivity. Heat stress arises when environmental factors such as temperature, humidity, solar radiation, and air movement collectively exceed the animal's thermoneutral zone. Under these conditions, animals are unable to dissipate sufficient body heat, resulting in elevated body temperature and diminished performance. High-producing animals are particularly susceptible due to their substantial metabolic heat generation.

Indicators of Heat Stress

The Temperature–Humidity Index (THI) is a widely utilised metric for assessing heat stress in dairy cattle. Cows typically do not experience stress when the THI is below 72. Mild stress occurs between 73 and 79, moderate stress between 80 and 89, and severe stress above 90. An increased respiration rate is often the initial visible sign of heat stress, followed by elevated rectal temperature, increased heart rate, reduced feed intake, and behavioural changes such as seeking shade and increased standing time.

Effect on Feed Intake and Metabolism

During heat stress, animals reduce feed intake to minimise metabolic heat production. Hormonal changes include decreased levels of thyroxine, triiodothyronine, somatotropin, and insulin, leading to a reduced basal metabolic rate. Increased secretion of aldosterone and antidiuretic hormone helps maintain water and electrolyte balance. These changes slow metabolic pathways and impair nutrient utilisation.

Impact on Growth Performance

Elevated temperatures adversely affect growth rate and daily weight gain. Reduced voluntary feed intake and increased maintenance energy requirements limit nutrient availability for growth. Catabolism of body reserves may increase, leading to reduced body condition and tissue loss.

Impact on Milk Production and Composition

Milk yield declines significantly under heat stress conditions. Research indicates that milk production decreases with each unit increase in THI above threshold levels. High-producing cows are more severely affected. Heat stress also reduces milk fat and protein percentages and increases somatic cell count, thereby affecting milk quality and economic returns.

Reproductive and Behavioural Effects

Heat stress leads to silent estrus, poor conception rates, and extended calving intervals. Buffaloes are particularly susceptible due to fewer sweat glands and darker skin pigmentation. Behavioural changes include increased panting, reduced rumination, and a preference for water and shade.

Management Strategies to Reduce Heat Stress

Effective management practices are essential to minimize production losses. The provision of clean, cool drinking water and adequate shade is fundamental. Artificial cooling systems such as fans, foggers, sprinklers, and evaporative cooling pads enhance heat dissipation. Adjusting feeding schedules to cooler hours of the day, providing high-energy dense diets, supplementing minerals and electrolytes, and selecting heat-tolerant breeds are practical strategies. Night grazing and improved housing ventilation also enhance thermal comfort.

Conclusion

Thermal stress is a major limiting factor in bovine growth and milk production, particularly in tropical regions. It affects physiological functions, hormonal balance, feed intake, reproduction, and milk quality. Monitoring THI and implementing appropriate cooling and nutritional strategies are essential for sustaining productivity. Adopting climate-resilient management practices will ensure improved animal welfare and economic sustainability in dairy farming.

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Efficient Watershed Management through climate resilient and sustainable practices for balancing carbon neutrality for sustainable future

Abstract

Climate-resilient, carbon-neutral watersheds integrate nature-based solutions, sustainable water management, sustainable land management and advanced technology with ecosystem restoration to enhance climate adaptation, minimize greenhouse gas emissions and water security while sequestering carbon. Key strategies include using nature-based solutions for carbon sequestration and flood control, adopting climate-smart agriculture, and implementing energy-efficient, decentralized waste management. agroforestry, soil erosion control, rainwater harvesting and adopting regenerative agriculture, which collectively improve resilience, biodiversity, and carbon storage.

Key words

Watershed, Carbon neutrality, climate resilient sustainable agriculture soil erosion, water harvesting etc.

Introduction

A watershed is an area of land that drains all the water it receives into a common outlet like a stream, river, lake, or ocean. Watersheds come in different shapes, sizes, and types depending on topography, soil, vegetation, and climate. Sustainable watershed management is a holistic, integrated approach that balances human needs with ecosystem health by managing land, water, and related resources within a drainage basin. It focuses on enhancing water availability, reducing soil erosion, and fostering community participation to ensure long-term environmental sustainability and climate resilience. Key strategies include reforestation, rainwater harvesting, and sustainable agriculture. Watershed management is a complete approach to managing water resources within a defined geographic area, aiming to sustain water quality, quantity and ecosystem health. This practice is essential in protecting natural water sources, supporting agricultural productivity, reducing pollution and ensuring reliable water supplies for communities. With increasing population pressures, climate change and industrialization, effective watershed management has become essential for sustainable environmental management. A watershed, also known as a catchment area, encompasses all land where precipitation collects and drains into a common outlet like a river, lake, or ocean. Watersheds are natural water filters that help purify water by trapping pollutants and facilitating groundwater recharge. They are precarious to biodiversity, water supply and agricultural and urban water demands.

Key components of watershed management

Watershed management integrates various practices and techniques that includes agricultural, social, ecological and hydrological factors. The primary components include:

- **Nature-Based Solutions:** Restoring mangroves, wetlands, and forests improves water quality, acts as carbon sinks, and protects against flooding.
- **Climate-Smart Agriculture:** Utilizing drought-tolerant crops and efficient irrigation (e.g., drip) ensures water sustainability while reducing agricultural emissions.
- **Integrated Watershed Management:** Coordinating land-use, water, and waste management enhances resilience, especially for coastal areas.
- **Mitigation Efforts:** Increasing carbon sinks by 25% or more and stopping practices like rice straw burning can significantly improve the carbon balance.
- **Infrastructure Optimization:** Reducing energy consumption in water and wastewater pumping.
- **Soil and water conservation:** Techniques such as terracing, contour farming and afforestation prevent soil erosion, promote water infiltration and enhance water quality. Soil conservation is particularly important in areas prone to land degradation.
- **Water resource assessment:** A thorough understanding of water availability, quality and demand within the watershed is necessary. This involves monitoring rainfall patterns, surface water levels and groundwater recharge rates.
- **Pollution control:** Managing agricultural runoff, industrial waste and urban pollutants is vital to prevent contamination of water bodies. Buffer strips, sediment ponds and constructed wetlands can trap pollutants before they enter waterways.
- **Land use planning:** Coordinating land use with water management goals helps to protect water resources. Proper zoning, sustainable agriculture and controlled urban expansion can significantly reduce strain on the watershed.

Challenges in watershed management

Several challenges impact watershed management efforts, including:

- **Climate change:** Changes in rainfall patterns and increased droughts strain water resources, making watershed management more complex. Unpredictable weather patterns make it difficult to plan long-term strategies.
- **Urbanization and industrialization:** Expanding cities and industrial activities lead to deforestation, soil erosion and increased pollution. Urban areas contribute to higher surface runoff and reduced groundwater recharge, while industrial waste can contaminate water sources.
- **Agricultural practices:** Unsustainable agricultural practices, such as overuse of chemical fertilizers and pesticides, contribute to water pollution and soil degradation. Intensive irrigation can also lead to groundwater depletion and water shortages.

Strategies for effective watershed management

To solve these challenges, different strategies can be used, including:

- **Integrated Water Resource Management (IWRM):** IWRM emphasizes coordinated planning and management of water, land and related resources. It aims to balance social, economic and environmental needs, ensuring sustainable water use within the watershed.
- **Use of technology:** Remote sensing, Geographic Information Systems (GIS) and hydrological modeling tools help monitor water resources and predict future trends. These technologies enable realtime data collection and analysis, aiding decision-making in watershed management.
- **Ecosystem-based approaches:** Incorporating ecosystem

services into watershed management can enhance resilience. This includes preserving forests and wetlands, which act as natural water filters, improve biodiversity and provide flood control.

- **Restoration projects:** Restoring degraded areas within watersheds, such as reforestation and wetland restoration, improves water quality, reduces soil erosion and enhances biodiversity. Restoration also aids in carbon sequestration and provides additional ecosystem benefits.
- **Education and community participation:** Community involvement in watershed management ensures sustainable practices are adopted. Educational initiatives that highlight the importance of water conservation encourage local management.

Benefits of watershed management

- **Enhanced Resilience:** Reduced vulnerability to floods, droughts, and sea-level rise.
- **Carbon Neutrality:** Achieving a balance between greenhouse gas emissions and removals.
- **Sustainable Development:** Increased water quality/quantity, improved food security, and protection of biodiversity.

Types of Watersheds

Watersheds come in different shapes, sizes, and types depending on topography, soil, vegetation, and climate. There are several ways of classifying watersheds based on their characteristics.

Physical Size: Watersheds can be categorized based on their physical size:

- Micro watersheds - Cover small areas up to 250 to 500 hectares with one or more villages.
- Mini watersheds - Cover areas between 500 to 2500 hectares with a few villages.
- Mid-sized watersheds - Cover 2500 to 10000 hectares with many villages.
- Macro watersheds - Cover large areas above 10000 hectares that may include many districts.

Shape: Watersheds can have different shapes based on the landscape:

- Dendritic watershed - Has a treelike pattern with many tributaries joining the mainstream. Common in areas with gentle slopes.
- Radial watershed - Has streams that originate from a central high point and flow outward in all directions. Found in dome-shaped hills.
- Rectangular watershed - Has long parallel sides and a nearly rectangular shape. Common on flat terrain with little relief.
- Cirque watershed - Formed in bowl-shaped depressions at the top of mountains. Streams flow outward from the cirque.
- Annular watershed - Formed around the rim of a volcano crater. Streams flow toward the crater.

Outlets: Watersheds are also classified based on the type of outlet:

- Stream watershed - Drains into a stream or river.
- Lake watershed - Drains into a lake. Runoff accumulates in the lake.
- Wetland watershed - Drains into a marshland, swamp, or peat bog.
- Estuarine watershed - An outlet is an estuary where a river meets the ocean.

Nature of Boundary: The natural boundaries that define a watershed determine its type:

- Topographic watershed - Boundaries defined by ridges and hilltops. Most common type.
- Hydrographic watershed - Boundaries follow a hydrological divide.
- Political watershed - Boundaries defined by artificial features like roads and property lines.

Water Source: according to the source of water that drains through them:

- Surface water watershed - Receives water only from rainfall, snowmelt, and surface runoff.
- Groundwater watershed - Receives water from aquifers and subsurface flow in addition to surface sources.

- Combined surface-groundwater watershed - Receives water from both surface and groundwater sources. Most common type.

Land Use: Some common watershed types based on land use:

- Rural watershed - Mostly agricultural land with few urban areas. Runoff has low pollutant levels.
- Urban watershed - Mostly covered by urban development with roads, buildings, and impermeable surfaces. Runoff is highly polluted.
- Forest watershed - Mostly covered with trees that help control erosion and runoff. Runoff has a low sediment load.
- Mixed land use watershed - Combination of urban, rural, and forested areas. Runoff quality depends on the land use mix.

Impact: Watersheds can be characterized based on human impact:

- Pristine watershed - With little or no human disturbance. In natural and undisturbed condition.
- Degraded watershed - Suffering from problems like soil erosion, loss of vegetation cover, and pollution due to human activities.
- Restored watershed - Previously degraded but recovered through management and conservation efforts. Runoff quality improved.

Implementation Examples

- Waste Management: Decentralized waste management in Kerala has reduced landfill emissions and transport costs.
- Urban Water Management: Green roofs on bus stops in Poland can retain 90% of stormwater, reducing flood risk.
- Reforestation: Increasing vegetation cover for carbon sequestration in Ladakh.

Conclusion

Sustainable watershed management is essential for long-term water security, ecosystem health, and community resilience, focusing on an integrated, participatory approach rather than isolated technical fixes. Effective strategies connect land, water, and human systems, combining soil conservation, reforestation, and community engagement to mitigate climate change effects, improve water quality, and boost rural livelihoods.

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NATURAL FARMING IN MANGO

Mango is known as the king of fruits. In sanskrit, it is known as Amram, Rasalum, Sahakarfalam, etc. In Malayalam, it is known as manga, based on this the Portuguese gave the name mango. From The Himalayas in the North to Kanyakumari in the South, no village is found without mango tree. Thus, mango has connected the diversity of India. Mango is cultivated in Uttar Pradesh, Bihar, Andhra Pradesh, West Bengal, Tamil Nadu, Odisha, etc. The production of mango is highest in Uttar Pradesh.

Varieties

In India, about 1000 mango varieties are cultivated and among these, same important varieties are Dashehari, Langra, Himsagar, Malda, Gopal Bhog, Krishna, Chausa, Alphanso, Suvarnarekha, Baneshan, Neelum, Kesar, Fazli, Jardalu, Gulab, Totapuri, etc.

The following technique helps manage mango orchards efficiency with good yields. Dig 3 ft. wide and 2 ft. deep trench. Mulch this trench with dry leaves. At the beginning of the monsoon, spray 200 to 400 litres jeevamrit one to two times a month on mulch. Due to rain, jeevamrit will reach to the bottom of the soil and with the combination of mulch, moisture and jeevamrit, earthworms will work faster. The plant will get nutrients due to composting. The decomposition of mulch will form humus. By adopting these practices, the tree will give fruits every year and the number of fruits and quality will also improve.

On both sides of the trench grow cowpea and pigeon pea. These crops fixes atmospheric nitrogen in the soil, which provides necessary nitrogen to the roots for humus formation during summer and winter, apply jeevamrit in trenches during evening. Spray jeevamrit 10 liters with 100 liters of water once in a month to get good results.

The trench harvests rainwater and mulching reduces evaporation of water. You can get good production without chemical fertilizers, biofertilizers, compost, FYM, irrigation and pesticides by adopting this method. Aonla, guava, pomegranate, castor, papaya, drumstick, banana, curry leaves, custard apple, chilli, turmeric, cowpea, tulsi, fenugreek, mint, marigold and cucurbits crops are the companion crops of mango.

Distance

In traditional orchards for planting seedling of mango trees, spacing is kept as 33 x 33 ft which will accommodate 40 plants per acre. However, at present high density mango cultivation of dwarf trees with narrow spacing is followed because spaced plants become tall, so harvesting fruits is complex. Due to the scarcity of skilled labour, even mature fruits are difficult to harvest and they reach the ripening stage and fall. In high density planting distance is kept 10 x 10 ft, accommodating 435 trees per acre. The fruit bearing starts 3 year after planting, but it is advisable to start harvesting after 5 years leading to the reduction of the yield. Pruning the touching branches after one month of harvesting is advisable to increase yield with better quality. In high density planting trees remain dwarf, which facilitate easy harvesting of fruits and spraying of jeevamrit.

Propagation

To raise the rootstock of mango, select fruits from desi mango varieties that have a wide-spread canopy, strong branches, sour, fruit and grow naturally without irrigation. Fresh mango stones have higher vigour, but with the time vigour decreases, so the stone should be removed from the fruit at the time of sowing. After treatment with beejamrit, sow 3 to 4 stones at 33 x 33 ft distance in the circular pit as per below diagram. After sowing stone, cover it with a mixture of 4 parts soil 3 parts ghan-jeevamrit and slightly press with hand followed by application of water. Spray jeevamrit and mulch it with dry grass. Mango is an evergreen tree that survives and gives yield without irrigation, however, grafts purchased from the nursery have broken taproot and sub root due to which it cannot survive for a long time against the storm, drought and scarcity of water. So, instead of purchasing graft from a nursery, prepare graft in situ. The stone sown in June, germinates within 20 to 40 days. One year after the germination, roots go deep more than 150 cm and 90 to 120 cm parallel to the surface. After 12 to 15 months sowing of stone, 15 to 16 leaves will emerge and provide food materials to the grafts. August-September months are the ideal for softwood grafting; scion should be attached on the top portion of rootstock.

When the spacing is kept 10 x 10 ft between four mango plants, plant one drumstick plant, and between two mango and two drumstick plants, sow pigeon pea and bajra. Between two rows of plants, dig a trench of 2.5 ft wide and 1.5 ft deep opposite the slope. In the alternate trench, add water + jeevamrit and on the edge of the trench, grow chilli, ginger, cowpea, and cucurbitaceous crops. Apply jeevamrit mixed with water once or twice a month along with spraying. The alternate row which is not irrigated should be filled with mulching materials. They do not compete with each other, but act as a companion to each other. No plant grabs the food of another plant. It is wrong to say that a tree planted nearby steals or divides the food of other. The real situation is quite different from this. In nature, exploitation is not there but there is a companionship.

During the plantation of mango, we have to follow the laws of nature. If mango is planted alone without any companion crops, then yield will suffer during natural calamities. But if we grow companion crops, *viz.*, aonla, pomegranate, drumstick, etc., as an intercrop, then at the time of natural disasters, even though one crop fails the yield of others will not be affected. We will get production because all the crops have different fruiting times. Inter crops help each other and provide mulching material. Mango pest predators live and survive on intercrops. Intercrop also provides income throughout the year.

Mother plant should have the following characters

1. Higher yield
2. Sweet fruit
3. Better quality and colour
4. Disease and pest free

Select straight branches for scions having 10 to 15 cm length and 8 to 10 buds. For the plantation, select double mother plant (scion) in comparison to actual trees to be plant. Scion should be prepared 8-10 days before grafting by removing leaves. Before separation of bud stick, spray jeevamrit twice in the first week. Then spray jeevamrit (10 liter /100 liters water) in a week. Grafting needs to be done on 14 to 15-month old rootstock by removing the top 6 to 8 cm portion. Insert a sharp knife in the middle part of the rootstock and make a 5 to 6 cm deep cut. Make a 'V' shape on the lower portion of the scion and insert it in the rootstock as shown in the picture. Keep in mind that the thickness of rootstock and scion should be the same. Tie this portion with a plastic tap. After 10 to 15 days, new leaves will emerge on scion. Remove leaves from the rootstock every 15 days; when graft becomes uniform and leaves become dark green, remove the grafting tap and spray jeevamrit once or twice a month. To protect the graft from cold to heat, from Oct.-Nov. and May-June grow pigeon pea, bajra, etc. as a mix crop or companion crop. In situ softwood grafting is the best method in which the main root goes deep. After planting the stone, we shall do the grafting of mother plant (scion) up to three years. This method is simple, easy and cheap.

Scion from outside

When you want to select any special mango variety from outside the farm, select the mother plant and remove leaves from the scion branch. After 8-10 days, cut scion from the mother plants. One third portion of the scion should be dipped in jeevamrit, then wrapped in a wet cloth, and bring it to the grafting site. If the temperature is high, then 3 to 4 time spraying of water shall be done. If it is grafted within 24 hours after cutting from mother plant, you can get 70-80% success; after 72 hours, the success rate reduces up to 50%. Because of mulching after grafting, weeds don't grow in surrounding area, and if any weed growth occurs, then cut it and mix it in a form of mulch. To protect from wind, tie the plant with support. After grafting, up to 4 years, remove the flowers and fruits so that the plant becomes strong. To pick fruits of the initial stage is unnatural that make the plant weak, and lifespan of the plant also decreases. From 5 to 10 years, take limited fruits, and then after ten years, pick all the fruits.

Flowering

The fruit should be picked with petiole after full blooming. As rain start in June, 2 to 3 new branches will emerge at the terminal portion. These new branches will mature from September to October, and flowering will start in January to February. In Mango, there are three types of flowers.

1. Male
2. Female
3. Hermaphrodite

The male flower matures first, so it is unable to fertilize the female flower. Wind pollination also does not occur. The possibilities of fruit setting are more if honeybees and house fly work as a pollinator, so to attract bees, grow flower crops in mango orchards. Honey bee pollinated fruits are of the best quality and healthy.

Maturity Indices of Mango Fruits

1. **Slight shoulder colour development -** light yellowish tinge appears on fruit shoulders
2. **Tapka method -** natural dropping of one or two ripe fruits indicates maturity
3. **Skin colour change -** shifts from dark green to olive green
4. **Days from fruit set -** maturity assessed by counting days from fruit set to harvest. It takes generally 110 to 130 days from fruit set to fruit harvesting
5. **Specific gravity -** fruits attain 1.01 to 1.02
6. **Flesh firmness -** slight softening of pulp indicates ripening stage
7. **Lenticel appearance -** become more prominent and waxy bloom starts disappearing
8. **Total Soluble Solids (TSS) -** reaches 11-15° Brix, showing proper sweetness
9. **Limitations -** methods like shoulder colour change and tapka are less reliable as they are not representative of whole-tree maturity, leading to uneven ripening.

Rejuvenation of old orchard

Generally, mango lives about 250 years, but due to lack of knowledge of natural farming, it lives only for 50 years and subsequently yield is reduced. Farmers should adopt the following steps to make the old mango orchard productive again.

Mango tree bearing small fruit, sour fruit and unproductive trees should be cut with the sharp cutter at 8-10 ft from ground level. At the time of cutting, care should be taken that root system should not be damaged. At the time of cutting, the primary branches should be kept safe. Apply neem paste on cut branches.

Preparation of neem paste

Take 30 liters water + 20 kg desi cow dung + 20 liters cow urine + 20 kg powder of dry neem leaves, mix all the ingredients, and keep it in the shade for 48 hours. Stir it with a stick 3 to 4 times day. Apply this neem paste on the trunk of the tree in May and October months. Application of neem paste will prevent different diseases. After 20 to 25 days of harvesting, a new shoot will emerge and get ready as a mother plant for grafting after 45 days. On the cut branches, keep only 8-10 shoots, and remove others. When the shoot achieves 10 to 15 cm length, at that time grafting of the scion of selected variety should be done.

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Beyond Registration: Beyond Registration: How FPOs Can Drive Technology, Knowledge, and Rural Transformation

Abstract

For many small and marginal farmers, agriculture today is becoming increasingly uncertain. Cultivation costs are rising every season, labour availability is declining, rainfall patterns are becoming unpredictable, and market prices often fluctuate beyond the farmer's control. Even after achieving good yields, many farmers struggle to get remunerative prices due to weak bargaining power and dependence on local traders. While farmers cultivate individually, markets operate collectively, and this imbalance often leaves small farmers economically vulnerable.

In Telangana, particularly in dryland districts, these challenges are becoming more visible. Farmers cultivating groundnut, redgram, cotton, millets, and vegetables frequently face problems related to input costs, storage, transport, and market access. Groundwater dependency, climate variability, and fragmented landholdings are further increasing production risks. Under such conditions, Farmer Collectives i.e., Farmer Producer Organizations (FPOs) are increasingly emerging as an important support system for collective farming-related business activities.

Over the last few years, FPOs have gained major policy attention across India. The Government of India launched a programme for formation and promotion of 10,000 FPOs with support from agencies such as SFAC, NABARD, NCDC, and state departments. However, the real question today is not how many FPOs are registered, but how many are actively functioning in a sustainable manner and genuinely benefiting farmers.

Why Farmers Need FPOs Today

A single farmer taking 10 or 15 bags of produce to the market has very limited bargaining power. Transport costs become high, weighing and commission deductions increase, and farmers often sell immediately due to urgent cash requirements. But when produce is aggregated collectively through an FPO, the situation changes. Bulk quantities attract larger buyers, transport costs reduce, and negotiation capacity improves.

The same principle applies to agricultural inputs. Seeds, fertilizers, bio-inputs, machinery services, and pesticides purchased individually are often costly. Through collective purchase, FPOs can reduce input costs and improve timely availability of quality materials. In several regions, farmer groups are also establishing custom hiring centers to reduce machinery costs for small farmers.

In many parts of Telangana, millet cultivation and pulse-based farming systems are gradually receiving renewed attention due to changing climatic conditions and increasing consumer demand. This creates new opportunities for commodity-based FPOs focusing on millets, pulses, seed production, groundnut, dairy, and vegetable cultivation. Such specialization can strengthen aggregation, branding, and market linkage.

Registration Alone Is Not Success

Although thousands of FPOs have been formed in recent years, many face difficulties after the initial formation stage. In several places, organizational activity slows down once project support stops. Some FPOs remain at only inputs distribution without any development of regular business activities. Weak member participation, limited working capital, lack of storage facilities, and poor market linkage continue to affect sustainability.

In several villages, farmers initially joined FPOs with enthusiasm, but regular participation gradually declined when aggregation and marketing activities remained weak. In some cases, farmers continued selling produce individually to local traders due to immediate payment needs and lack of confidence in collective systems. This highlights the importance of trust, transparency, and continuous business activity within farmer institutions.

This is why the future strength of FPOs depends less on registration numbers and more on business performance, farmer confidence, and continuous member engagement.

From Farmer Groups to Farmer Businesses

The next phase of FPO development must focus on building professionally managed farmer-owned enterprises. Successful FPOs increasingly function not just as farmer associations, but as rural agribusiness organizations. Trained CEOs, proper bookkeeping, market planning, digital payments, and transparent management systems are becoming essential for long-term sustainability.

FPOs can also help farmers move beyond raw produce sales. Dal mills, millet processing units, grading facilities, packaging centers, seed production activities, bio-input preparation units, and primary processing infrastructure can create additional income opportunities within villages themselves. In future, value addition may become as important as production itself. For dryland regions in Telangana, FPOs can also play an important role in promoting climate-resilient agriculture. Collective approaches can support crop diversification, seed systems, agroecological farming practices, natural farming initiatives, and low-cost farming methods. As climate risks increase, collective institutions may become important for reducing vulnerability among small farmers.

Digital Agriculture and Emerging Opportunities

Agriculture is gradually entering a digital phase, and FPOs can benefit significantly from this transition. Mobile-based communication, online payments, digital bookkeeping, e-NAM linkage, and social media marketing are slowly becoming part of agricultural business systems. Consumers are also increasingly interested in naturally grown, residue-free, and traceable food products. This creates opportunities for FPOs involved in pulses, millets, traditional crops, and agroecological farming systems. In future, traceability and branding may help farmer groups access premium markets and establish direct consumer linkages. At the same time, rural youth can find new opportunities within FPO systems through activities such as digital marketing, aggregation, transport management, processing, bookkeeping, custom hiring services, and agri-entrepreneurship. Women-led FPOs are also gradually showing encouraging results in value addition and local enterprise development.

What Should Be Strengthened?

For FPOs to become truly effective, certain areas require continuous attention:

Leadership and Governance: Many FPOs struggle not because of lack of registration or training alone, but due to weak leadership, poor professional management, and limited accountability. In several cases, Board of Directors (BoDs) are selected based on local influence or social relations rather than commitment, business understanding, collective vision, and willingness to spend time on FPO activities. Strong FPOs require active, trustworthy, and farmer-oriented leaders with basic knowledge of markets, communication, institutional management, and member needs. Similarly, CEOs should not function merely as record keepers or scheme coordinators; they should act as professional rural managers capable of business planning, market negotiation, digital coordination, financial management, and farmer mobilization. Although

CEOs and BoDs are regularly exposed to trainings, the expected transformation often remains limited because many trainings become routine activities focused on attendance and compliance rather than practical institutional strengthening. This again highlights the need for merit-based selection, continuous handholding, and clear accountability frameworks.

Another major concern is low or irregular remuneration for CEOs and staff, which leads to poor motivation, high turnover, and weak professionalism. Therefore, strengthening FPOs requires investment in qualified human resources, fair compensation, performance-based accountability, and professional management support. Experiences from FPOs promoted under institutions such as *NABARD and BAIF* show that continuous handholding, professional management, institutional networking, and active leadership improve sustainability, especially where leaders coordinate aggregation, quality management, buyer linkages, and farmer communication beyond mere scheme implementation.

Farmer Participation and Trust Building: In several FPOs, ordinary farmer members remain disconnected from decision-making processes and participate only during meetings linked to subsidiary schemes or procurement. Strong FPOs are built when farmers feel ownership and receive regular services such as input guidance, market information, training, advisory support, or value addition opportunities. Transparent communication, regular interaction, and equitable benefit sharing are necessary to maintain member confidence.

For instance, many community-based FPOs supported by KVKs, departments and NGOs in states such as Maharashtra, Odisha, and Andhra Pradesh have shown better member retention and collective action where farmers regularly receive information related to input supply, market prices, training programs, and crop management support.

Such experiences demonstrate that farmer trust and participation are strengthened when FPOs function not merely as procurement agencies, but as responsive farmer-centered institutions addressing local needs and maintaining transparent communication with their members.

Technology and Extension Integration: A major missing component in many FPOs is their limited role in technology dissemination and extension support. FPOs can become village-level knowledge and service centres by connecting farmers with universities, KVKs, startups, digital advisory platforms, drone services, weather advisories, traceability systems, and e-markets. With increasing emphasis on digital agriculture, climate-smart farming, and precision technologies, FPOs can act as trusted intermediaries helping small farmers adopt innovations more effectively.

For instance, many FPOs associated with the Digital Green model have used community-based video advisories and digital communication tools to improve farmer learning and technology adoption. Similarly, FPOs linked with drone service initiatives supports precision agriculture programs in states such as Andhra Pradesh, Telangana, and Maharashtra are helping farmers access mechanization, digital advisories, weather information, and market intelligence at the local level. In several cases, CSR-supported initiatives by private companies and development organizations are also assisting FPOs in establishing Custom Hiring Centres. In many regions, agricultural universities, KVKs, and research institutions are also increasingly working with FPOs for frontline demonstrations, seed production, climate-resilient agriculture, natural farming promotion, and farmer training programs. Several FPOs promoted with the support of Indian Council of Agricultural Research institutes and State Agricultural Universities are acting as local platforms for technology dissemination and farmer mobilization.

Institutional Convergence and Networking: Many FPOs function in isolation without proper convergence with departments, banks, research institutions, NGOs, startups, or private companies. Sustainable FPOs often succeed because they build strong partnerships for training, finance, processing, branding, and marketing. Strengthening institutional networks can improve access to schemes, working capital, technical expertise, and market opportunities.

Producer organizations that actively collaborate with institutions such as NABARD, SFAC, KVKs, agricultural universities/institutes, banks, and private agribusiness companies often gain better access to technical guidance, financial services, infrastructure support, training, and market opportunities. In several states including Maharashtra, Odisha, and Karnataka, successful FPOs have strengthened their operations through partnerships for seed production, value addition, digital marketing, custom hiring services, and export linkages. These experiences highlight that continuous institutional networking and convergence play a crucial role in improving the sustainability of farmer collectives.

Business Orientation and Value Addition: Several FPOs remain dependent on grants and struggle after project support ends. There is a need to move beyond subsidy-driven functioning towards sustainable business models based on aggregation, primary processing, branding, seed production, custom hiring, bio-input production, or local value addition enterprises. Identifying location-specific business opportunities and developing entrepreneurial thinking among leadership is critical for long-term sustainability.

For example, Sahyadri Farms successfully built a farmer-led model around processing, export marketing, and retail linkage for fruits and vegetables, while Mahagrapes demonstrated the importance of collective marketing and export-oriented grape value chains through farmer institutions. Similarly, millet-based producer collectives promoted under *Odisha Millet Mission (OMM)* and *turmeric producer groups in Kandhamal* district of Odisha have shown how local processing, branding, and GI-linked marketing can improve farmer income and create institutional sustainability. These examples highlight that FPOs become stronger when they move beyond procurement towards value addition, branding, processing, and direct market engagement.

The Road Ahead

Indian agriculture is slowly moving from a production-centered approach towards a market-oriented and value-chain-based system. In this changing environment, small farmers cannot remain isolated participants in the market. Collective institutions such as FPOs may become increasingly important for improving profitability, reducing risk, and strengthening rural livelihoods.

Farmer Producer Organizations (FPOs) should not remain limited to input supply and collective marketing alone; they have the potential to emerge as decentralized, technology-driven extension and rural service institutions. In many regions, the public agricultural extension system faces limitations in manpower, last-mile connectivity, and continuous farmer engagement. In this context, FPOs can function as an effective “extended arm” of the extension system by facilitating technology diffusion, digital advisories, climate information, market intelligence, traceability, and custom hiring services at the village level.

Recent developments in Indian agriculture such as the Digital Agriculture Mission, AgriStack, digital crop surveys, drone-based services, ONDC-enabled market linkages, and AI-based advisory systems are increasingly creating opportunities for farmer collectives to become local technology intermediaries. Government initiatives including Drone Didi, Custom Hiring Centres, digital farmer registries, and precision agriculture programs also indicate a shift toward community-based technology delivery models where FPOs can play a central role in ensuring adoption, trust building, capacity development, and localized problem-solving among smallholder farmers.

However, the real success of FPOs will not come merely through registration certificates or government schemes. It will emerge when farmers begin using these institutions as their own business platforms for aggregation, value addition, market access, and long-term economic security. When collective strength translates into collective prosperity, the true potential of FPOs can be realized in rural India.

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Nutrional Importance and uses of Watermelon (*Citrullus lanatus*), muskmelon (*Cucumis melo*) and snap melon (*Cucumis melo var. momordica*)

Abstract:

Watermelon (*Citrullus lanatus*), muskmelon (*Cucumis melo*) and snap melon (*Cucumis melo var. momordica*) are important cucurbit fruits known for their nutritional value. They are rich in vitamins A and C, minerals, polyphenols, and carotenoids, which contribute to antioxidant activity and overall health. In addition to the pulp, their seeds are good sources of protein, fats, carbohydrates, and dietary fiber, enhancing their nutritional importance. These fruits are commonly consumed fresh as juices, salads, and desserts, providing hydration and energy during summer. The seeds can be processed into flour and used in bakery and value-added products, while snap melon is also used as a vegetable in traditional diets.

Introduction:

Watermelon (*Citrullus lanatus*), muskmelon (*Cucumis melo*), and snap melon (*Cucumis melo var. momordica*) are important cucurbitaceous fruits widely consumed during summer due to their refreshing taste and cooling effect (National Institute of Nutrition, 2020). These fruits are rich in water content and essential nutrients, making them highly beneficial for maintaining hydration and overall health. Melons contain significant levels of vitamins, polyphenols, carotenoids, and minerals, which contribute to their nutritional and medicinal value (Dhillon et al., 2007). In addition to their edible pulp, melon seeds are also rich in nutrients such as protein, fats, carbohydrates, and dietary fiber, but are often underutilized.

Furthermore, these fruits possess antioxidant properties that help in reducing oxidative stress and protecting the body from chronic diseases (Tarazona-Díaz et al., 2011). They are also low in calories and high in dietary fiber, making them suitable for weight management and improving digestive health.

Nutritional composition:

Nutrient	**Watermelon (*Citrullus lanatus*)**	**Muskmelon (*Cucumis melo*)**	**Snap melon (*Cucumis melo var. momordica*)**
Moisture (%)	91–92	88–90	85–88
Energy (kcal)	30	34	70–75
Protein (g)	0.6	0.8	0.8–1.0
Fat (g)	0.2	0.2	0.3–0.5
Fiber (g)	0.4	0.9	1.0–1.5
Vitamin C (mg)	8–10	30–36	18–20
Vitamin A (IU)	500–600	3300–3400	250–300
Calcium (mg)	7	9	20–25
Potassium (mg)	110–120	260–270	200–220

Nutrional importance and uses:

i. Watermelon (*Citrullus lanatus*)

Nutrional importance:

Watermelon is a highly hydrating fruit containing about 90–92% water, making it ideal for maintaining body fluid balance during summer. It is rich in vitamin C, which boosts immunity, and vitamin A (beta-carotene), which supports vision and skin health. The presence of lycopene, a powerful antioxidant, helps reduce oxidative stress and lowers the risk of cardiovascular diseases and certain cancers. Watermelon also contains citrulline, an amino acid that improves blood circulation and may reduce muscle fatigue. It is low in calories and fat-free, making it suitable for weight management and healthy diets Lester, G.E. (1997).

Uses:

Watermelon is widely consumed fresh as slices, juices, and fruit salads due to its sweet taste and cooling effect. It is extensively used in beverages such as smoothies, mocktails, and flavored drinks. The fruit is also used in desserts like ice creams, sorbets, puddings, and fruit bowls. The rind, often discarded, can be utilized for preparing pickles, jams, and candies, reducing food waste. Watermelon seeds are rich in protein, fats, and minerals and are consumed as roasted snacks or incorporated into sweets, bakery products, and traditional dishes. Seed oil extraction is also gaining importance due to its nutritional value.

ii. Muskmelon (*Cucumis melo*)

Nutrional importance:

Muskmelon is a nutrient-dense fruit rich in beta-carotene (vitamin A), which is essential for eye health and skin maintenance. It also contains high levels of vitamin C, which enhances immunity and acts as an antioxidant. The fruit is a good source of potassium, which helps regulate blood pressure and maintain heart health, and dietary fiber, which improves digestion and prevents constipation. Its high moisture content aids in hydration and detoxification, while its natural sugars provide quick energy. The presence of antioxidants further helps in protecting the body against free radical damage. (Liu, C. *et al*., 2012)

Uses:

Muskmelon is commonly consumed fresh as slices, juices, and salads, especially during summer. It is widely used in milkshakes, smoothies, fruit bowls, and flavoured beverages. The pulp can be processed into jams, jellies, syrups, and candies, enhancing its shelf life and value. Muskmelon is also used in dairy products such as yogurt, ice creams, and desserts. The seeds are highly nutritious and are used in traditional sweets, bakery products, and protein supplements. In some cuisines, seed kernels are used as thickening agents in gravies and sauces.

iii. Snap melon (*Cucumis melo var. momordica*)

Nutrional importance:

Snap melon is an underutilized but nutritionally important cucurbit crop rich in carbohydrates, providing a good source of energy. It contains vitamin C, which supports immunity, and essential minerals such as calcium and iron, which are important for bone health and haemoglobin formation. It also contains bioactive compounds like phenolics and flavonoids, which contribute to antioxidant activity and overall health benefits. Compared to other melons, snap melon has relatively higher carbohydrate content, making it suitable for energy supply in hot climates. (Pandey, 2015)

Uses:

Snap melon is used both as a fruit and as a vegetable in traditional diets. Immature fruits are cooked as vegetables in curries, while mature fruits are consumed fresh. It is widely used in rural areas for preparing chutneys, stews, and traditional dishes. The fruit can also be processed into pickles and fermented products. Seeds are rich in protein and fats and are used in snacks, flour preparation, and oil extraction. Snap melon has good potential for value-added products such as juices and processed foods. Additionally, it is valuable in crop improvement programs due to its adaptability to drought and harsh climatic conditions.

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Sulfur-Oxidizing Bacteria: Nature's Hidden Allies for Oilseed Crop Production

Introduction

Sulfur (S) is an essential macronutrient for plants and plays a significant role in improving both crop yield and quality, particularly in oilseed crops. It is a vital constituent of sulfur-containing amino acids such as methionine, cysteine, and cystine, which are required for protein synthesis. Oilseed crops generally have a higher sulfur requirement than cereals and many other agricultural crops. Sulfur deficiency adversely affects protein and oil synthesis, resulting in considerable reductions in crop productivity and quality. Although chemical fertilizers can effectively correct sulfur deficiency, their excessive and prolonged use may contribute to environmental pollution and deterioration of soil health. Therefore, biological alternatives are gaining increasing importance. Sulfur-oxidizing bacteria (SOB), which naturally mediate sulfur transformations in soil, offer an eco-friendly approach to improve sulfur availability. Sulfur oxidation is a key process in the sulfur cycle, leading to the formation of sulfate ions that are readily absorbed by plants. The sulfuric acid produced during oxidation also enhances nutrient solubilization and improves the fertility of alkaline soils.

Oilseed Production in India

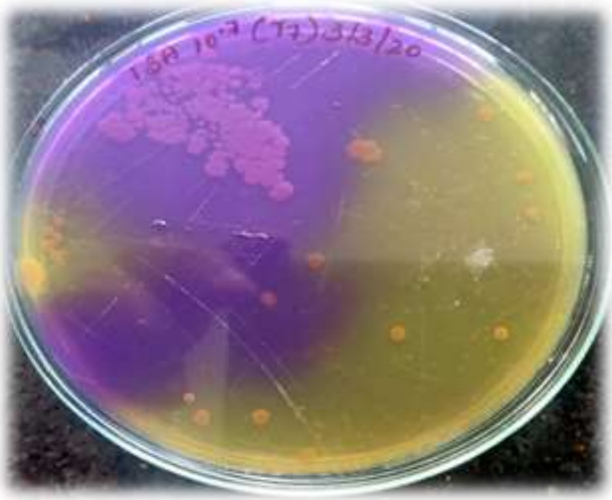
India occupies a prominent position in global oilseed cultivation and production. It is the fourth-largest edible oil economy in the world and contributes nearly 10% of global oilseed production. During the 2024–25 crop year, India's total oilseed production is projected to reach a record 429.89 lakh tonnes, compared to 396.69 lakh tonnes in 2023–24. This increase is mainly attributed to the expansion of cultivation area to 304.40 lakh hectares, with soybean, rapeseed–mustard, and groundnut serving as the major contributors to overall production growth.

The Role of Sulfur in Oilseed Crops

Sulfur constitutes approximately 0.1–0.5% of the dry weight of oilseed crops and occurs in both organic and inorganic forms. Plants primarily absorb sulfur through roots in the form of sulfate ions (SO_4^{2-}), although foliar absorption of atmospheric sulfur dioxide (SO_2) may also occur to a limited extent. Sulfur is indispensable for the synthesis of proteins, oils, vitamins, enzymes, and several coenzymes. Nearly 90% of the reduced sulfur in plants is utilized in protein synthesis through sulfur-containing amino acids such as methionine, cysteine, and cystine. Methionine alone contributes approximately 50% of the total sulfur present in plant proteins, while cystine is formed through the oxidation of two cysteine molecules. Sulfur also plays a crucial role in chlorophyll formation, chloroplast development, enzymatic activity, and redox reactions. In addition, it is associated with flowering, nodulation, seed development, and improvement in oil quality, especially in crops such as groundnut and mustard. Sulfur deficiency typically manifests as pale green to yellow discoloration of younger leaves due to the relatively low mobility of sulfur within plants. In oilseed crops, sulfur deficiency may reduce yields by 20–40%, even in the absence of clear visual symptoms.

Sulfur-Oxidizing Bacteria (SOB): The Soil Natural Chemists

Sulfur-oxidizing bacteria are a diverse group of microorganisms capable of converting reduced sulfur compounds into sulfate. Many SOB belong to the class Gammaproteobacteria and are generally Gram-negative, rod-shaped bacteria. Species of the genus *Thiobacillus* are among the most important sulfur oxidizers in soil ecosystems. Prominent sulfur-oxidizing species include *Acidithiobacillus thiooxidans*, *Acidithiobacillus ferrooxidans*, *Thiobacillus thioparus*, and *Thiobacillus denitrificans*, which are obligate chemolithotrophs. In contrast, *Thiobacillus novellus* is considered a facultative chemolithotroph. Apart from autotrophic SOB, several heterotrophic bacteria such as *Pseudomonas*, *Paracoccus*, *Klebsiella*, *Alcaligenes*, and *Xanthobacter* species can also oxidize inorganic sulfur compounds and contribute to sulfur cycling in soil.



Growth of sulfur-oxidizing bacteria on thiosulfate agar

How Do SOB Transform Sulfur in Soil?

Sulfate is the principal form of sulfur utilized by plants and microorganisms. In soil, sulfur transformation is primarily mediated by microbial activities including oxidation, reduction, mineralization, immobilization, and biotransformation. Sulfur-oxidizing bacteria convert elemental sulfur and other reduced sulfur compounds into sulfate through biological oxidation. During this process, sulfur compounds are oxidized in the presence of oxygen, leading to the production of sulfuric acid. Increased oxygen availability generally enhances sulfur oxidation activity. The sulfuric acid generated during oxidation lowers soil pH, which in turn increases the solubility and availability of several nutrients, particularly in alkaline and calcareous soils. Consequently, microbial sulfur oxidation contributes significantly to nutrient cycling and soil fertility enhancement.

Applications of SOB as Biofertilizers

1. **Enhanced Sulfur Availability:** SOB accelerate the oxidation of elemental sulfur into sulfate, thereby increasing sulfur availability to plants during different growth stages and improving crop productivity.
2. **Improvement in Secondary Metabolites:** SOB enhance the production of sulfur-containing secondary metabolites such as alkyl thiocyanates and allyl isothiocyanates in mustard (*Brassica juncea*), which contribute to improved oil quality and plant defense.
3. **Improved Phosphorus Solubilization:** The combined application of SOB with elemental sulfur and rock phosphate enhances phosphorus availability in soil through acidification and nutrient solubilization.
4. **Soil Reclamation and Health Improvement:** Biological sulfur oxidation lowers soil pH, reduces salt accumulation, and stimulates beneficial microbial activity, thereby improving soil structure and fertility.
5. **Regulation of Soil Sodium and Pathogen Suppression:** Sulfur oxidation helps regulate sodium content in soil and may contribute to the suppression of certain soil-borne plant pathogens.
6. **Biocontrol Potential:** SOB is associated with the production of compounds such as glucosinolates, isothiocyanates, thiocyanates, and nitriles, which possess insecticidal and antimicrobial properties.
7. **Environmental Monitoring:** SOB have been utilized as biosensors for detecting metal ion contamination in soil and water through changes in electrical conductivity (EC) and

pH, as their activity is sensitive to pollutant levels.

8. **Enhancement of Plant Stress Tolerance:** SOB improve plant tolerance to salinity, drought, pests, and diseases through the production of plant growth-promoting substances such as indole-3-acetic acid (IAA), gibberellins, salicylic acid, ACC deaminase, and siderophores, as well as by enhancing sulfur-containing defense compounds.

How to Apply SOB: Practical Methods for Farmers

1. Soil Application (Pre-sowing or During Crop Growth): The recommended quantity of SOB inoculum is mixed with farmyard manure (FYM), compost, or other organic amendments and uniformly incorporated into the soil 7–10 days before sowing. It may also be applied near the root zone of standing crops.

2. Seed Treatment: Seeds are coated uniformly with liquid or carrier-based SOB inoculum and subsequently shade-dried before sowing to ensure effective colonization.

3. Fertigation or Soil Drenching: Liquid formulations of SOB can be applied through drip irrigation systems or directly drenched around the rhizosphere, particularly in horticultural and high-value crops.

Conclusion

The application of elemental sulfur (S^0) is an economical and efficient approach for correcting sulfur deficiency in soils. However, elemental sulfur must first be biologically oxidized into sulfate before it becomes available for plant uptake. The rate of sulfur oxidation depends upon several factors, including soil properties, environmental conditions, sulfur particle size, and the diversity and activity of soil microorganisms. The utilization of sulfur-oxidizing bacteria represents a promising biotechnological strategy for sustainable agriculture. These microorganisms not only improve sulfur availability and soil fertility but also enhance nutrient solubilization, plant growth, and stress tolerance. Therefore, SOB-based biofertilizers have considerable potential as eco-friendly alternatives to chemical fertilizers for improving the productivity and quality of oilseed crops.

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Artificial Intelligence

Transforming Sustainable Agriculture Through Smart Farming

Abstract

Modern agriculture is facing serious challenges due to climate variability, declining natural resources, rising production costs, and increasing food demand. Sustainable agricultural practices are essential to maintain productivity while protecting environmental resources for future generations. In recent years, Artificial Intelligence (AI) has emerged as an important technological advancement in the agricultural sector. AI-based technologies help farmers improve efficiency, reduce resource wastage, and make better farm management decisions. Applications such as precision farming, smart irrigation, disease diagnosis, crop monitoring, and yield forecasting are becoming increasingly useful in modern agriculture. This article discusses the importance of AI in sustainable agriculture, major applications, advantages, limitations, and future opportunities.

Keywords: Artificial Intelligence, Sustainable Farming, Precision Agriculture, Smart Irrigation, Crop Monitoring, Agricultural Technology

Introduction

Agriculture continues to be the foundation of livelihood and food security in many countries, especially India. Farmers are constantly dealing with unpredictable weather conditions, soil degradation, pest infestations, and limited water availability. Traditional farming practices alone are often insufficient to overcome these emerging challenges. Therefore, the agricultural sector is gradually shifting towards advanced technologies that can support sustainable production systems.

Artificial Intelligence refers to computer-based systems that can perform tasks requiring human intelligence, such as learning, analyzing data, identifying patterns, and making predictions. AI technologies are now being integrated into agriculture to improve crop management and farm productivity. By combining machine learning, sensors, drones, satellite imaging, and automation, AI can assist farmers in taking timely and accurate decisions.

The use of AI in agriculture not only increases productivity but also helps conserve natural resources by reducing excessive use of fertilizers, pesticides, and water. As the global population continues to grow, AI-supported sustainable agriculture can play an important role in ensuring food security while maintaining environmental balance.

Applications of Artificial Intelligence in Agriculture

Precision Agriculture

Precision agriculture is one of the most significant applications of AI in farming. It involves the collection and analysis of field data to manage crops more efficiently. AI systems evaluate information related to soil fertility, moisture levels, nutrient availability, and crop growth.

With the help of precision agriculture, farmers can apply fertilizers, pesticides, and irrigation in the required quantity and at the right time. This approach improves input-use efficiency and minimizes environmental pollution.

Major benefits include:

- Reduced input costs
- Improved nutrient management
- Better crop productivity
- Conservation of soil and water resources

Smart Irrigation Systems

Water scarcity is becoming a serious issue in agriculture. AI-based irrigation systems help determine the exact water requirement of crops by analyzing weather conditions, soil moisture, and crop stage.

These systems prevent unnecessary irrigation and improve water-use efficiency. Automated irrigation scheduling also reduces labor requirements and energy consumption.

Important advantages are:

- Efficient utilization of water
- Prevention of waterlogging
- Reduced energy consumption
- Improved crop growth

Disease and Pest Identification

Crop diseases and insect pests are responsible for considerable yield losses every year. AI technologies can identify symptoms of diseases and pest attacks through image analysis and sensor-based monitoring.

Farmers can use mobile applications or drones equipped with cameras to detect problems at an early stage. Timely diagnosis helps in reducing crop damage and unnecessary pesticide applications.

Benefits include:

- Early disease detection
- Lower pesticide use
- Reduced crop losses
- Better quality produce

Crop Monitoring Using Drones

Drones are increasingly used in modern agriculture for monitoring crop conditions. AI-powered drones capture high-resolution images of agricultural fields and identify nutrient deficiencies, weed infestation, and stress conditions.

This technology enables farmers to observe large areas quickly and accurately. Crop monitoring through drones helps improve farm management practices and productivity.

Weather Forecasting and Yield Prediction

Uncertain weather conditions directly affect agricultural production. AI models analyze historical weather data and real-time information to provide accurate forecasts.

Farmers can use these predictions for planning sowing, irrigation, fertilizer application, and harvesting operations. AI also helps estimate crop yield, which supports better market planning and economic management.

Automation and Agricultural Robotics

AI-driven agricultural machines and robots are capable of performing tasks such as planting, spraying, harvesting, and weeding. Automation reduces dependence on manual labor and increases operational efficiency.

Robotic technologies are especially useful in large-scale farming systems where labor shortages are common.

Importance of AI in Sustainable Agriculture

The use of AI in agriculture supports sustainability in several ways. It improves productivity while reducing environmental impacts. Proper resource management helps maintain soil fertility, conserve water, and reduce chemical contamination.

AI-based farming systems also contribute to climate-smart agriculture by helping farmers adapt to changing climatic conditions. Sustainable use of agricultural inputs ultimately improves long-term farm profitability and environmental health.

Some important contributions of AI to sustainability are:

1. Efficient utilization of natural resources
2. Reduction in environmental pollution
3. Improved farm productivity
4. Better economic returns for farmers
5. Support for climate-resilient agriculture
6. Reduction in post-harvest losses

Challenges in Adoption of AI

Although AI has enormous potential in agriculture, several challenges limit its widespread adoption.

High Cost of Technology

Advanced technologies such as drones, sensors, and automated systems require substantial investment. Small and marginal farmers may find it difficult to afford these technologies.

Lack of Technical Awareness

Many farmers are not familiar with AI-based tools and digital technologies. Lack of training and technical knowledge restricts effective implementation.

Inadequate Digital Infrastructure

Reliable internet connectivity and digital infrastructure are necessary for AI applications. Many rural areas still face poor network access and limited technological facilities.

Data Management Issues

AI systems rely heavily on data collection and analysis. Concerns regarding data privacy, ownership, and management are becoming increasingly important.

Future Scope of AI in Agriculture

The future of AI in agriculture appears highly promising. Rapid advancements in digital technologies are making AI tools more efficient and accessible. Governments and research organizations are also promoting smart farming initiatives to support sustainable agricultural development.

In the coming years, AI may contribute to the development of fully automated farms, advanced climate forecasting systems, and affordable decision-support tools for farmers. Integration of AI with remote sensing, biotechnology, and precision agriculture can further strengthen agricultural sustainability.

India has significant opportunities to adopt AI-based farming practices due to its expanding digital infrastructure and large agricultural sector. Proper policy support, farmer training, and technological awareness can accelerate the use of AI in agriculture.

Conclusion

Artificial Intelligence has the potential to transform conventional agriculture into a more sustainable, productive, and efficient system. AI technologies help farmers improve decision-making, optimize resource utilization, and reduce environmental impacts. Applications such as precision farming, smart irrigation, crop monitoring, and disease diagnosis are contributing significantly to sustainable agricultural development.

Despite certain limitations related to cost and infrastructure, continuous technological progress and government support can promote wider adoption of AI in agriculture. Sustainable farming supported by AI can help meet future food demands while preserving natural resources and environmental quality.

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Agriculture 4.0:

The Digital Revolution in Agriculture

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Agriculture 4.0 is a digital revolution in agriculture that uses technologies like the Internet of Things (IoT), artificial intelligence (AI), and robotics to improve sustainability and productivity. Agriculture 4.0, also known as smart farming or digital farming, represents the fourth major revolution in agricultural practices & technologies to optimize food production and resource management. Agriculture is a prominent sector of Indian economy. The agriculture sector of India has occupied almost 47 percent of geographical area. Over 100 percent of rural household depends on agriculture (Avinash *et al.* 2018). During the year 2022-23, total food grain production in India was 329.69 million tonnes and as per 3rd advance estimation, total horticulture production was 351.92 million tonnes (Agricultural Statistics at a Glance 2023). A total of 521.27 lakh million tonnes rice has been anticipated for procurement for the upcoming KMS 2023-24, up from 496 lakh million tonnes produced during the KMS 2022-23.
India is one of the major players in the agriculture sector worldwide and it is the primary source of livelihood for around 55 percent of India's population. While, according to second advance estimates agriculture & allied sector share 17.60 percent in total GVA at current prices in year 2023-24 and the share of industry and service share 27.60 percent and 54.90 percent respectively thus 82.50 percent GVA contributed by around 45 percent Indian population.
India has the world's largest cattle herd (buffaloes), the largest area planted for wheat, rice, and cotton, and is the largest producer of milk, pulses, and spices in the world. It is the second-largest producer of fruit, vegetables, tea, farmed fish, cotton, sugarcane, wheat, rice, cotton, and sugar. The agriculture sector in India holds the record for second-largest agricultural land in the world generating employment for about half of the country's population. Thus, farmers become an integral part of the sector to provide us with a means of sustenance. As India aims to double farmers' income and ensure food security for its 1.4 billion people, the adoption of Agriculture 4.0 practices holds the potential to transform the agricultural sector, making it more attractive to younger generations and positioning India as a global leader in sustainable food production.

Agriculture 4.0, based on the concept of sustainable agriculture, represents the latest evolution in Precision Agriculture (Kovács 2018, Sott *et al.* 2020, Zambon *et al.* 2029). This fourth revolution emerged around the early 2010s, involving the use of the mentioned technological advancements of Industry 4.0, combined with sensors, robots and AI, particularly machine learning (ML) techniques, for advanced data analysis(Kovács 2018, Zambon *et al.* 2029). Allied with connectivity between mobile devices and other platforms, Agriculture 4.0 generates and processes a huge volume of data that will serve as a foundation for decision-making.

It is believed that Agriculture 4.0 can bring major global improvements, in terms of increasing the productivity and efficiency of agricultural and food systems, improving quantity, quality and accessibility of agricultural products, adapting to climate change, reducing food loss and waste, optimising the use of natural resources in a sustainable way, and, consequently, reducing the environmental impact in the years to come.

Key Agricultural Revolutions:

1. **Agriculture 1.0:** The initial transition from hunting-gathering to settled agriculture, beginning around 10,000 BCE, marked by the domestication of plants and animals.
2. **Agriculture 2.0:** The Industrial Revolution in agriculture (18th-19th centuries), characterized by mechanization, improved crop rotation, and the use of chemical fertilizers and pesticides.
3. **Agriculture 3.0**: The Green revolution (mid-20th century), featuring high-yielding crop varieties, expanded irrigation, and increased use of synthetic fertilizers and pesticides to boost food production.

Key Benefits of Agriculture 4.0

1. **Increased Productivity and Yield:-** Using data from sensors, GPS, and drones, farmers can precisely target their input use (e.g., water, fertilizers, pesticides) to optimize plant growth. In India, the adoption of precision agriculture techniques has led to yield increases of up to 30 % in some crops. The partnership of Microsoft and ICRISAT developed an AI-powered sowing app that increased groundnut yields by 30 % in Andhra Pradesh.
2. **Resource Efficiency: -** Smart irrigation systems like drip irrigation use sensors and weather data to supply water only when needed, reducing waste and conserving resources. Apart from this, use of fertilizer and chemical can be minimizes to overuse by targeting specific areas for treatment as precision use. It's also leading to cost savings and environmental benefits.
3. **Data-Driven Decision Making: -** In real-time monitoring, sensors provide continuous data on soil health, crop status, and weather conditions, enabling farmers to make informed decisions and respond quickly to changes. AI and machine learning models analyse historical and real-time data to forecast crop yields, disease outbreaks, and optimal harvest times.
4. **Sustainability and Environmental Protection: -** Efficient use of machinery, energy, and inputs leads to lower greenhouse gas emissions.
5. **Labor Optimization: -** Automation and robotics reduce the dependency on manual labor, which can help address labor shortages and reduce costs. By using machinery and remote technologies for hazardous tasks, the safety and well-being of farmworkers are improved.
6. **Economic Growth: -** Improved efficiency, higher yields, and optimized resource use contribute to increased profits for farmers. The integration of technology in farming opens avenues for new services, such as data analysis, farm-as-a-service models, and precision agriculture consulting.
7. **Improved Supply Chain Management: -** Digital records of crops from farm to table enhance transparency and traceability in the supply chain, which benefits both farmers and consumers. Real-time data can inform farmers about market trends, prices, and demands, enabling them to time their sales for better returns.
8. **Adapting to Climate Change: -** Technologies help develop and implement strategies to adapt to climate variability and reduce the risks associated with extreme weather events. Improved monitoring and management systems support sustainable agriculture, which is essential for long-term food security in a changing climate

Indian government initiatives related to agriculture digitalization

1. **AgriStack: -** AgriStack is an ambitious initiative by the Indian government aimed at creating a unified digital ecosystem for the agricultural sector. It compiles comprehensive data on farmers, land records, crop patterns, and weather forecasts to provide personalized services and insights. AgriStack is designed to benefit over 120 million farmers by facilitating better access to services like crop advisory, insurance, and credit.
2. **E-NAM (National Agriculture Market):-** **E**-NAM is an online trading platform launched in 2016 to create a unified national market for agricultural commodities. The platform has integrated over 1,260 mandis (markets) and connected 17.5 million farmers and 200,000 traders as of 2023. Farmers using e-NAM have reported up to 15-20% higher income due to improved price transparency and wider market access.
3. **Kisan Suvidha Mobile app: -** This app disseminates crucial information on weather, market price, plant protection and input dealers.
4. **AGMARKNET: -** A G2C e-governance portal providing agricultural marketing related information, including daily prices and arrivals of commodities in agricultural markets.
5. **Digital Agriculture Mission (2021–2025):-** This mission was launched to promote the use of technologies such as AI, block chain, remote sensing, and drones in Indian agriculture. The initiative focuses on enhancing agricultural productivity, reducing input costs, and providing real-time data to farmers.
6. **PM Kisan Samman Nidhi (PM-KISAN):-** PM-KISAN has integrated digital systems to identify beneficiaries and transfer funds directly to farmers' bank accounts. Over 11 crore (110 million) farmers have benefitted from the scheme, receiving ₹6,000 annually in three instalments. The program uses a database linked to land records to ensure transparency and effective fund distribution.
7. **Kisan Drones Initiative: -** Under the government's push for advanced technology, the use of drones in agriculture is being promoted for tasks such as pesticide spraying and crop health monitoring. The government provides subsidies and training programs for farmers to adopt drone technology. Pilot projects have shown up to a 20-25% increase in spraying efficiency and significant reductions in labor costs.
8. **Soil Health Card Scheme: -** Aimed at promoting precision farming by providing farmers with soil nutrient status and tailored fertilizer recommendations. Since its inception, over 22 crore (220 million) soil health cards have been distributed. Reports indicate a 10-15% increase in crop productivity and reduced fertilizer usage due to more precise applications.
9. **National e-governance programme plan in Agriculture (NeGP-A):-** The National e-Governance Plan in Agriculture (NeGP-A) is a centrally sponsored scheme with 3.3 crore senction in 2022-23, that uses information and communication technology (ICT) to provide farmers with timely access to agricultural information.

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MUSHROOMS: NUTRITIONAL VALUE, EDIBLE VARIETIES, AND VALUE-ADDED PRODUCTS

Mushrooms, edible fungi, have been a part of the human diet for centuries. Rich in nutrients, they are valued not only for their taste but also for their potential medicinal properties. Mushrooms have long been used in traditional diets, especially across Asia, and are now gaining popularity worldwide in modern, health-conscious cuisines. Often classified as "functional foods," they offer a unique combination of nutrition and health benefits. Mushrooms are sometimes referred to as "poor man's meat" because they provide a relatively high-quality protein along with a wide range of essential and non-essential amino acids, making them a valuable alternative to meat in many diets. This article examines the nutritional composition of mushrooms, highlights commonly consumed edible varieties, and discusses the increasing importance of mushroom-based value-added products in today's food industry.

1. Nutritional value of mushroom

Mushrooms are widely recognized as nutrient-dense and low-calorie foods, making them suitable for people of all age groups. They are neither plants nor animals but belong to the fungi kingdom, which gives them a distinctive nutritional profile.

1.1 Macronutrient composition

Mushrooms contain:

- High water content (85-95%), making them light and hydrating
- Low calories and fat, ideal for weight management
- Moderate protein content, higher than most vegetables
- Dietary fibre, including chitin and beta-glucans

A typical serving of raw mushroom (about 100 g) contains:

- Calories: ~15–21 kcal
- Protein: ~2–3 g
- Carbohydrates: ~3–4 g
- Fat: negligible

This makes mushrooms a low-energy but nutrient-rich food, perfect for balanced diets.

1.2 Protein quality

Mushrooms are especially valuable for vegetarians because they:

Edible mushrooms provide essential **amino acids**, including methionine, arginine (semi-essential), tryptophan, threonine, valine, isoleucine, phenylalanine, lysine, and histidine, which are vital for the proper functioning of the human body. These amino acids play important roles in protein synthesis, tissue growth and repair, enzyme and hormone production, and immune function. For example, lysine supports growth and calcium absorption, tryptophan is a precursor for serotonin (important for mood regulation), and methionine aids in metabolism and detoxification.

Due to this balanced amino acid profile, mushrooms serve as a valuable plant-based alternative to meat, especially for vegetarians and vegans. While not as protein-dense as animal sources, they still contribute significantly to daily protein intake and provide additional health benefits such as low-fat content, absence of cholesterol, and presence of bioactive compounds.

1.3 Fats and Carbohydrates

Edible mushrooms are a rich source of **fatty acids,** including linoleic acid, stearic acid, palmitic acid, adrenic acid, and nervonic acid. Among these, linoleic acid is an essential polyunsaturated fatty acid that contributes to heart health and helps maintain proper cell membrane function. Palmitic and stearic acids are saturated fatty acids that provide energy and structural support to cells. Adrenic acid plays a role in brain and tissue function, while nervonic acid is important for the formation and maintenance of nerve cell membranes, particularly in the brain. Overall, these fatty acids contribute to energy supply, cellular integrity, and neurological health.

Mushrooms also contain a variety of **carbohydrates,** such as sucrose, xylose, rhamnose, mannose, and fructose, which serve as sources of energy. In addition to simple sugars, mushrooms are known to contain complex carbohydrates like dietary fiber and polysaccharides (e.g., beta-glucans). These compounds are beneficial for digestive health, help regulate blood sugar levels, and support the immune system. The presence of such carbohydrates makes mushrooms not only energy-providing but also functionally beneficial for overall health.

1.4 Vitamins and Minerals

Mushrooms are rich in essential micronutrients, including:

B-complex vitamins such as B1 (Thiamine), B2 (Riboflavin), B3 (Niacin), B9 (Folate), and B12 (Cyanocobalamin) play a vital role in energy metabolism by helping convert carbohydrates, proteins, and fats into usable energy. They also support nervous system function, red blood cell formation, and overall cellular health.

Vitamin D_2 (Ergocalciferol) is particularly important because it is rare in plant-based foods. In mushrooms, it is formed when they are exposed to sunlight or ultraviolet (UV) light, converting ergosterol into vitamin D_2. This vitamin is essential for calcium and phosphorus absorption, thereby supporting bone strength and immune function.

Vitamin C (Ascorbic acid) and **Vitamin E (Tocopherol)** are present in smaller amounts but contribute significantly as antioxidants. Vitamin C helps in collagen synthesis, immune support, and wound healing, while Vitamin E protects cells from oxidative damage and supports skin and immune health.

Mineral contents of edible mushrooms:

- **Calcium (Ca):** Essential for strong bones and teeth, also supports muscle function and nerve signalling.
- **Magnesium (Mg):** Plays a key role in enzyme activity, muscle relaxation, nerve function, and energy production.
- **Potassium (K):** Helps maintain fluid balance, supports heart health, and regulates blood pressure.
- **Phosphorus (P):** Important for bone formation, energy metabolism (ATP), and cell structure.
- **Sodium (Na):** Maintains fluid balance and aids in nerve impulse transmission (mushrooms are naturally low in sodium).
- **Iron (Fe):** Required for the formation of hemoglobin and oxygen transport in the blood.
- **Copper (Cu):** Involved in iron metabolism, red blood cell formation, and antioxidant defence.
- **Zinc (Zn):** Supports immune function, wound healing, and enzyme activity.
- **Molybdenum (Mo):** Acts as a cofactor for enzymes involved in metabolism and detoxification processes.

1.4 Bioactive compounds

Beyond basic nutrition, mushrooms contain several bioactive compounds, such as:

- **Beta-glucans (immune-boosting fibre):**

Mushrooms are rich in beta-glucans, a type of soluble dietary fiber known for its strong immunomodulatory properties. These compounds help activate immune cells such as macrophages and natural killer (NK) cells, enhancing the body's defense against infections. Beta-glucans also contribute to lowering cholesterol levels, improving gut health, and helping regulate blood sugar levels, making them beneficial for overall metabolic health.

- **Polyphenols and antioxidants:**

Mushrooms contain a variety of polyphenols and antioxidant compounds that help neutralize harmful free radicals in the body. These compounds reduce oxidative stress, which is linked to aging and the development of chronic diseases such as heart disease, diabetes, and cancer. Their antioxidant properties support cellular protection, improve immune function, and promote overall well-being.

- **Ergothioneine** (a powerful antioxidant):

Ergothioneine is a unique sulphur-containing antioxidant abundantly found in mushrooms. It plays a crucial role in protecting cells from oxidative damage, particularly in sensitive tissues such as the brain, liver, and kidneys. Ergothioneine is known for its potential in reducing inflammation, supporting healthy aging, and protecting against neurodegenerative diseases. These compounds contribute to disease prevention and overall well-being.

1.5 Health benefits of mushroom

Regular consumption of mushrooms is associated with multiple health benefits:

- Boosts immunity due to antioxidants and beta-glucans
- Supports heart health by lowering cholesterol and blood pressure
- Helps in weight management due to low calorie and high satiety
- Reduces risk of chronic diseases, including certain cancers
- Improves gut health by acting as prebiotics
- Enhances brain health through antioxidant activity

Thus, mushrooms are often referred to as a 'superfood' due to their combined nutritional and medicinal properties.

2. Edible mushrooms

Out of thousands of mushroom species, only a limited number are safe and commonly consumed. Edible mushrooms are cultivated and widely available in markets.

2.1 Common edible mushroom varieties

Here are some popular edible mushrooms:

1. Button mushroom (*Agaricus bisporus*)

Button mushroom is the most commonly consumed edible mushroom in the world. It is widely cultivated and forms an important part of daily diets due to its mild taste and versatility.

Key features:

- Small, round, white cap (turns brown as it matures)
- Soft texture and mild flavor
- Grows well in controlled conditions
- Optimal temperature: 15-25°C

Nutritional value:

- Good source of protein
- Contains essential and non-essential amino acids
- Rich in B-complex vitamins and minerals (like selenium)
- Low in fat and calories

Uses:

- Used in curries, soups, salads, pizzas, pasta, and stir-fries
- Consumed fresh, canned, or processed
- Suitable for low-calorie and vegetarian diets

Importance:

- High commercial value and demand
- Widely cultivated on compost
- Provides employment and income opportunities

- Important in food and processing industries

2. Oyster mushroom (*Pleurotus ostreatus*)

Oyster mushroom is a widely cultivated edible fungus known for its oyster-shaped cap and soft texture. It is popular across the world and grows well in a variety of climatic conditions.

Key features:

- Oyster-shaped cap with smooth surface
- White, grey, or light brown color
- Soft texture and mild flavor
- Grows in clusters on agricultural waste (wheat and paddy straws)
- Optimum temperature range: 20-30°C

Nutritional value:

- Good source of protein
- Contains essential and non-essential amino acids
- Rich in vitamins (B-complex) and minerals
- Low in fat and calories

Uses:

- Used in curries, soups, stir-fries, noodles, and snacks
- Popular as a meat substitute due to its texture
- Can be dried and stored for later use
- Use in nutraceuticals

Importance:

- Easy and low-cost cultivation
- Grown on agricultural waste like straw, sawdust, or husk
- Helps in recycling waste (eco-friendly)
- Provides income and employment opportunities

3. Shiitake mushroom (*Lentinula edodes*)

Shiitake mushroom is one of the most popular edible mushrooms worldwide, especially in Asian countries like China and Japan.

Key features:

- Brown cap with a rich, smoky umami flavor
- Soft texture when cooked
- Distinct aroma

Nutritional value:

- Contains proteins, vitamins especially B-complex and minerals
- Known for bioactive compounds that support health

Uses:

- Widely used in soups, stir-fries, noodles, and sauces
- Available fresh and dried
- Used in traditional medicine
- Medicinal properties

Importance:

- High market value globally
- Known for potential immune-supporting properties

4. Milky Mushroom (*Calocybe indica*)

Milky mushroom is a tropical edible mushroom broadly cultivated in India. It is well suited to warm and humid climates and is gaining popularity due to is good shelf life and ease of cultivation.

Key features:

- White, thick fleshy, and attractive fruiting body
- Firm texture with mild flavor

- Longer shelf life compared to many other mushrooms
- Grows well in warm temperatures around 25-35°C
- Increasingly cultivated in South Asia

Nutritional value:

- Good source of protein
- Contains essential and non-essential amino acids
- Rich in B-complex vitamins and minerals
- Low in fat and calories

Uses:

- Used in curries, stir-fries, soups, and salads
- Can be dried and stored for later use
- Suitable for vegetarian diets as a nutritious food

Importance:

- Easy to cultivate using agricultural waste (like paddy straw)
- Requires low investment
- Provides income and employment opportunities for farmers

5. Paddy Straw Mushroom (*Volvariella volvacea*)


- Common in Southeast Asia
- Grows on agricultural waste like straw
- Short shelf life but highly nutritious
- Paddy straw mushroom is a tropical edible fungus commonly grown in South and Southeast Asia. It is one of the fastest-growing mushrooms and is especially popular in regions with warm and humid climates.

  Key features:
- Soft, delicate fruiting body with a smooth surface
- Greyish to brown cap when mature
- Grows best at 30-35°C
- Very short shelf life (highly perishable)

  Nutritional value:
- Good source of protein
- Contains essential amino acids
- Rich in vitamins (especially B-complex) and minerals
- Low in fat and calories

  Uses:
- Widely used in soups, curries, stir-fries, and Asian dishes
- Consumed fresh due to short storage life
- Can be dried or canned for preservation

  Importance:
- Grown on agricultural waste like paddy straw
- Requires low investment and simple techniques
- Provides quick returns due to short growth cycle
- Supports rural employment and sustainable farming

2.2 Importance of edible mushrooms

Edible mushrooms play a vital role in:

- Food security, especially in developing countries
- Sustainable agriculture, as they grow on waste materials
- Nutritional improvement, particularly for vegetarians

They are also environmentally friendly, requiring less land and water compared to animal protein sources.

3. Value-added products of Mushrooms

Due to their nutritional and economic importance, mushrooms are processed into various value-added products. These products help in:

- Extending shelf life
- Increasing market value
- Providing convenience to consumers

3.1 Types of value-added Mushroom products

1. Dried Mushrooms


- Moisture removed for longer storage
- Retains nutrients and flavor
- Used in soups and sauces
- Protein content increases in dried mushrooms, reaching approximately 20–23%.

2. Mushroom powder


- Made by grinding dried mushrooms
- Used as a flavor enhancer or supplement
- Used in preparing various products like mushroom laddoo, papad, cookies, protein powder etc
- Rich in protein and minerals

3. Mushroom pickle

- Popular in Indian households
- Combines taste with preservation
- Adds variety to traditional meals

4. Mushroom soup and ready-to-eat products

- Instant soups and curries
- Convenient for urban consumers
- Widely available in packaged form

5. Mushroom snacks

- Includes chips, nuggets, and biscuits
- Healthier alternative to junk food
- Rich in fiber and nutrients

6. Mushroom-based Nutraceuticals


- Capsules and extracts for health benefits
- Used for immunity, brain health, and stress management
- Derived from medicinal mushrooms

7. Mushroom laddoo

- Prepared by mixing mushroom powder with flour, jaggery, and ghee
- Acts as a nutritious sweet snack, especially for children
- Rich in protein, iron, and energy
- A good way to include mushrooms in diets without altering taste much

8. Mushroom biscuits

- Made using mushroom powder blended with wheat flour
- Provides enhanced protein and fibre content compared to regular biscuits
- Suitable as a healthy snack option
- Popular in school nutrition programs and health-conscious diets

9. Mushroom papad

- Prepared by mixing mushroom powder with pulse flour (like urad dal)
- Retains traditional taste with added nutritional benefits
- Easy to store and cook
- Improves protein and mineral intake in daily meals

10. Mushroom badi (wadi)

- Made by combining mushroom paste or powder with lentils and sun-drying
- Used in curries and gravies
- Increases protein quality and digestibility
- Helps in long-term storage and rural food security

3.2 Benefits of Value addition

Value-added mushroom products offer several advantages:

- Reduced post-harvest losses
- Increased income for farmers and entrepreneurs
- Year-round availability
- Enhanced consumer convenience
- Diet diversity

These products also support the growth of mushroom-based industries and rural employment.

4. Economic and social importance

Mushroom cultivation and processing provide:

- Employment opportunities, especially in rural areas
- Income generation with low investment
- Sustainable use of agricultural waste

In India, mushroom farming is emerging as a profitable agribusiness due to increasing awareness of health foods.

Conclusion

Mushrooms are a highly nutritious and sustainable food that offer numerous health benefits due to their rich composition of proteins, vitamins, minerals, and bioactive compounds. Widely consumed varieties such as button, oyster, and shiitake mushrooms provide both dietary value and culinary versatility. In addition, the development of value-added products like dried mushrooms and nutraceuticals has expanded their role in food processing and entrepreneurship. As the demand for healthy and sustainable foods continues to grow, mushrooms stand out as an affordable and nutrient-dense option. Their inclusion in daily diets can contribute significantly to improved health, food security, and economic development.

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Crop Feeding to Soil Feeding: The Core Philosophy of Integrated Nutrient Management

Introduction

India occupies a prominent position in the global fertilizer sector, ranking as the second largest consumer, the third largest producer and the third largest importer of fertilizers. The long-term and imbalanced use of fertilizers, especially nitrogenous fertilizers, has resulted in serious deterioration of soil physical, chemical, and biological properties across many agro-ecological regions of the country. Reduced application of organic manures and crop residues, coupled with intensive tillage, has led to poor soil aggregation, compaction, reduced water infiltration, and lower microbial activity. Excessive nitrogen fertilization also contributes to nitrate (NO_3^-) leaching into groundwater, posing environmental and public health risks. nitrogen losses through volatilization and denitrification increase greenhouse gas emissions, particularly nitrous oxide (N_2O), contributing to climate change. This situation, characterized by declining soil health, imbalanced nutrient use, environmental degradation, and economic pressure, highlights the urgent need for a holistic and sustainable approach to nutrient management. Integrated Nutrient Management (INM) emerges as a scientifically sound strategy to restore soil fertility, improve nutrient use efficiency, enhance crop productivity, and ensure long-term sustainability of Indian agriculture while conservation environmental quality.

Concept

The concept of shifting from crop feeding to soil feeding is the core philosophy of Integrated Nutrient Management. Conventional agriculture followed a crop feeding approach, where nutrients were supplied mainly through chemical fertilizers to obtain immediate yield response. In contrast, INM promotes soil feeding by maintaining and improving soil health through the combined use of Chemical fertilizers (balanced and need-based application), Organic manures, Crop residues and Bio-fertilizers.

Under INM, the soil is treated as a living system. By enhancing soil organic matter, biological activity, and nutrient cycling, the soil itself becomes capable of supplying nutrients to crops in a sustained manner. Thus, instead of only feeding the crop directly, INM strengthens the soil's natural fertility and nutrient buffering capacity. Therefore, Integrated Nutrient Management represents a scientific transition from a narrow crop-centered approach to a holistic soil-centered nutrient management strategy, ensuring sustainable agriculture and environmental protection. INM does not reject inorganic fertilizers, but it clearly states that chemical fertilizers should not be the first and only choice for soil fertility management. The concept emphasizes the judicious, balanced, and combined use of inorganic fertilizers, organic manures, crop residues, and bio-fertilizers to supply essential nutrients to crops while maintaining or improving soil health.

According to the Food and Agriculture Organization (FAO): Integrated Nutrient Management is the maintenance of soil fertility and plant nutrient supply at an optimum level for sustaining desired crop productivity through optimization of benefits from all possible sources of plant nutrients in an integrated manner.

Fig. 1. Principles of Integrated Nutrient Management

Fig. 2. Objectives of Integrated Nutrient Management

Table 1. Different components and sources of INM

	Component	Major Sources	Primary Functions
1.	**Inorganic Fertilizers**	Urea, DAP, SSP, MOP, NPK complexes	Meet crop nutrient demand quickly
2.	**Organic Manures**	FYM, Compost, Vermicompost, Oil cakes	Improve SOC and slow and gradual nutrient supply
3.	**Biofertilizers**	Rhizobium, Azotobacter, PSB, Mycorrhiza, BGA	Fixation of N, solubilization of P, mobilization of nutrients
4.	**Crop Residue Recycling**	Conservation tillage, Biochar, Mulching of crop residue,	Nutrient recycling and carbon addition
5.	**Green Manuring**	Dhaincha, Sunnhemp, Cowpea	Adds biologically fixed nitrogen and organic matter
6.	**Crop Diversification**	Legume-cereal rotation, Intercropping, Cover crops,	Biological N fixation, balanced nutrient use, improved soil health
7.	**Micro & Secondary Nutrients**	$ZnSO_4$, Borax, Gypsum, $MgSO_4$	Correct specific nutrient deficiencies
8.	**Scientific Nutrient Management Practices**	Soil test-based application, SSNM, Split application, Deep placement, Fertigation	Optimized timing & placement enhances fertilizer use efficiency

Modification of fertilizers:

Modified fertilizers are advanced fertilizer formulations developed to improve Nutrient Use

Efficiency (NUE) and their primary function is to synchronize nutrient availability with crop demand while minimizing losses through leaching, volatilization, and runoff. Such fertilizers not only increase fertilizer efficiency and crop yield but also reduce environmental pollution and input costs. These include neem-coated, slow-release, controlled-release, stabilized, nano, chelated, fortified, water-soluble, customized, and bio-activated fertilizers.

Fertilizer application methods

Different fertilizer application methods significantly influence nutrient availability and NUE. Broadcasting is simple but less efficient due to greater nutrient losses, whereas methods such as band placement, deep placement, split application, foliar spray, and fertigation improve nutrient uptake by synchronizing nutrient supply with crop demand. Advanced methods like fertigation and foliar application provide very high efficiency by ensuring precise and targeted nutrient delivery. Therefore, selecting an appropriate fertilizer application method is essential for sustainable agriculture, higher productivity, reduced input costs, and environmental protection

Summary

The core philosophy of INM is not only to feed crops for short-term yield gains, but to nourish the soil for sustaining long-term agricultural productivity, environmental quality, and economic profitability. INM does not reject inorganic fertilizers, but it clearly states that chemical fertilizers should not be the first and only choice for soil fertility management. INM is a sustainable approach to soil fertility management that emphasizes the balanced and combined use of chemical fertilizers, organic manures, crop residues, green manures, and biofertilizers to maintain soil health and ensure stable crop productivity. The transition from crop feeding to soil feeding represents a scientific and ecological shift in modern farming. When farmers nourish the soil with balanced nutrients, organic matter, and beneficial microorganisms, the soil becomes more productive, resilient, and alive. Ultimately, healthy soil is the true foundation of healthy crops, healthy people, and a healthy environment.

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Beyond Seeds and Weather Forecasts: Why 'Trust' is the Ultimate Climate-Smart Technology

If you walk into a village in the semi-arid ravines of the Chambal region or the undulating terrains of the Satpura Plateau in Madhya Pradesh, the conversation among farmers inevitably turns to the sky. The monsoons, once the reliable rhythm of Indian agriculture, have become wildly unpredictable. Prolonged dry spells are suddenly interrupted by unseasonal, high-intensity rainfall, while severe heat waves threaten crop physiology.

For the small and marginal farmers who make up the backbone of India's agrarian economy, climate change is no longer a distant, theoretical debate—it is a daily, existential threat to their livelihoods.

In response to this crisis, agricultural scientists and policymakers have championed **Climate-Smart Agriculture (CSA)**. From drought-resilient seed varieties and zero-tillage farming to micro-irrigation and weather-based agro-advisories, we have a robust toolkit of technologies designed to sustainably increase productivity, build climate resilience, and reduce greenhouse gas emissions.

Yet, despite the availability of these technologies, widespread grassroots adoption remains frustratingly slow. Why? Because we have largely treated climate adaptation as a purely *technical* problem, ignoring the deeply *psychological and social* realities of farming.

The Hidden Barrier: The Psychology of Risk

To understand the slow adoption of Climate-Smart Agriculture, we must put ourselves in the shoes of a smallholder farmer. When an extension worker advises a farmer to abandon a generational farming practice, invest in a new crop variety, or alter their traditional sowing schedule based on an agro-meteorological forecast, they are essentially asking that farmer to gamble their family's entire seasonal income on that advice.

Farmers are inherently risk-averse, and rightfully so. The critical, often overlooked bottleneck in the adoption of CSA is not a lack of technology—it is a deficit of **institutional trust**.

Possessing scientifically sound technology in a university laboratory is useless if the target audience refuses to adopt it. A farmer's willingness to take the risk of adopting a new climate-smart practice is directly proportional to the trust they place in the source of that information. If farmers perceive State Agricultural Universities (SAUs) and Krishi Vigyan Kendras (KVKs) as credible, empathetic, and reliable, they are significantly more likely to overcome their cognitive barriers and climate fatalism.

The Power of the Agrarian 'Grapevine'

Farmers do not make decisions in isolation. They are deeply embedded within complex socio-technical networks. Information flows through the village via a dynamic "grapevine" of formal channels (government line departments, KVKs) and informal channels (progressive peers, local input dealers, kinship networks).

Historically, agricultural extension in India relied heavily on a top-down "Transfer of Technology" model. Scientists created the knowledge, and extension workers "pushed" it down to the farmers. However, mitigating the complex, localized impacts of climate change requires abandoning this unidirectional approach.

Recent research utilizing **Social Network Analysis (SNA)** is revealing that information within farming communities clusters around specific individuals. In every village or block, there are "Information Brokers" or "Boundary Spanners"—highly influential, progressive farmers who act as gatekeepers of knowledge. When a State Agricultural University introduces a new climate-smart practice, the broader farming community rarely adopts it immediately. Instead, they watch the "Information Brokers." If these trusted central figures adopt and validate the technology, the rest of the network swiftly follows suit.

Rethinking Agricultural Extension: A Networked Approach

To effectively scale up Climate-Smart Agriculture, our extension systems must evolve. We must move beyond just distributing pamphlets and hosting generalized village meetings. Here are three crucial steps for modernizing our approach:

1. Map the Local Network, Don't Just Broadcast: Extension agencies must invest in understanding the social architecture of the villages they serve. Who do the farmers actually talk to when a crop fails? Who do they trust for seed recommendations? By identifying these central, trusted farmers, extension officers can stop broadcasting information blindly and instead target these "nodes" to rapidly accelerate the diffusion of CSA practices.

2. Shift from 'Directing' to 'Facilitating':

The complexity of local climatic threats demands a participatory flow of information. Farmers are not passive recipients of knowledge; they hold invaluable generational wisdom about local micro-climates. SAUs and KVKs must involve farmers in the *co-design* of climate-smart interventions. When farmers feel they are partners in the research rather than just test subjects, institutional trust deepens profoundly.

3. Build "Reservoirs of Trust":

Trust is not built during a crisis; it is built through consistent, reliable presence. Extension workers and university scientists must maintain high visibility and regular interaction within the village networks. Prior positive interactions with agricultural advisory services create a "reservoir of trust" that farmers will draw upon when asked to make high-risk, climate-smart structural changes to their farms.

Conclusion

As the climatic challenges in regions like Chambal and Satpura continue to escalate, our agricultural strategies must become as sophisticated socially as they are scientifically.

Climate-smart seeds, precision irrigation, and satellite weather data are essential tools. But the ultimate vehicle for delivering these tools is the human network. By actively mapping rural communication systems, leveraging the influence of trusted progressive farmers, and relentlessly building institutional credibility, State Agricultural Universities can turn the tide on climate change.

In the fight for agricultural sustainability, technology is the engine, but **trust** is the fuel.

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NUTRITION GARDENS AS A STRATEGY FOR IMPROVING HOUSEHOLD NUTRITION, DIETARY DIVERSITY, AND RURAL LIVELIHOODS

Introduction

Agriculture plays a crucial role not only in food production but also in improving the nutritional well-being of rural households. In many developing countries, including India, a large proportion of the population depends on agriculture for their livelihood. However, despite sufficient food production in several regions, problems such as malnutrition, micronutrient deficiencies, and poor dietary diversity continue to persist. This situation highlights the need to strengthen the connection between agriculture and nutrition through innovative and sustainable approaches. In recent years, the concept of **nutrition-sensitive agriculture** has gained increasing attention among researchers, policymakers, and development agencies. Nutrition-sensitive agriculture aims to design and implement agricultural systems that not only increase food production but also enhance the nutritional quality of diets. It focuses on improving access to diverse, safe, and nutrient-rich foods while promoting healthy food consumption practices at the household level. This approach recognizes that agriculture has the potential to influence nutrition through various pathways, including food production, income generation, and women's empowerment.

One of the most effective and practical strategies for implementing nutrition-sensitive agriculture is the establishment of **nutrition gardens**. Nutrition gardens, also known as kitchen gardens or homestead gardens, involve the cultivation of a variety of vegetables, fruits, pulses, and medicinal plants in a small plot of land near the household. These gardens are designed to provide a continuous supply of fresh and nutritious foods throughout the year, thereby improving the dietary diversity of rural families. Nutrition gardens offer several advantages for rural and tribal households. They ensure easy access to fresh vegetables and fruits, reduce dependence on market purchases, and promote the consumption of balanced diets. The produce from these gardens is often free from harmful chemicals, as farmers usually adopt organic or low-input cultivation practices. Moreover, nutrition gardens require limited land and resources, making them suitable for small and marginal farmers. Another important aspect of nutrition gardens is their role in empowering rural women. In many households, women are primarily responsible for managing these gardens, selecting crops, and preparing nutritious meals for their families. This involvement enhances their awareness about healthy dietary practices and strengthens their decision-making role in household nutrition management.

Recognizing the importance of linking agriculture with nutrition, several organizations and government programmes have started promoting nutrition gardens across rural communities. Institutions such as the Indian Council of Agricultural Research and national initiatives like POSHAN ABHIYAAN encourage households to adopt nutrition gardens as an effective strategy to combat malnutrition and improve food and nutritional security.

Therefore, nutrition gardens represent a simple, sustainable, and community-based approach to achieve the objectives of nutrition-sensitive agriculture. By integrating diverse crops within small household spaces, nutrition gardens can significantly contribute to improving dietary diversity, strengthening family health, and enhancing the overall nutritional status of rural populations.

Recent Advances in Agricultural Extension

Agricultural extension has undergone significant transformation in recent years due to rapid developments in technology, communication systems, and institutional approaches. Traditionally, extension mainly relied on face-to-face methods such as farm visits, demonstrations, and training programs. However, modern agricultural extension has shifted toward more **innovative, participatory, and technology-driven systems** that enhance the efficiency and reach of advisory services. These advances help farmers access timely information, adopt improved technologies, and improve agricultural productivity and sustainability.

One of the most important advances in agricultural extension is the use of **Information and Communication Technologies (ICTs)**. Digital tools such as smartphones, mobile applications, SMS services, and online platforms enable extension workers to disseminate agricultural information quickly and effectively. Farmers can now receive real-time updates on weather conditions, pest outbreaks, market prices, and crop management practices. Digital platforms also provide access to online training programs, agricultural videos, and knowledge portals, allowing farmers to learn new practices without geographical limitations.

Another major advancement is the integration of **Artificial Intelligence (AI) and machine learning** in extension services. AI-based advisory systems can analyze large datasets related to soil conditions, weather patterns, crop diseases, and farm management practices. These systems provide personalized recommendations to farmers regarding crop selection, pest management, and input use. Image-based AI applications can identify crop diseases and pests through photographs taken on smartphones, helping farmers take timely control measures and reduce crop losses.

The use of the **Internet of Things (IoT)** has also transformed agricultural extension. IoT devices such as soil moisture sensors, weather monitoring stations, and smart irrigation systems collect real-time data from farms. This information helps extension professionals provide precise and location-specific recommendations to farmers. By monitoring soil moisture levels, temperature, and crop health, farmers can make better decisions regarding irrigation, fertilization, and crop protection.

Another important advancement is **precision agriculture**, which uses technologies such as GPS, drones, and remote sensing to manage farm operations more efficiently. Drones are now used to monitor crop growth, detect pest infestations, and spray pesticides or fertilizers in a targeted manner. Remote sensing technologies and satellite imagery help extension agencies assess crop conditions over large areas and provide early warnings about droughts, floods, or pest outbreaks.

Modern agricultural extension also emphasizes **participatory and farmer-centered approaches**. Instead of the traditional top-down model of technology transfer, extension systems now encourage active involvement of farmers in the learning and decision-making process. Approaches such as Farmer Field Schools, Participatory Rural Appraisal, and farmer-to-farmer extension enable farmers to share their experiences, learn collectively, and adapt technologies according to local conditions.

In recent years, agricultural extension has also focused on **climate-smart agriculture** to address the challenges posed by climate change. Extension services promote practices such as water conservation, integrated farming systems, agroforestry, and climate-resilient crop varieties. These strategies help farmers adapt to changing climatic conditions while ensuring sustainable agricultural production. Another emerging trend is the development of **pluralistic extension systems**, where multiple stakeholders participate in providing extension services. Government agencies, agricultural universities, private companies, non-governmental organizations, and farmer producer organizations work together to deliver advisory services. Agri-startups and digital platforms are also playing an important role in providing market information, input supply, and technical guidance to farmers. The integration of digital technologies, artificial intelligence, IoT, participatory approaches, and climate-smart strategies has made extension services more efficient, inclusive, and responsive to farmers' needs. These innovations are essential for achieving sustainable agricultural development and improving the livelihoods of farming communities.

What are Nutrition Gardens?

Nutrition gardens, also known as kitchen gardens or homestead gardens, are small-scale gardens established near households for the cultivation of a variety of vegetables, fruits, pulses, and medicinal plants. The primary objective of a nutrition garden is to ensure a **regular supply of fresh, safe, and nutrient-rich foods** for household consumption throughout the year. Unlike commercial farming, nutrition gardens are mainly developed to meet the **nutritional needs of the family rather than for market sale**. Nutrition gardens are an important component of nutrition-sensitive agriculture because they help bridge the gap between agricultural production and nutritional outcomes. These gardens are carefully planned to include different types of crops that provide essential nutrients such as vitamins, minerals, proteins, and dietary fibre. Common crops grown in nutrition gardens include leafy vegetables like spinach and amaranthus, vegetables such as tomatoes, brinjal, okra, and beans, as well as fruit plants like papaya, banana, guava, and drumstick. Pulses and tuber crops may also be included to enhance protein and energy intake. One of the key features of nutrition gardens is **crop diversity**. By cultivating multiple crops with different nutritional benefits, families can obtain a balanced diet from a relatively small area of land. Seasonal crop planning is also an important aspect of nutrition gardens, ensuring that different vegetables and fruits are available at different times of the year. This helps maintain continuous food supply and reduces dependence on markets for purchasing nutritious foods.

Nutrition gardens are particularly beneficial for **small and marginal farmers, rural households, and tribal communities** who often face challenges related to food access and dietary diversity. Even families with limited land can establish small gardens using available spaces around their homes, such as backyards, rooftops, or small plots of land. These gardens require minimal investment and can be maintained using locally available resources such as compost, farmyard manure, and organic pest control methods. Another important aspect of nutrition gardens is their role in **promoting sustainable and eco-friendly agricultural practices**. Farmers usually adopt organic or low-input farming techniques in these gardens, which helps maintain soil fertility, conserve biodiversity, and reduce environmental pollution. Crop rotation, mixed cropping, and the use of indigenous plant varieties are commonly practiced in nutrition gardens to ensure better productivity and sustainability.

Recognizing the importance of nutrition gardens in improving dietary diversity and reducing malnutrition, several institutions and development programmes promote their adoption among rural households. Organizations such as the Indian Council of Agricultural Research encourage the establishment of nutrition gardens as part of their extension activities aimed at improving household nutrition and food security in India. Thus, nutrition gardens serve as a simple yet powerful approach to ensure that families have access to a variety of nutritious foods, contributing significantly to improved health, better nutrition, and sustainable rural livelihoods.

Importance of Nutrition Gardens for Household Nutrition

Nutrition gardens play a vital role in improving the nutritional status of rural households by ensuring easy access to a variety of fresh and nutrient-rich foods. In many rural and tribal areas, families often depend mainly on staple foods such as rice or wheat, which may provide sufficient calories but lack essential vitamins and minerals. This imbalance in diet can lead to micronutrient deficiencies, commonly referred to as hidden hunger. Nutrition gardens help address this issue by providing diverse vegetables, fruits, and other nutrient-dense foods that contribute to a balanced diet. One of the major advantages of nutrition gardens is their ability to **improve food availability at the household level**. By cultivating different crops in a small area around the house, families can harvest fresh produce regularly. This ensures that vegetables and fruits are readily available for daily consumption, reducing the need to purchase them from markets. As a result, households can save money while simultaneously improving their dietary quality.

Nutrition gardens also contribute significantly to **enhancing dietary diversity**, which is an important indicator of good nutrition. A diverse diet includes foods from different food groups such as vegetables, fruits, pulses, cereals, and animal products. When families grow a variety of crops in their nutrition gardens, they are more likely to include these foods in their daily meals. Increased dietary diversity improves the intake of essential nutrients like vitamins A and C, iron, calcium, and folate, which are crucial for maintaining good health and preventing diseases. Another important benefit of nutrition gardens is the **consumption of fresh and chemical-free food**. Since most household gardens use organic manures such as compost and farmyard manure, the produce is often free from harmful pesticide residues. Freshly harvested vegetables and fruits retain more nutrients compared to those stored or transported over long distances. This helps improve the nutritional quality of the food consumed by the family.

Nutrition gardens are particularly beneficial for **children, pregnant women, and elderly family members**, who require nutrient-rich diets for proper growth, development, and health maintenance. Regular consumption of vegetables and fruits from nutrition gardens can strengthen immunity, improve overall health, and reduce the risk of nutrition-related diseases. Furthermore, nutrition gardens promote **nutrition awareness and healthy food habits** within households. When family members are directly involved in growing vegetables and fruits, they develop a better understanding of the importance of consuming nutritious foods. This awareness often leads to positive changes in dietary practices and encourages families to adopt healthier lifestyles. Recognizing the potential of nutrition gardens in improving household nutrition, several programmes and institutions promote their adoption across rural communities. In India, agricultural and nutrition initiatives supported by organizations such as the Food and Agriculture Organization encourage the development of household nutrition gardens as an effective strategy to reduce malnutrition and enhance food and nutrition security. Therefore, nutrition gardens serve as an important tool for improving household nutrition by ensuring the availability of diverse, fresh, and nutritious foods while simultaneously promoting sustainable and healthy dietary practices.

Role of Nutrition Gardens in Improving Dietary Diversity

Dietary diversity is an important indicator of a healthy and balanced diet. It refers to the consumption of a variety of foods from different food groups to meet the body's nutritional requirements. In many rural and tribal households, diets are often dominated by staple foods such as cereals and millets, which mainly provide energy but lack essential vitamins, minerals, and proteins. As a result, people may suffer from micronutrient deficiencies despite having sufficient food intake. Nutrition gardens play a significant role in improving dietary diversity by providing a wide range of nutrient-rich foods at the household level. Nutrition gardens encourage the cultivation of diverse crops including leafy vegetables, root and tuber crops, fruits, pulses, and sometimes medicinal plants. Each crop contributes different nutrients that are essential for maintaining good health. For example, leafy vegetables such as spinach and amaranthus are rich in iron and calcium, while fruits like papaya and guava provide vitamins and antioxidants. Pulses and legumes grown in nutrition gardens contribute to protein intake, which is essential for growth and tissue repair.

By producing different crops in a small space, nutrition gardens help families include multiple food groups in their daily meals. This diversity in food consumption improves nutrient intake and supports better physical growth, especially among children and adolescents. Regular consumption of vegetables and fruits from nutrition gardens also helps strengthen immunity, prevent deficiencies, and reduce the risk of nutrition-related diseases. Another advantage of nutrition gardens in promoting dietary diversity is **seasonal crop planning**. Different crops are grown according to seasons, ensuring that some form of vegetable or fruit is available throughout the year. For instance, leafy vegetables can be grown during cooler seasons, while fruit crops and gourds thrive in warmer periods. Such seasonal planning helps maintain a continuous supply of fresh produce and prevents gaps in food availability.

Nutrition gardens also encourage the cultivation of **traditional and locally adapted crops**, which are often rich in nutrients and well suited to local climatic conditions. These crops are sometimes neglected in commercial agriculture but play an important role in improving the nutritional quality of diets in rural communities. In addition to improving household food consumption, nutrition gardens contribute to greater awareness about balanced diets and healthy eating habits. When families grow and consume diverse crops from their gardens, they become more conscious about including vegetables and fruits in their meals. This behavioural change gradually improves the overall nutritional status of households. Recognizing the importance of dietary diversity for achieving nutrition security, institutions such as the Indian Council of Agricultural Research promote nutrition gardens as part of their agricultural extension programmes in India. These initiatives aim to encourage households to adopt diversified cropping patterns that support both agricultural sustainability and improved nutritional outcomes. Thus, nutrition gardens play a crucial role in enhancing dietary diversity by ensuring the availability and consumption of various nutrient-rich foods, ultimately contributing to better health and well-being of rural families.

Nutrition Gardens and Women Empowerment

Nutrition gardens play a significant role in empowering rural women by enhancing their participation in household food production and decision-making related to family nutrition. In many rural communities, women are primarily responsible for managing household food resources, preparing meals, and ensuring the nutritional well-being of their families. The establishment of nutrition gardens provides women with an opportunity to actively participate in agricultural activities while directly contributing to improving the health and nutrition of their households. Women often take the lead in planning, cultivating, and maintaining nutrition gardens. They select appropriate crops, manage watering and fertilization, and harvest vegetables and fruits for daily consumption. Through this involvement, women gain practical knowledge about crop cultivation, nutrition, and healthy dietary practices. This increased awareness helps them make better decisions regarding food preparation and balanced diets for their family members.

Nutrition gardens also enhance women's **knowledge and awareness about nutrition**. By growing a variety of vegetables and fruits, women learn about the nutritional value of different foods and the importance of including them in daily meals. This awareness is particularly important for improving the health of vulnerable groups such as children, pregnant women, and elderly family members. Another important aspect of nutrition gardens is their contribution to **economic empowerment**. In some cases, households may produce more vegetables or fruits than they require for their own consumption. Women can sell the surplus produce in local markets or within the community, generating small additional income for the family. This income can be used to support household expenses, education, or healthcare needs. Nutrition gardens also encourage **participation of women in community-based programmes and self-help groups**. Through training and awareness programmes organized by agricultural extension agencies, women can develop new skills related to gardening, nutrition education, and sustainable farming practices. Participation in such programmes strengthens their confidence, leadership abilities, and social networks within the community.

Government and development programmes in India increasingly recognize the importance of women's involvement in agriculture and nutrition initiatives. Organizations such as the National Rural Livelihood Mission promote women-led activities including nutrition gardens through self-help groups and community-based organizations. These initiatives aim to improve both household nutrition and women's socio-economic status. Thus, nutrition gardens serve not only as a source of nutritious food but also as an effective tool for empowering rural women. By enhancing their knowledge, skills, and economic participation, nutrition gardens strengthen women's role in improving family health and ensuring better nutrition for future generations.

Sustainable Practices in Nutrition Gardens

Sustainability is an important aspect of nutrition gardens, as these gardens are designed to provide nutritious food while maintaining environmental balance and efficient use of natural resources. Nutrition gardens generally follow eco-friendly farming practices that promote soil health, conserve water, and protect biodiversity. By adopting sustainable agricultural techniques, households can ensure long-term productivity and continuous availability of nutritious food.

One of the key sustainable practices in nutrition gardens is the use of **organic manures and natural fertilizers**. Materials such as compost, farmyard manure, and vermicompost are commonly used to enrich the soil and improve its fertility. These organic inputs enhance soil structure, increase microbial activity, and support healthy plant growth without causing environmental pollution. The use of organic fertilizers also ensures that the vegetables and fruits produced in the garden are safe and free from harmful chemical residues.

Another important practice is **crop diversification and mixed cropping**. Nutrition gardens typically include a wide variety of vegetables, fruits, and sometimes medicinal plants grown together in the same plot. This diversity helps improve soil fertility, reduces the risk of pest and disease outbreaks, and ensures a continuous supply of different crops throughout the year. Mixed cropping also maximizes the efficient use of available land and resources. **Crop rotation** is another sustainable technique commonly practiced in nutrition gardens. By rotating crops with different nutrient requirements, soil nutrients are used more efficiently and soil degradation is prevented. For example, legumes such as beans and peas can be grown to improve soil nitrogen levels, which benefits the growth of other crops in the following seasons. Efficient **water management practices** are also important for maintaining nutrition gardens. Techniques such as mulching, drip irrigation, and the use of locally available water sources help conserve water and maintain soil moisture. Mulching with crop residues or leaves helps reduce water evaporation, suppress weed growth, and maintain soil temperature.

Nutrition gardens also encourage the use of **natural pest and disease management methods**. Farmers often rely on traditional practices such as neem-based sprays, plant extracts, and biological pest control to protect crops. These methods help reduce the use of chemical pesticides, which can harm both the environment and human health. Many agricultural research and extension institutions promote sustainable gardening practices as part of nutrition garden initiatives. In India, institutions such as the Indian Council of Agricultural Research encourage farmers and rural households to adopt eco-friendly gardening techniques that enhance both agricultural sustainability and nutritional security. Therefore, sustainable practices in nutrition gardens not only help produce healthy and nutritious foods but also contribute to environmental conservation, resource efficiency, and long-term agricultural sustainability. By adopting these practices, households can maintain productive gardens while protecting natural ecosystems and promoting healthy lifestyles.

Role of Agricultural Extension in Promoting Nutrition Gardens

Agricultural extension plays a crucial role in promoting nutrition gardens and strengthening the link between agriculture and nutrition. Extension services act as a bridge between research institutions, government programmes, and rural communities by transferring knowledge, technologies, and best practices to farmers and households. Through awareness campaigns, training programmes, and demonstration activities, extension professionals help rural families understand the importance of nutrition gardens and encourage their adoption. One of the major responsibilities of agricultural extension workers is to **create awareness about the benefits of nutrition gardens**. Many rural households are not fully aware of the importance of consuming a balanced diet or the role of vegetables and fruits in maintaining good health. Extension workers conduct educational programmes, workshops, and village meetings to educate farmers and women about the nutritional value of different crops and the advantages of establishing household gardens.

Extension agencies also provide **technical guidance for establishing and managing nutrition gardens**. This includes training on garden planning, crop selection, seasonal planting schedules, soil preparation, compost preparation, and pest management practices. Demonstration plots and model nutrition gardens are often established in villages to show farmers practical methods of growing diverse crops within limited spaces. Another important function of extension services is **capacity building of rural women and self-help groups**. Since women are usually responsible for maintaining household gardens, extension programmes often focus on enhancing their skills and knowledge related to gardening and nutrition. Training programmes organized through community groups help women learn improved cultivation practices, food preparation techniques, and nutrition education, which ultimately benefits the entire household.

Agricultural extension also promotes **community participation and collective action** in establishing nutrition gardens. Extension personnel work with village institutions, schools, and community organizations to develop community gardens and promote nutrition awareness among children and families. Such participatory approaches encourage knowledge sharing and strengthen local support systems for sustaining nutrition garden initiatives. Several national programmes and institutions support the promotion of nutrition gardens through extension activities in India. Organizations such as the Indian Council of Agricultural Research provide training materials, technical guidance, and extension programmes aimed at improving household nutrition through diversified crop production. Development initiatives such as the POSHAN ABHIYAAN also emphasize the role of extension and community awareness in addressing malnutrition. Thus, agricultural extension plays a key role in encouraging the adoption of nutrition gardens by providing knowledge, technical support, and community mobilization. Through effective extension strategies, nutrition gardens can be widely promoted, leading to improved dietary diversity, better nutrition, and healthier rural communities.

Government Initiatives Supporting Nutrition Gardens in India

Recognizing the importance of linking agriculture with nutrition, the Government of India has implemented several programmes and initiatives to promote nutrition gardens across rural and urban communities. These initiatives aim to improve household food and nutritional security, reduce malnutrition, and encourage the consumption of diverse and nutritious foods. Nutrition gardens are increasingly being integrated into national policies and development programmes as a practical strategy to address the problem of hidden hunger. One of the major initiatives supporting nutrition gardens is POSHAN ABHIYAAN (National Nutrition Mission), which focuses on improving the nutritional status of women and children across the country. Under this programme, households are encouraged to establish kitchen or nutrition gardens to increase the availability of fresh vegetables and fruits. Community awareness campaigns and training programmes are conducted to educate families about the importance of balanced diets and the role of nutrition gardens in preventing malnutrition.

Another important programme promoting nutrition gardens is the National Rural Livelihood Mission (NRLM), which supports women's self-help groups in rural areas. Through this initiative, women are encouraged to establish nutrition gardens as part of their livelihood and nutrition improvement activities. Self-help groups receive training and support for crop cultivation, garden management, and nutrition education. These efforts not only improve household nutrition but also strengthen women's participation in agricultural and economic activities. Agricultural research and extension institutions also play a major role in promoting nutrition gardens. The Indian Council of Agricultural Research has introduced several extension programmes and demonstration models to encourage rural households to adopt nutrition gardens. These programmes provide technical guidance on crop selection, seasonal planning, organic farming practices, and sustainable garden management. In addition, several state governments, agricultural universities, and non-governmental organizations have implemented community-based nutrition garden programmes. These initiatives often involve schools, anganwadi centres, and village communities to promote awareness about healthy diets and encourage the cultivation of vegetables and fruits in available spaces. Such government initiatives highlight the growing recognition of nutrition gardens as an effective approach to address malnutrition and improve dietary diversity. By promoting household and community-level nutrition gardens, these programmes contribute to strengthening food systems, improving public health, and ensuring better nutritional outcomes for rural populations.

Challenges in Adoption of Nutrition Gardens

1. Although nutrition gardens offer numerous benefits for improving household nutrition and food security, their adoption among rural communities still faces several challenges. These challenges can limit the effective establishment and long-term sustainability of nutrition gardens, particularly in resource-poor and tribal areas. Identifying and addressing these constraints is essential for the successful promotion of nutrition gardens as part of nutrition-sensitive agriculture.
2. One of the major challenges is **limited awareness and knowledge about nutrition gardens** among rural households. Many families are not fully aware of the importance of growing diverse vegetables and fruits for improving dietary diversity and nutritional health. In some cases, farmers focus mainly on staple crops for market sale and may not prioritize the cultivation of vegetables or fruits for household consumption.
3. Another important constraint is **limited availability of land and water resources**. Small and marginal farmers often have very limited land holdings, and they may prioritize crop production for income generation rather than allocating space for nutrition gardens. Water scarcity in certain regions can also affect the regular maintenance of gardens, especially during dry seasons.
4. **Lack of technical knowledge and inputs** is another barrier to the adoption of nutrition gardens. Many households may not have adequate information about suitable crop varieties, seasonal crop planning, pest and disease management, or soil fertility improvement techniques. Without proper training and support from extension agencies, farmers may face difficulties in maintaining productive gardens.
5. **Pest and disease problems** can also discourage households from continuing nutrition garden activities. Since many nutrition gardens are managed with minimal chemical inputs, crops may sometimes be affected by pests or diseases if proper organic pest management practices are not followed.
6. Socio-economic factors also influence the adoption of nutrition gardens. In some communities, **limited time availability**, especially for women who are already engaged in multiple household and livelihood activities, can restrict the proper maintenance of gardens. In addition, lack of access to quality seeds, planting materials, and other inputs may reduce the effectiveness of nutrition garden initiatives.
7. Despite these challenges, many development programmes and institutions are working to address these issues through training, capacity building, and community support systems. Organizations such as the Food and Agriculture Organization and agricultural extension institutions in India promote awareness programmes and provide technical assistance to encourage wider adoption of

nutrition gardens. Therefore, overcoming these challenges through effective extension services, community participation, and policy support is essential to ensure the successful implementation and sustainability of nutrition gardens in rural and tribal communities.

Strategies to Promote Nutrition Gardens in Rural and Tribal Areas

1. Promoting nutrition gardens in rural and tribal areas requires a combination of awareness creation, capacity building, and institutional support. Since many rural households face challenges such as limited knowledge, resources, and access to inputs, well-planned strategies are essential to encourage the adoption and sustainability of nutrition gardens. Effective promotion of nutrition gardens can significantly contribute to improving dietary diversity, nutritional security, and household well-being.
2. One of the most important strategies is **creating awareness about the importance of nutrition and balanced diets**. Many rural families are not fully aware of the link between agriculture and nutrition. Awareness programmes, community meetings, and educational campaigns can help people understand the health benefits of consuming diverse vegetables and fruits grown in nutrition gardens. These activities can be conducted through village-level institutions, schools, and community organizations.
3. Another key strategy is **capacity building through training and demonstrations**. Farmers and rural households need practical knowledge about establishing and maintaining nutrition gardens. Training programmes can provide information on garden layout, crop selection, seasonal planting schedules, compost preparation, and organic pest management practices. Demonstration gardens established in villages or schools can serve as learning centres where farmers can observe and adopt improved practices.
4. **Involving women and self-help groups** is also an effective strategy for promoting nutrition gardens. Since women play a central role in household food preparation and nutrition management, empowering them through training and support can greatly enhance the success of nutrition garden initiatives. Women's groups can collectively establish and manage gardens, share experiences, and encourage other households in the community to adopt similar practices.
5. Providing **access to quality seeds, planting materials, and basic inputs** is another important factor for promoting nutrition gardens. Distribution of vegetable seeds, fruit saplings, and gardening kits can help households establish gardens easily. Local agricultural departments and extension agencies can facilitate the availability of such inputs at affordable prices.
6. The use of **school and community nutrition gardens** can also serve as an effective strategy to promote awareness among children and families. School gardens help students learn about healthy eating habits, crop cultivation, and environmental conservation. These gardens can also act as demonstration sites for the surrounding community.
7. Government programmes and institutional support are equally important in scaling up nutrition garden initiatives. Programmes such as POSHAN ABHIYAAN and initiatives supported by the Indian Council of Agricultural Research encourage households to adopt nutrition gardens as part of strategies to improve nutritional outcomes in India. Integration of nutrition gardens with agricultural extension and rural development programmes can further strengthen their impact. Thus, promoting nutrition gardens through awareness, training, women's participation, input support, and institutional collaboration can significantly enhance their adoption in rural and tribal areas. These strategies can help ensure sustainable

household food production and contribute to improved nutrition and health among rural populations.

Conclusion

Nutrition-sensitive agriculture has emerged as an important approach for addressing the persistent challenges of malnutrition and poor dietary diversity in rural communities. While traditional agricultural systems have primarily focused on increasing food production, there is a growing recognition that agriculture must also contribute directly to improving nutritional outcomes. In this context, nutrition gardens serve as a simple, practical, and sustainable strategy for linking agriculture with better health and nutrition. Nutrition gardens provide households with a reliable source of fresh vegetables, fruits, and other nutrient-rich foods throughout the year. By cultivating diverse crops in small spaces around their homes, families can improve dietary diversity, increase the intake of essential vitamins and minerals, and reduce the risk of micronutrient deficiencies. These gardens are particularly beneficial for vulnerable groups such as children, pregnant women, and elderly family members who require nutrient-rich diets for proper growth and health. In addition to improving household nutrition, nutrition gardens contribute to women's empowerment, sustainable farming practices, and community awareness about healthy food habits.

The active participation of women in managing these gardens enhances their knowledge of nutrition and strengthens their role in ensuring family health. Sustainable practices such as organic manure use, crop diversification, and natural pest management further support environmental conservation and long-term agricultural productivity.

The successful promotion of nutrition gardens requires strong support from agricultural extension systems, community organizations, and government programmes. Initiatives led by institutions such as the Indian Council of Agricultural Research and national programmes like POSHAN ABHIYAAN have played an important role in encouraging households to adopt nutrition gardens as a strategy for improving food and nutrition security in India. Therefore, nutrition gardens represent a powerful tool for achieving the goals of nutrition-sensitive agriculture. By promoting diversified food production at the household level, these gardens can significantly contribute to reducing malnutrition, improving dietary diversity, and enhancing the overall health and well-being of rural and tribal populations. Strengthening awareness, capacity building, and institutional support will further expand the impact of nutrition gardens and help build healthier and more resilient communities.

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Interview with inducer polysaccharide: Meet β-Glucan

Plants may look calm and motionless, but inside them works an intelligent defense system that never sleeps. When danger approaches such as disease-causing fungi or bacteria plants rely on natural warning signals to prepare for battle. One such powerful signal is β-glucan, a natural polysaccharide molecule found in many living organisms. β-glucans are present in cereals like barley and oats, as well as in fungi, algae, and yeast. Beyond being composed of simple structural components, they act as natural messengers that alert plants about potential threats. Scientists have discovered that β-glucans can "train" plants to defend themselves better, making them promising tools for sustainable agriculture. To make this fascinating science easier to understand, let us hear directly from the molecule itself through a fictional interview with β-glucan.

β-glucan, tell us about yourself. Who are you, and why should plants care about you?
Hello! I'm β-glucan, a naturally occurring polysaccharide made of glucose units linked together in a special way. I'm found in grains, mushrooms, fungi, and even seaweeds. My structure may look simple, but it carries an important message for plants: *"Be alert danger might be coming!"* When plants sense me, they strengthen their immune system to prepare for disease attacks.

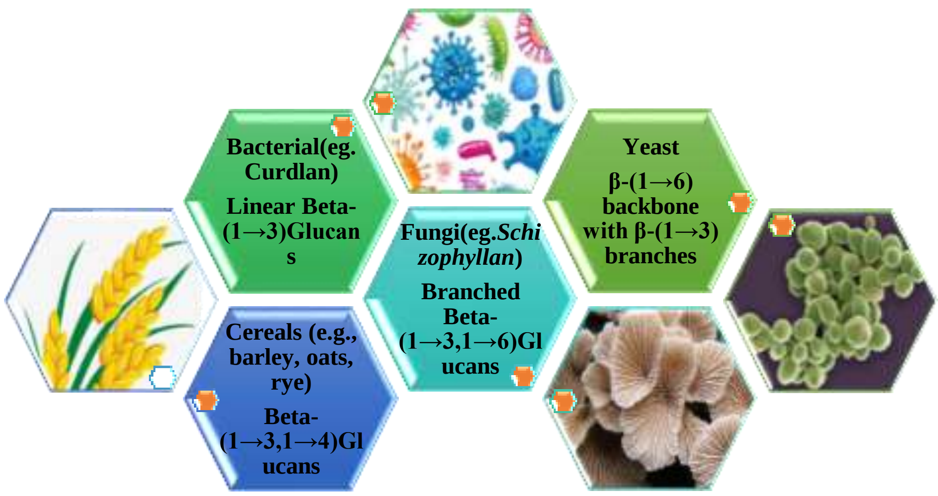

Figure 1: Sources and type of Beta-Glucan

How do plants recognize you so quickly?
Plants have special sensors on their cell surfaces think of them as security guards. These sensors can recognize patterns that don't belong to the plant itself. When I appear, my structure signals that a potential pathogen is nearby. This recognition triggers a chain reaction inside the plant, activating its defense responses.

We often hear about different types of β-glucans. Are all of you the same?

Not exactly! Some of us, like β-(1→3)-glucans, are commonly found in fungal cell walls and are well-known for activating plant immunity. Others, such as β-(1→2)-glucans, also play a role by boosting defensive signals like reactive oxygen species and defense-related genes. Each type contributes differently, but together we help plants stay protected.

Do you interact with specific plant receptors?

Absolutely! I bind to special receptors in plants that act like switches. Once I attach, the plant's defense system turns on. Some receptors are particularly good at recognizing my shape, such as LysM (Lysin Motif), LRR (Leucine-Rich Repeat) proteins, CERK1 is an immunological co-receptor for linear 1,3-β-glucans, and GEBP (β-glucan elicitor-binding protein) allowing plants to respond quickly and effectively. This interaction is like a perfect handshake once it happens, defense responses follow.

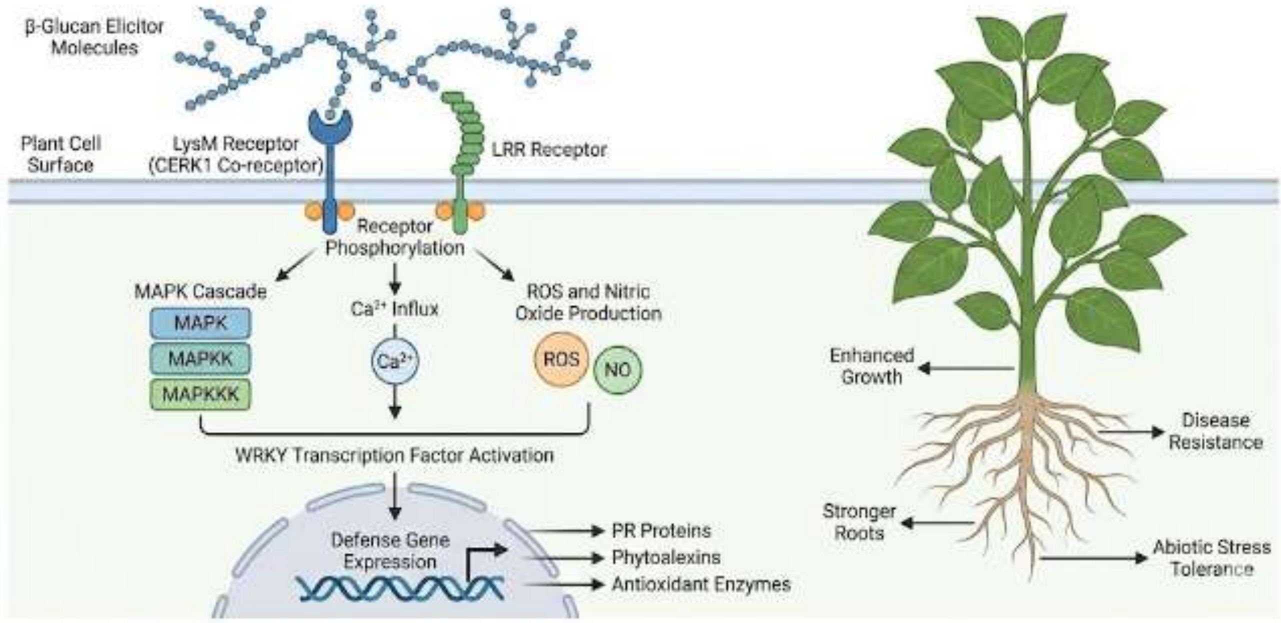

Figure 2 : Mechanism of action of β-glucan

Are you involved in short-term or long-term plant protection?

Both! I can trigger rapid local responses where infected cells sacrifice themselves to stop disease spread. At the same time, I help plants develop systemic acquired resistance, which protects the entire plant for a longer period almost like giving the plant a vaccine.

Does your structure really matter that much?

Oh yes! My shape, branching, and linkages are key to how plants recognize me. Plants have learned to identify these specific patterns as danger signals. The better my structure fits the plant receptor, the stronger the immune response.

Are your talents limited to plants, or do you help others too?

I'm quite famous across kingdoms! In humans, I'm valued for health benefits such as lowering cholesterol, regulating blood sugar, and supporting immunity. In microorganisms, I help strengthen cell walls and improve survival under stress. I like to think of myself as a multitasker.

Do pathogens ever try to escape your detection?

Yes, some pathogens are clever. They produce enzymes that break me down or hide me to avoid being noticed. But plants and I keep evolving. It's an ongoing arms race, and nature is very good at adapting.

What about your future in agriculture?

I see a bright future! Instead of killing pathogens with chemicals, farmers can use me to prime plant immunity naturally. New technologies like nano-formulations may help deliver me more effectively. This approach can reduce chemical use and support sustainable farming.

Any final advice for young scientists and plant researchers?

Work with nature, not against it. By understanding natural defense signals like me, you can design smarter, greener strategies to protect crops. A little curiosity and creativity can go a long way in making plants healthier and agriculture more sustainable.

Conclusion

β-glucan is more than just a carbohydrate it is a natural communicator that strengthens plant defenses and supports sustainable agriculture. By turning complex science into simple stories, we can inspire young minds to appreciate the hidden intelligence of plants and the power of nature-based solutions.

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Bridging the Resilience Knowledge Gap in Agricultural Extension via the Heart-to-Heart Strategy

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Abstract

Global agricultural societies face profound challenges exacerbated by economic instability and climatic shocks. The 'Resilience Knowledge Gap' prevents smallholder farmers from adopting sustainable practices. This article proposes integrating the 'Heart-to-Heart' (H2H) strategy into agricultural extension networks. The H2H model replaces top-down, technocratic mandates with localized, peer-mediated knowledge transfer. Evidence from the Andhra Pradesh Community-Managed Natural Farming (APCNF) initiative and the Campesino-a-Campesino movement demonstrates that this empathetic approach strengthens agricultural supply chains, improves dietary diversity, and fosters ecological sustainability. By systematically bridging the resilience knowledge gap, the H2H strategy ensures robust economic viability and secures enduring human dignity for rural communities.

Introduction

The contemporary global architecture governing agricultural production is highly vulnerable to exogenous shocks. Escalating planetary challenges—ranging from the catastrophic socio-economic ruptures triggered by the COVID-19 pandemic to the increasing frequency of extreme meteorological events—have exposed the 'Resilience Knowledge Gap'. This gap represents a structural and psychological distance between the institutional core, where scientific advancements are generated, and the grassroots periphery, where these advancements must be implemented.

Traditional agricultural extension relies on a "Transfer of Technology" (ToT) model. In this vertical paradigm, knowledge is pushed from urban research centers to rural fields. However, this approach frequently fails due to the "Heterophily Gap," where the perceived social distance between urban-educated experts and rural producers creates a barrier of skepticism. Furthermore, the chronic stress of poverty imposes a "bandwidth tax" on smallholder farmers, making it difficult to process complex, foreign instructions.

To address these systemic failures, the 'Heart-to-Heart' (H2H) strategy offers a transformative socio-technical framework. Originating as a geopolitical tool for fostering deep international cooperation, H2H at the grassroots level emphasizes empathetic, peer-led, and culturally embedded pedagogies. By shifting the focus from information-pushing to empathy-pulling, the strategy bypasses traditional bureaucratic hierarchies and utilizes trusted local facilitators.

Methodology

The H2H Strategy is operationalized using a Process Maturity Method (PMM), which formalizes the intervention into four systematic phases:

1. **Identification of Indigenous Helpers:** Recognizing natural leaders within pre-existing community hierarchies through sociometric mapping. These facilitators serve as primary conduits for localized knowledge transmission.
2. **Micro-Curriculum Standardization:** Distilling complex scientific data into a standardized micro-curriculum optimized for grassroots application. The curriculum prioritizes zero-cost natural farming techniques to reduce external dependencies.
3. **The Family-to-Family Protocol:** Situating the intervention within the domestic sphere to equalize power dynamics between facilitators and participants. This intimate setting restores the cognitive bandwidth consumed by scarcity-driven stress.
4. **Recursive Policy Feedback:** Establishing a bidirectional data nexus that bridges grassroots outcomes with national administrative policy, ensuring that localized successes inform district-level budgetary planning.

Results

The efficacy of the H2H strategy is evident across multiple global case studies, consistently outperforming traditional top-down extension models in technical adoption velocity and economic resilience.

Andhra Pradesh Community-Managed Natural Farming (APCNF)

The APCNF program in southern India represents the largest global transition to agroecology, involving over 630,000 farmers. By employing Community Resource Persons (CRPs) to disseminate knowledge, the program successfully transitioned massive populations away from chemically intensive monocultures. Crop-cutting experiments demonstrate that diversified natural farming plots generate net incomes 20 to 40 percent higher than conventional farms, driven almost entirely by the elimination of expensive synthetic inputs.

Table 1. Agronomic formulation of the Beejamrit biostimulant within the APCNF framework.

Bio-Input Name	PrimaryAgronomic Function	Base Ingredients (per 100 kg of seeds)
Beejamrit	Pre-sowing seed treatment and microbial inoculation	5 kg indigenous cow dung; 5 liters cow urine; 50 gm lime; 20 liters water; 1 handful of local soil.

The Campesino-a-Campesino Movement

During Hurricane Mitch in Central America, the peer-led Campesino-a-Campesino movement demonstrated significant biophysical resilience. Field observations revealed that farms employing sustainable, peer-taught agroecological methods (such as complex multi-cropping and soil conservation) suffered significantly less topsoil erosion and infrastructural damage than conventional neighboring farms.

Nutritional Continuity in Bihar

Longitudinal studies in Bihar, India, illuminated the resilience of peer-supported agricultural networks during the COVID-19 pandemic. Households that engaged in diversified agriculture and maintained active socio-political community contacts exhibited significantly lower rates of nutritional decline, actively maintaining dietary diversity despite severe supply chain disruptions.

Conclusion

The 'Resilience Knowledge Gap' exposes global food systems to catastrophic failures. Bridging this chasm requires abandoning purely technocratic extension models in favor of the empathetic, peer-driven Heart-to-Heart strategy. By leveraging the deep social capital of smallholder networks, initiatives like APCNF and Campesino-a-Campesino catalyse massive transitions toward agroecological stability. Standardising this grassroots model and formally integrating it into national policy frameworks transforms social capital into a high-yield economic asset. Ultimately, the H2H Strategy reconfigures the structural relationship between institutional science and grassroots realities, providing a validated roadmap for permanent societal transformation and ecological sustainability.

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Between Rocks and Clouds: Exploring the Living Ecology of Horsley Hills

Introduction

Rising gently from the dry plains of southern Andhra Pradesh, Horsley Hills near Madanapalle form one of the most ecologically distinctive hill systems of the Eastern Ghats. High above the surrounding plains, Horsley Hills stands a quiet refuge where climate, terrain and living systems meet in subtle but fascinating ways. What appears at first to be a simple hill station is, in reality, a layered ecological space shaped by altitude, weather and time. The shift from the dry, warmer lowlands to the cooler hilltop creates conditions that allow a variety of plants and animals to coexist, each responding differently to change in moisture, temperature and soil. The landscape is marked by exposed rock surfaces, scattered, scattered vegetation and seasonal mist that rolls across the slopes. These features are not just scenic they influence how life is distributed across the hills. Certain plant species take root in shallow soils over rocks, while others thrive in sheltered pockets where moisture lingers longer. Similarly, birds, insects and small animals make use of these varied niches, forming a network of interaction that sustain the ecosystem. Despite its ecological richness, Horsley Hills has received limited attention in popular environmental writing. Exploring this landscape offers an opportunity to understand how delicate ecological balance is maintained in such transitional environments and why these lesser known hill ecosystems deserve closer observation and care.

Forest trail of Horsley Hills showing dry deciduous vegetation interspersed with rocky outcrops

A meeting point of climate and vegetation

Situated at elevations of roughly 1200-1300 meters above mean sea level, Horsley Hills experience milder temperatures and higher humidity than the surrounding plateau. This altitudinal advantage, combined with undulating terrain and rocky substrates has given to a mosaic vegetation types. Dry deciduous forests dominate much of the landscape, interspersed with scrub, grassland and small moist pockets along shaded slopes and valleys.

Near roads and habitations, plantation species as eucalyptus and silver oak are common, reflecting historical management and tourism development. However, as the trek moved away from these areas, native forest elements became increasingly evident, revealing the original ecological character of the hills.

The structure and stability of forest trees

The forests of Horsley Hills are supported by a diverse assemblage of dry deciduous tree species adapted to seasonal rainfall and shallow soils. Genera such as *Terminalia, Anogeissus, Albizia, Dalbergia, Diospyros*, *Cassia*, *Shorea* and *Ficus* form the backbone of the forest. These trees provide shade, regulate microclimate, stabilize slopes and sustain a wide range of associated flora and fauna.

Field observations during the trek recorded several ecologically and culturally important tree species. These include ivory wood (*Wrightia tinctoria*) and *Wrightia arborea*, both valued for their medicinal properties and durable timber, peacock chaste tree (*Vitex altissima*) and five leaved chaste tree (*Vitex negundo*), commonly associated with traditional medicine and roxburgh sal (*Shorea roxburghii*), a characteristic species of dry species of dry deciduous forests of the Eastern Ghats. Other notable trees encountered were scarlet sterculia (*Firmiana colorata*), locally recognized for its striking seasonal flowering, the yellow silk cotton tree (*Cochlospermum religiosum*), often conspicuous on rocky slopes during the dry season, jamun (*Syzygium cumini*), providing food for birds and mammals and bamboo, which plays a key role in slope stabilization and supports rural livelihoods. Large individuals of fig trees (*Ficus spp.*) were also observed, acting as keystone species by sustaining birds, insects and mammals across seasons. During the trek, local villagers identified many of these trees through their practical value, timber for agricultural tools, bark and leaves for medicine, fruits for food and shade for livestock. For students, this interaction highlighted an important ecological truth, forests here are not isolated wilderness but working systems shaped by long term human association.

Orchids are the subtle indicators of forest health

Among the most fascinating components of Horsley Hills are its orchids, plants that demand attention through patience rather than display. Although small in number compared to some Western Ghats regions, the orchids diversity of Horsley Hills is ecologically significant because of the highly specific habitats these plants require. Both terrestrial and epiphytic orchids occur in the hills. Terrestrial species of *Habenaria* emerge briefly during the monsoon from grassy and rocky parches, while epiphytic orchids inhabit tree trunks and branches, relying on atmospheric moisture and stable forest conditions. Students observed that orchids were often restricted to very small patches, absent even a short distance away, underscoring their sensitivity to microhabitat variation.

***Diplocentrum recurvum*: A Rediscovered Presence** (Mahendranath *et al*., 2015)

Orchid (*Diplocentrum recurvum*)

One orchid in particular gives Horsley Hills a special place in the botanical history of Andhra Pradesh. *Diplocentrum recurvum*, an epiphytic orchid once known only from old historical collections, was rediscovered in these hills after nearly a century. Growing on mature tree trunks in open dry deciduous forests, the species is characterized by leathery, recurved leaves and long arching inflorescences bearing numerous small pinkish purple flowers. Field observations indicate that this orchid is largely confined to elevations around 1200 to 1250 metres, making it especially vulnerable to changes in forest structure and microclimate. Its continued survival depends on the presence of old host trees and relatively undisturbed conditions, making it a quiet but powerful indicator of ecosystem stability.

Orchids and traditional knowledge

Beyond their ecological value, orchids of the Eastern Ghats hold an important place in traditional knowledge systems. Ethnobotanical studies Andhra Pradesh document the use of several orchid species by indigenous communities such as the chenchus, koyas, konda reddies, valmikis, banjaras and gonds. Tubers, roots, stems and leaves have traditionally been used in remedies for wounds, fevers, digestive disorders, bone fractures and veterinary ailments.

While such uses are now less common in areas with access to modern healthcare, discussions with villagers during the trek revealed that this knowledge still survives, particularly among elders. These practices reflect generations of careful observation of plant properties, seasons and sustainable harvesting methods. Importantly, they also underline the need for conservation, as many medicinal orchids are highly sensitive to over collection and habitat disturbance.

Horsley Hills in the Wider Eastern Ghats Context

Arjuna tree (*Terminalia arjuna*)

Dyers rottlers (*Mallotus philippensis*)

Peacock chaste tree (*Vitex altissima*)

Donkeyberries (*Grewia glandulosa*)

When viewed alongside nearby hill systems such as the Seshachalam Biosphere Researve, Horsley Hills represents a smaller but ecologically valuable component of the Eastern Ghats orchid landscape. Studies from the region show that genera such as *Habenaria, Eulophia, Vanda, Bulbophyllum and Cleisostoma* are characteristic of these hill ranges, each responding differently to altitude, moisture and forest type. This regional perspective helps place Horsley Hills in context, not as an isolated pocket, but as part of connected chain of habitats that collectively sustain Eastern Ghats biodiversity.

A Living Classroom on the Trail

The trek itself became a shared learning experience. For agriculture students, concepts such as habitat specificity, human forest interaction and conservation moved beyond textbooks into real landscapes. For villagers, conversations about orchids and forest plants brought renewed attention to familiar species whose ecological importance is often overlooked. Such interactions demonstrate the value of field based education in fostering respect for both scientific knowledge and local experience.

Pressures and the Path Ahead

Despite its ecological richness, Horsley Hills faces increasing pressure from grazing, fuelwood extraction, plantation expansion, tourism infrastructure and changing climate patterns. Orchids and medicinal plants, because of their narrow ecological requirements are often the first to decline under such pressures.

During trek - learning biodiversity through direct observation

Conservation here does not demand strict exclusion but thoughtful balance, protecting sensitive habitats while recognizing local dependence on forest resources. Awareness, guided tourism and community involvement are crucial to ensuring that ecological integrity is maintained.

Quiet Forests, Enduring Value

Horsley Hills may be widely known for pleasant weather and panoramic views, but their deeper value lies in quieter details. An orchid flowering briefly on a tree trunk, a medicinal herb growing unnoticed beside a trail and a forest shaped by both natural processes and human memory. Walking these hills makes one thing clear, Horsely Hills are not merely a destination. They are a living archive of Eastern Ghats biodiversity and traditional knowledge. Preserving them means walking gently, observing closely and ensuring that these subtle stories continue to be told.

Additional Field Observations from the Trek

The trek also offered several memorable encounters that enriched our understanding of Horsley Hills as a biologically diverse and functionally complex ecosystem. Along moist stream edges and well drained slopes, we observed mature individuals of the Arjuna tree (*Terminalia arjuna*), easily recognised by its smooth, pale bark. Although commonly associated with riverbanks in peninsular India, its presence here highlights the availability of seasonal moisture and relatively undisturbed niches within the hills.

Caralluma sp.

In contrast, exposed rocky patches supported succulent species of the genus *Caralluma*, adapted to harsh conditions through water storing tissues and reduced leaves. These plants illustrated how life persisted even in nutrient poor substrates, making efficient use of limited resources. One of the most striking sightings for students was the sundew (*Drosera sp.*), a small insectivorous plant growing in moist, open patches. Its sticky, glandular leaves trapping insects provided a vivid example of evolutionary adaptation to nutrient deficient soils, turning the forest floor into a living lesson in plant ecology.

Peacock's tail fern

Scattered along forest paths and clearings, the bright reddish powder coating the fruit of dyers rottlers (*Mallotus philippensis*) drew attention. Villagers explained its traditional use as a natural dye and in medicinal preparations, reinforcing the close link between forest plants and rural livelihood. Tall trees of peacock chaste tree (*Vitex altissima*) were observed forming part of the upper canopy in mature forest patches, contributing shade and structural diversity. Under their canopy, delicate fronds of the peacock's tail fern (*Actiniopteris radiate*) emerged from rock crevices, especially after recent moisture, demonstrating the importance of microhabits even with dry deciduous systems.

Sundew (*Drosera sp.*)

Giant honey bee (*Apis dorsata*).

Shrubby species such as lavender star flower or donkeyberries (*Grewia glandulosa*) were noted along forest edges and open slopes, providing forage for wildlife and adding to the shrub layer diversity that supports insects and birds. Adding a dynamic faunal dimensions to these plant observations was the presence of the giant honey bee (*Apis dorsata*). Large, exposed combs seen on tall trees served as a reminder of the ecological services forests provide. These bees play a crucial role in pollination, linking tree canopies, shrubs and orchids into a single functional network. Together, these observations reinforced an important message for students and villager's alike biodiversity in Horsley Hills is not confined to rare species alone, but expressed through everyday interactions between plants, insects, terrain and people.

Conclusion

Horsley Hills of Madanapalle represents a finely balanced Eastern Ghats landscape shaped by altitude, climate and long association with people. Dry deciduous forests dominated by *Terminalia*, *Shorea*, *Vitex*, *Wrightia*, bamboo and figs provide ecological stability, while orchids such as *Diplocentrum recurvum* reflect the sensitivity of these habitats. Species adapted to rocks and seasonal moisture, along with pollinators like the giant honey bee (*Apis dorsata*), together sustain a functioning forest system. Equally significant is the traditional knowledge of local communities, which complements scientific understanding and highlights responsible use of forest resources. As tourism and land use pressures grow, the future of Horsley Hills depends on careful observation, informed management and shared stewardship. Preserving this landscape ensures that its biodiversity and ecological lessons remain intact for generations to come.

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Non-Monetary Returns from Crop Production: The Hidden Benefits of Farming

When we think about crop production, the first thing that usually comes to mind is economic return, the income farmers earn by selling food, fiber or fuel crops. However, agriculture provides many benefits that are not measured in money. These are known as non-monetary returns, and they play a crucial role in sustaining ecosystems, supporting human well-being and maintaining environmental balance.

Most of these non-monetary benefits are part of what scientists call ecosystem services, the direct and indirect advantages that nature provides to people. Crop production contributes to all four major categories of ecosystem services: provisioning, regulating, supporting, and cultural services. While provisioning services such as food, fiber and fuel generate monetary returns, the regulating, supporting and cultural services represent the non-monetary returns of agriculture. These benefits may not appear in a farmer's income statement, but they are essential for long-term sustainability. Broadly, the non-monetary returns from crop production can be grouped into regulating services, supporting services and cultural services.

1. Regulating Services

Regulating services are natural processes that help maintain environmental balance. Through crop cultivation, agricultural ecosystems help regulate climate, control erosion, manage pests and diseases and prevent natural hazards.

- **Carbon Sequestration and Climate Regulation**

One of the most important environmental contributions of crop production is carbon sequestration, the process of capturing and storing carbon dioxide (CO_2) from the atmosphere.

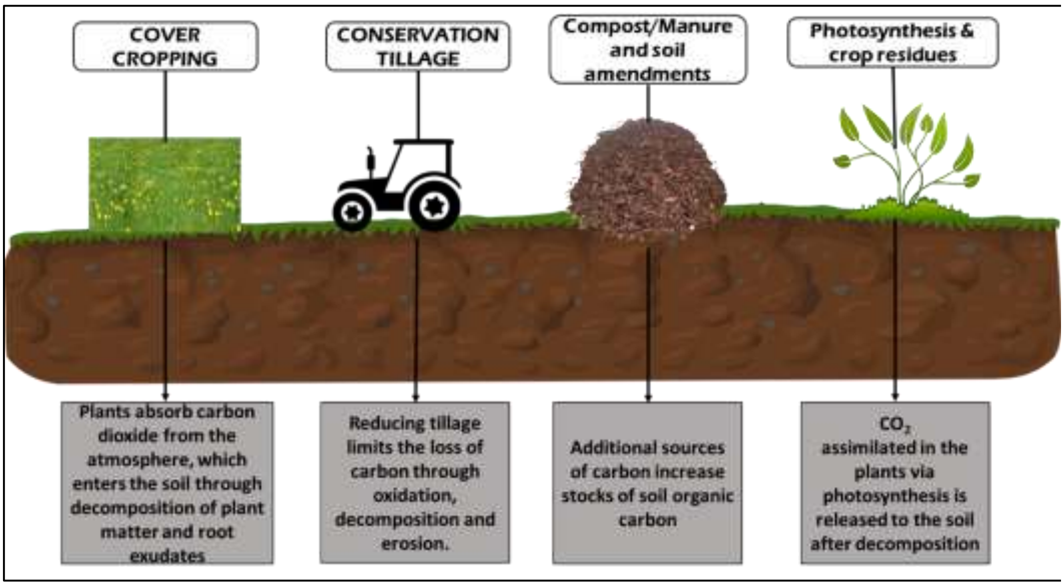

Figure 1: Different ways of carbon sequestration on crop lands

During photosynthesis, plants absorb CO_2 and convert it into glucose. Some of this carbon becomes part of plant tissues, while a significant portion is stored in the soil as soil organic carbon (SOC). Plant residues, roots, and root exudates add organic matter to the soil, increasing its ability to store carbon. By trapping carbon in plant biomass and soil, crop production helps reduce greenhouse gases and mitigate climate change.

♦ **Prevention of Soil Erosion**

Crop plants act as a natural protective layer for the soil. Their roots bind soil particles together, preventing them from being washed away by rain or wind. Plants reduce soil erosion in several ways:

- Roots hold the soil firmly in place.
- Plant stems slow down the flow of water, reducing runoff velocity.
- Leaves and crop canopy reduce the impact of raindrops hitting the soil surface.

Because of these protective mechanisms, fields covered with crops experience significantly less soil erosion than bare land.

♦ **Maintenance of Soil Fertility**

Soil fertility refers to the soil's natural ability to provide nutrients to plants in adequate and balanced amounts. Crop plants contribute to soil fertility through several processes:

- Roots release root exudates - organic compounds that help dissolve nutrients in the soil.
- These compounds also serve as food for beneficial microorganisms.
- After harvest, crop residues remain in the soil and are decomposed by microorganisms and earthworms.

Through these processes, nutrients are gradually returned to the soil, improving soil fertility and sustaining future crop growth.

♦ **Maintenance of Biodiversity**

Crop fields support a wide range of organisms, including insects, microorganisms, birds, and soil fauna. These organisms contribute to the biological balance of agricultural ecosystems. For example:

- Ladybird beetles prey on aphids and help control pest populations.
- *Trichogramma chilonis*, an egg parasitoid, helps control pests like fall armyworm.
- Soil fungi such as *Trichoderma*, *Aspergillus*, and *Penicillium* act as biological control agents against several plant diseases.

Thus, crop production indirectly supports beneficial organisms that help maintain ecological balance.

♦ **Water Regulation and Prevention of Natural Hazards**

Vegetation plays a key role in regulating water movement across landscapes. Crop plants slow down runoff water and reduce its volume and speed. This helps in improve water infiltration into the soil, reduce flooding risks and minimize water-related natural hazards. Therefore, cultivated fields can contribute to better water management and flood prevention.

2. Supporting Services

Supporting services are fundamental ecological processes that make other ecosystem services possible. Crop production supports several key processes such as nutrient cycling, soil formation, oxygen production, water cycling, and habitat creation.

♦ **Nutrient Cycling**

Nutrient cycling is the continuous movement of nutrients between living organisms and the environment. In crop ecosystems:

- Plants absorb nutrients from the soil.
- When plants die or residues remain after harvest, decomposers break them down.
- Nutrients are released back into the soil in inorganic form.
- These nutrients are again taken up by plants.

Through this cycle, nutrients continuously move between soil, plants, animals, and the atmosphere, ensuring the sustainability of agricultural ecosystems.

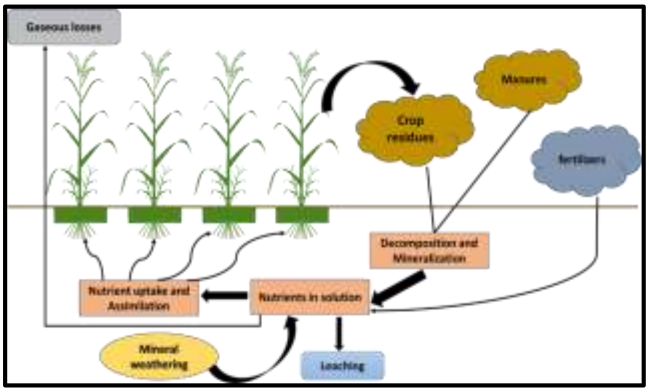

Figure 2: Nutrient cycling

◆ **Soil Formation**

Crop plants also contribute to soil formation and development through several mechanisms.

- Physical weathering: Plant roots penetrate cracks in rocks and break them into smaller particles.
- Chemical weathering: Roots release organic acids that dissolve minerals and accelerate chemical breakdown.
- Addition of organic matter: Dead plant materials decompose and enrich the soil with organic matter.
- Soil profile development: Plant activity gradually leads to the formation of distinct soil layers.
- Microbial influence: Plants interact with soil microorganisms, shaping the soil's biological community.

Together, these processes gradually transform raw geological material into fertile agricultural soil.

◆ **Production of Oxygen**

Crop plants also contribute to atmospheric balance by producing oxygen. During photosynthesis, plants absorb carbon dioxide and water, using sunlight to produce sugars. In this process, water molecules split in a reaction called photolysis, releasing oxygen as a by-product. Thus, agricultural crops play a role in maintaining the oxygen supply necessary for life on Earth.

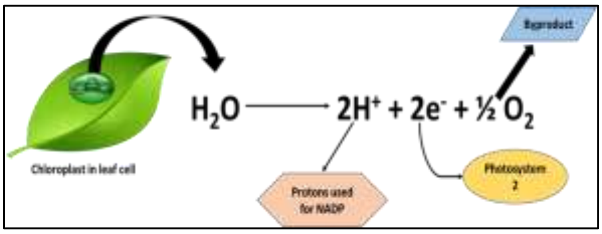

Figure 3: Photolysis of water

◆ **Water Cycling**

Plants play an important role in the water cycle through a process known as transpiration. In transpiration, water absorbed by plant roots moves to the leaves. Some of this water evaporates from leaf surfaces into the atmosphere. It is estimated that around 10% of water entering the atmosphere comes from plant transpiration. This process contributes to atmospheric moisture and influences rainfall patterns.

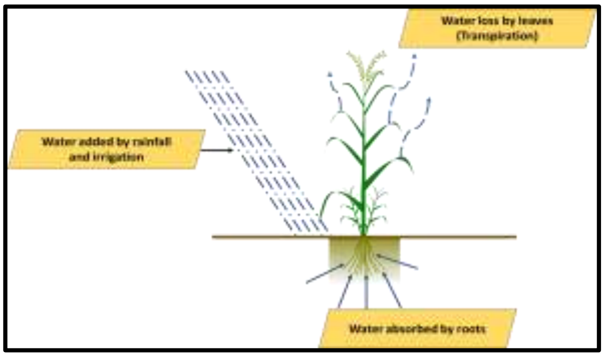

Figure 4: Water cycling

◆ **Habitat for Species**

Crop fields provide food, shelter, and nesting sites for many organisms. Insects, birds, and small animals often depend on agricultural landscapes for survival. Biodiversity within crop ecosystems enhances agricultural productivity by improving pollination and natural pest control. Practices such as agroforestry, where perennial trees are integrated into farmland, further enhance habitat availability for beneficial species. Similarly, sustainable farming practices like, reduced soil disturbance, maintaining crop residues as mulch, growing cover crops help increase biological diversity and ecological activity within the production system.

3. Cultural Services

In addition to ecological benefits, crop production also provides cultural and social value. These cultural services enrich human life through recreation, aesthetics, and connection with nature.

♦ **Agritourism**

Agritourism combines traditional farming with tourism, allowing visitors to experience rural life and learn about agriculture. Visitors to agritourism farms can, observe farming activities, participate in planting and harvesting, learn about crop cultivation and understand sustainable agriculture practices. Agritourism not only provides educational experiences but also helps people appreciate the hard work behind food production.

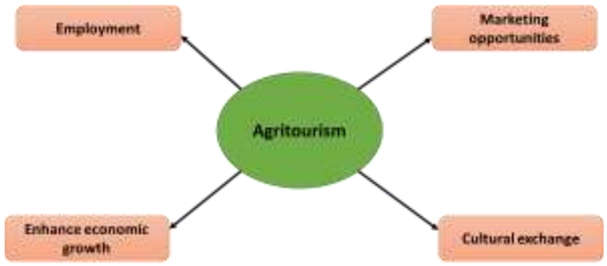

Figure 5: Benefits of Agritourism

♦ **Aesthetic Value of Agricultural Landscapes**

Agricultural landscapes often offer beautiful and inspiring scenery. Well-managed crop fields create, open rural spaces, lush green landscapes, vibrant seasonal crop colors and organized field patterns. These landscapes contribute to visual beauty, cultural identity, and emotional well-being. People often feel a deeper connection with nature when surrounded by fertile fields and thriving crops.

Conclusion

Crop production is far more than an economic activity. Beyond generating food and income, agriculture provides a wide range of non-monetary benefits that support environmental health, ecological balance, and human well-being. Through regulating services such as climate control and erosion prevention, supporting services like nutrient cycling and soil formation, and cultural services such as agritourism and aesthetic landscapes, crop production plays a vital role in sustaining life on Earth. Recognizing and valuing these hidden benefits is essential for promoting sustainable agriculture and responsible environmental management in the future.

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Nematodes in Citrus Crops: Identification, Diagnosis and Integrated Management

Introduction

The citrus family, including sweet oranges, mandarin, kinnow, lemon, lime, grapefruit, and sweet lime, ranks among the most valuable and nutritious fruits produced in India. The production of citrus fruits takes place on a large scale in various Indian states like Maharashtra, Punjab, Rajasthan, Andhra Pradesh, Telangana, Karnataka, Madhya Pradesh, and Uttar Pradesh. These fruits are very nutritious, rich in vitamin C, minerals, flavonoids, antioxidants, and fibre content. Hence, the cultivation of citrus fruits provides significant economic benefits to farmers owing to their growing demands in domestic and international markets. However, the productivity of citrus fruits gets severely impacted due to the presence of various biotic and abiotic stresses. Biotically, plant-parasitic nematodes are regarded as one of the most destructive hidden pests of citrus orchards. These soil-borne pathogens affect plant roots and reduce water and nutrient uptake, leading to poor plant health and yield loss.

Nematodes are tiny worm-like organisms without any body segments, usually cylindrical and microscopic in size. Most of these worms are harmless, even beneficial in improving soil nutrients. However, there are a few species that are plant parasites and pose severe economic threats to plants. The distinguishing feature of nematodes is the presence of a needle-like organ in their mouth called stylet, through which they puncture cells and obtain nutrition from plants.

In citrus orchards, the citrus nematode (*Tylenchulus semipenetrans*) and sheath nematode (*Hemicycliophora* spp.) are the two most devastating plant parasites. These nematodes cause harm to the roots and reduce nutrient uptake from the soil, leading to yellowing of leaves, growth stunting, death of branches, and reduction in yield and fruit quality.

Major symptoms of nematode infestation in Citrus:

Figure 1. Citrus roots heavily infected by citrus nematode

Figure 2. Yellowing and stunted growth in citrus plants:

Fig. 2 Affected plants show chlorosis, poor canopy development, sparse foliage, and reduced vegetative growth due to impaired root function.

Figure 3. Microscopic view of plant-parasitic nematodes:

Fig. 3 Under the microscope, swollen female & nematodes appear slender and thread-like with a distinct stylet used for feeding on plant tissues.

Commonly occurring nematodes of Citrus crops

1. Citrus nematode (*Tylenchulus semipenetrans*)

The citrus nematode is the most prevalent and economically significant plant-parasitic nematode that infects citrus crops in various parts of the world. This nematode is present in virtually all citrus production areas and tolerates a variety of soil conditions. Apart from citrus plants, this nematode can attack grapevines, olives, persimmon, and trifoliate oranges. This nematode is considered semi-endoparasitic since the female adult nematode penetrates the root tissues partially while the rear portion of the body remains outside the root. Feeding activity of the nematode affects root development adversely and hinders the uptake of nutrients and water by the plant.

Life cycle

The life cycle of *Tylenchulus semipenetrans* involves an egg stage, four juvenile stages, and adult male and female individuals. Second-stage juvenile (J2) is the infective stage. Adult male nematodes have vermiform shape, do not feed and normally do not enter the roots. Female juveniles enter the feeder roots and establish permanent feeding sites.

An adult female lay about 100 eggs encased in a gelatinous coat that protects them from unfavourable environmental conditions. At temperatures ranging from 20 to 30 degrees Celsius, the life cycle is completed within 4 to 8 weeks. Population density increases during spring and fall when root growth is vigorous.

The disease caused by infection by this nematode is referred to as **"*Citrus Slow Decline*."** The disease develops slowly and may remain undetected for many years.

2. Sheath nematode (*Hemicycliophora* spp.)

Sheath nematodes are less prevalent compared to citrus nematodes but have a wide host range. These nematodes are distinguished by having an additional cuticular sheath covering their body. These nematodes are usually found in sandy soils.

Sheath nematodes feed near root tips and lateral roots in the meristematic zone. Root feeding results in the formation of galls in the root system, causing poor root development. Young citrus plants are especially susceptible to sheath nematodes.

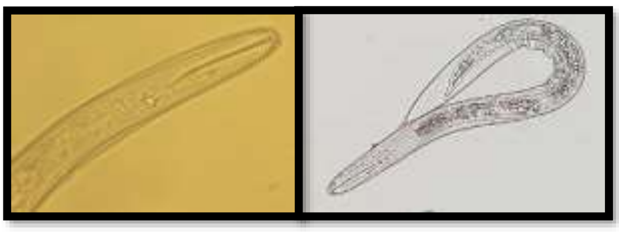


Figure 4. Microscopic view of Sheath nematode

Damage and symptoms of nematodes

Infestation with nematodes in citrus orchards may take place gradually, and sometimes, symptoms are not visible initially. With the progress of infestation, plants start showing signs of decline and poor productivity.

Symptoms above-ground:

- Dwarfism in plants
- Yellowing of leaves
- Leaf curling and leaf size reduction
- Sparse foliage
- Branched death
- Tiny fruit sizes
- Poor fruit yield and quality
- Symptoms resembling nutrient deficiencies

Symptoms below-ground:

- Destruction of feeder roots
- Slow growth in roots
- Swelling and darkening of roots
- Particles of soil clinging to roots
- The formation of swellings/galls on roots
- Limited branching of roots

Plants suffering from nematodes are more prone to secondary infections from fungi, bacteria, and other pathogens. Also, the effects of environmental stress such as drought, salt stress, water logging, and cold injury become more pronounced in infected orchards.

Diagnosis and identification

Accurate identification of nematode infection is very important in their management in citrus plants. Identification based on above-ground symptoms is not always reliable because other factors such as nutrient deficiencies and root diseases may cause similar symptoms. For accurate identification, laboratory tests need to be performed.

Indications of nematode infestation in the field

1. Ununiform growth of plants in the orchard
2. Weakness and decline in trees
3. Deficient root growth
4. Sparse occurrence of feeder roots
5. Continued poor plant vigor despite efficient management

Soil and root sampling procedures

Before planting

- Divide the orchard into sampling blocks according to soil texture and drainage.
- Collect 10-20 sub-samples from each block.

In existing orchards

- Collect soil and root samples from the drip line area of the affected plants.
- From drip irrigated orchards, take samples around the emitter area having dense feeder roots.
- Take comparative samples from apparently healthy plants.

Recommended sampling depth

- Up to 60 cm in loamy soil
- Up to 90 cm in sandy soil

Precautions during sampling

- Avoid taking samples from excessively dry or wet areas.
- Use plastic bags with labels for sample storage.
- Protect samples from direct sunlight.
- Submit samples to the lab as soon as possible.
- In case of delay, keep samples in cold conditions.

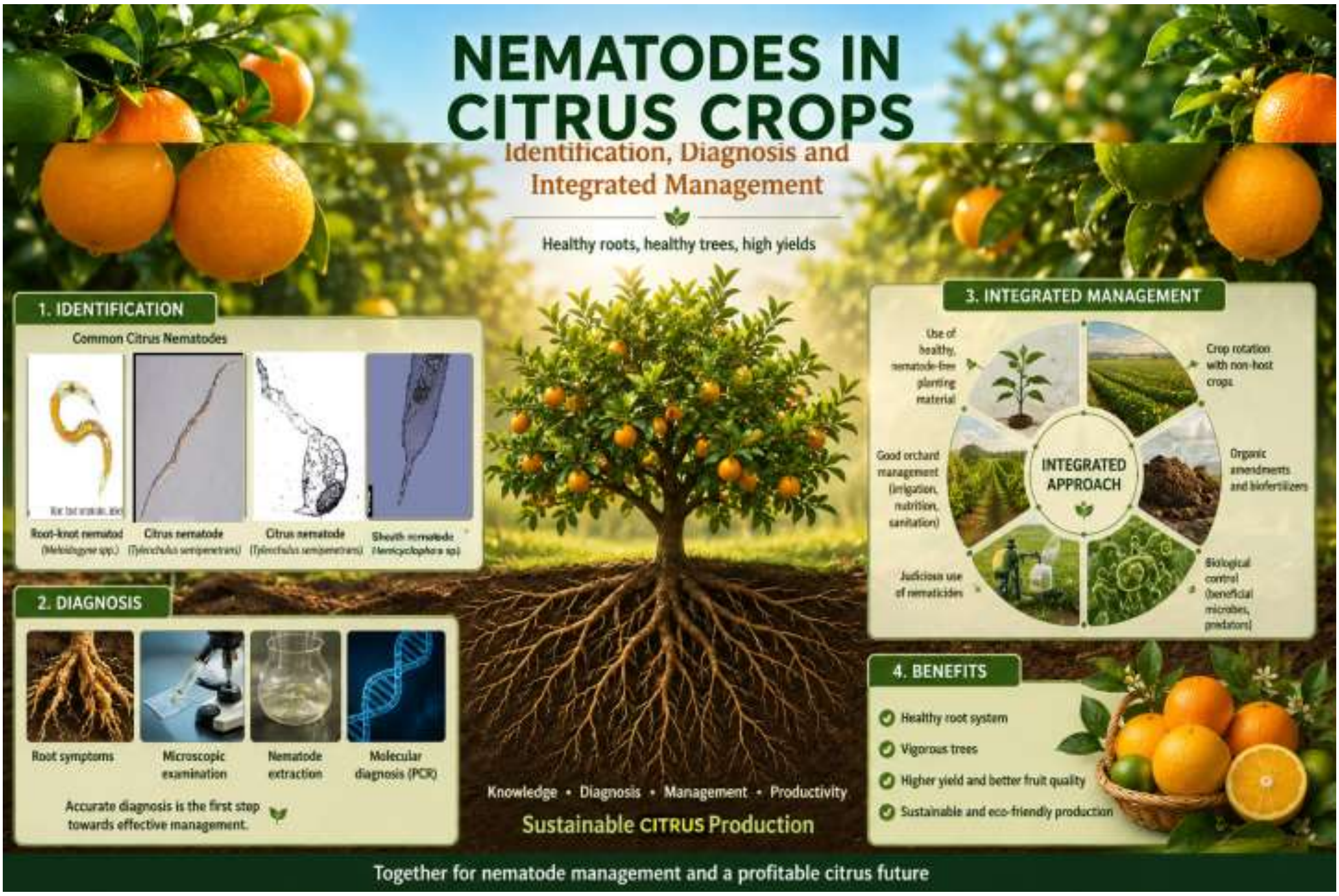
Laboratory analysis

Nematodes are extracted from soil and root samples collected from the field using techniques like Baermann funnel, floatation, and elutriation. The number of juveniles in soil and adult females on roots indicates the severity of infestation. Higher population density of nematodes usually implies high risks of yield reduction and orchard decline.

Integrated nematode management in Citrus

Management of nematodes in citrus requires an integrated approach comprising prevention, biological, cultural, and chemical means. It would not be economically and environmentally sustainable to rely only on chemical nematicides.

1. **Sanitation and prevention**
    - Use healthy and nematode-free planting material.
    - Prevent movement of infested soil from infected orchards.
    - Prevent spread of nematodes via irrigation water.
    - Clean agricultural implements regularly.
    - Maintain orchard hygiene and proper drainage.



2. Crop rotation

Before re-planting, use annual non-host crops for 1-3 years. This helps in reducing nematode population in soil.

3. Resistance/tolerance to rootstocks

Use of resistant/tolerant rootstocks is the most effective management strategy in the long run.

Amongst various rootstocks, trifoliate orange and its hybrids are comparatively tolerant to citrus nematodes. They also offer tolerance to Phytophthora and tristeza virus.

4. Biological control

Biological control of nematodes is a sustainable way of suppressing nematode populations.

Biocontrol agents of Nematodes

- *Purpureocillium lilacinum*
- *Pochonia chlamydosporia*
- *Trichoderma* spp.
- *Bacillus subtilis*

These biocontrol agents feed on nematode eggs and juveniles, inhibit nematode multiplication, and improve soil microbial community.

5. Organic amendments

Organic matter application improves soil fertility and reduces nematode populations.

Popular organic amendments

- Neem cake
- Mustard cake
- Vermicompost
- Decomposed farmyard manure
- Mahua cake

Organic amendments improve the health of soil and its microbes.

6. Chemical control:

In case of heavy nematode infestations, chemical nematicides may be applied selectively.

Common nematicides

- Velum Prime

- Phorate
- Carbofuran
- Fluensulfone
- Oxamyl

Chemical nematicides must be applied in accordance with the recommendations of agricultural scientists and regulatory agencies. Overuse or misuse of nematicides may cause harmful effects on human health, beneficial organisms, and the environment.

Recommendations for integrated nematode management

1. Use nematode-free planting material.
2. Regular monitoring of orchards.
3. Conduct periodic soil and root testing.
4. Use biological and organic management options.
5. Use resistant/tolerant rootstocks.
6. Apply chemicals only if necessary.
7. Practice balanced fertilization and irrigation.
8. Prevent waterlogging and poor drainage.

Conclusion

Plant-parasitic nematodes are increasingly becoming serious hidden pests in citrus orchards. Through damage to feeder roots, they inhibit nutrient absorption and eventually weaken plants, resulting in poor growth, lower productivity, and poor fruit quality. Early symptoms are usually difficult to identify; hence, regular monitoring and laboratory identification are important.

Through integrated management comprising use of clean planting material, resistant rootstocks, biological control agents, organic amendments, and balanced crop management, nematode damage can be minimized in citrus orchards. Not only does it improve citrus productivity and fruit quality, but also maintains soil health and sustainability. With coordinated efforts from researchers, extension officers, and farmers, nematode management will contribute greatly to profitable and sustainable cultivation of citrus in India.

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Eco-Physiological Influences on Growth and Development of Fruit Crops

Introduction

Fruit crop growth and development are heavily regulated by eco-physiological elements such as light, temperature, water, nutrition and carbon dioxide (CO_2). These variables regulate critical physiological processes like photosynthesis, respiration, transpiration, flowering, fruit set and maturation. Proper interaction among these environmental components provides optimum development, productivity and fruit quality. However, changes induced by climate change may adversely affect crop productivity (Haokip *et al*., 2020). Understanding these factors is vital for creating effective management techniques and improving sustainable fruit production systems under changing environmental conditions (Ameen *et al*., 2023).

Effect of Light on Fruit Crop Growth

Light plays a vital role in the growth and development of fruit crops as it provides energy for photosynthesis. It influences important physiological processes such as chlorophyll formation, flowering, fruit set, transpiration and fruit quality. Adequate light promotes healthy vegetative growth, better canopy development and improved fruit coloration. In crops like apple and grape, sufficient light enhances anthocyanin synthesis, resulting in attractive fruit color. On the other hand, low light reduces photosynthesis, leading to poor flowering, low yield and inferior fruit quality. Excessive light may also cause sunburn injury in sensitive fruits. Therefore, proper orchard management practices such as pruning, training and optimum spacing are necessary to ensure efficient light distribution and maximum productivity (Lal *et al*., 2018).

Table 1. Major Eco-Physiological Factors Affecting Fruit Crops (Choudhary *et al*., 2018)

S. No.	Factor	Major Role	Effect on Fruit Crops
1.	Light	Photosynthesis	Flowering, fruit color, yield
2.	Temperature	Metabolic regulation	Fruit set, ripening
3.	Water	Nutrient transport	Fruit size, quality
4.	Nutrients	Plant growth	Yield and fruit development
5.	CO2	Carbohydrate synthesis	Biomass and productivity

Effect of Temperature on Fruit Crop Development

Temperature is an important environmental factor affecting the growth, development and productivity of fruit crops (Singh *et al*., 2020). It regulates physiological and biochemical processes such as photosynthesis, respiration, flowering, fruit set and ripening. Each fruit crop requires a specific temperature range for optimum growth. Favorable temperature promotes vegetative growth, root development and nutrient uptake, while also improving fruit size, color and sweetness rate fruits like apple and pear require chilling for dormancy breaking, whereas tropical fruits such as mango and banana perform well under warm conditions.

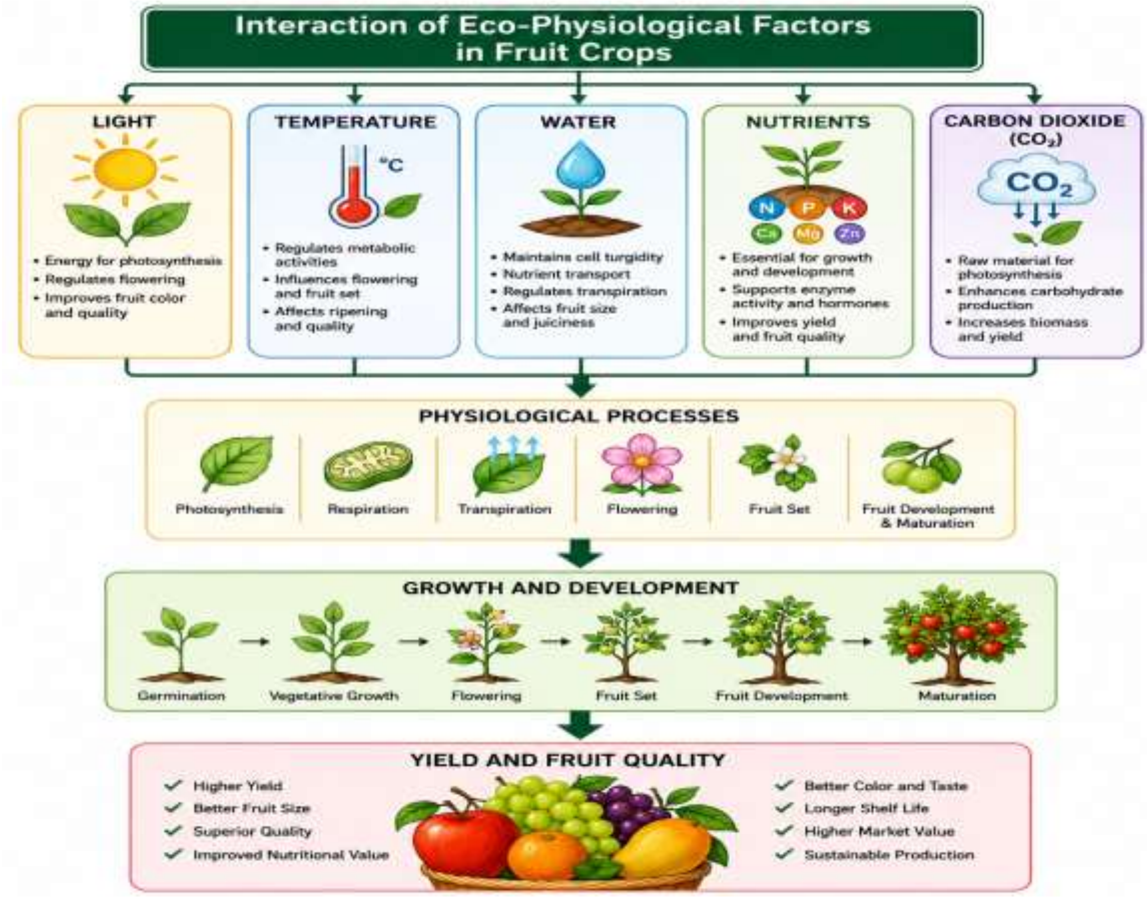


Fig. 1. Interaction of Eco-physiological factor in fruit crops (Fischer *et al*., 2016)

Extremely high temperatures may cause flower drop, sunburn, water stress and poor fruit set, while low temperatures can lead to frost injury, delayed flowering and reduced fruit development (Rane and Jangid, 2024; Tandel *et al*., 2025). Therefore, proper temperature management through mulching, protected cultivation and suitable orchard practices is essential for obtaining better yield and fruit quality.

Influence of Nutrients on Fruit Crop Growth and Development

Nutrients are essential for the proper growth, development and productivity of fruit crops. They play an important role in physiological and biochemical processes such as photosynthesis, respiration, flowering, fruit set and fruit development (Sharma *et al*., 2024). Fruit crops require both macronutrients and micronutrients for healthy growth.

Macronutrients like nitrogen, phosphorus and potassium are needed in larger amounts, where nitrogen promotes vegetative growth, phosphorus supports root development and flowering, and potassium improves fruit quality, size and stress tolerance. Secondary nutrients and micronutrients are also necessary for enzyme activity, chlorophyll formation and reproductive growth (Singh *et al*., 2022). Deficiency of nutrients leads to poor growth, low yield, fruit drop and inferior fruit quality, while excessive nutrient application may create toxicity and nutrient imbalance. Therefore, balanced nutrient management through proper fertilizer application, organic manures and soil testing is essential for sustainable fruit production and better crop performance (Bhardwaj *et al*., 2024).

Role of Water in Fruit Crop Physiology

Water is a vital eco-physiological factor required for the growth and development of fruit crops. It plays an important role in photosynthesis, nutrient transport, transpiration and other metabolic activities. Adequate water availability maintains cell turgidity and supports vegetative growth, flowering, fruit set and fruit enlargement. It also helps in nutrient absorption and regulates stomatal opening for proper gas exchange. Sufficient water supply improves fruit size, texture, juiciness and overall fruit quality. Water deficiency causes moisture stress, resulting in wilting, poor fruit set, reduced fruit size and lower yield, while excess water may lead to waterlogging, poor root respiration and root diseases. Therefore, efficient irrigation practices such as drip irrigation, mulching and proper water scheduling are essential for sustainable fruit production and better crop performance (Hribar and Vidrih, 2015).

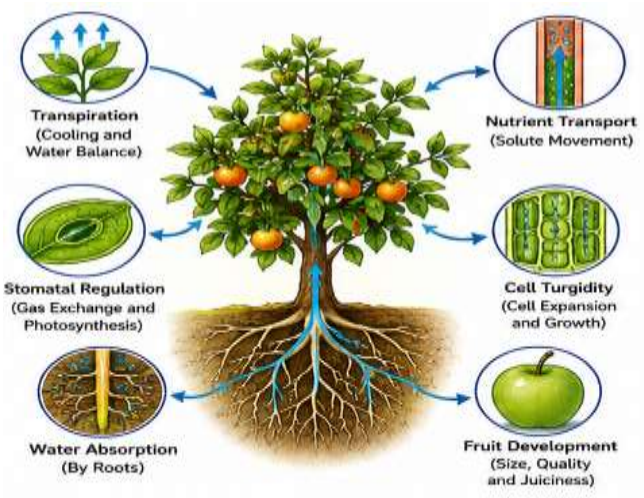
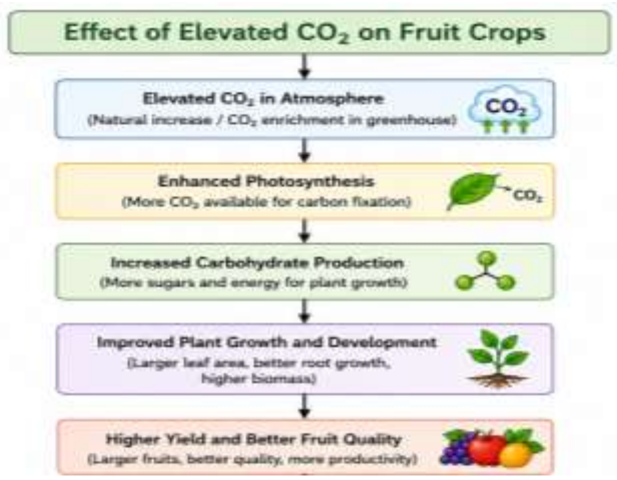


Fig. 2. Water functions and effects in fruit plants

Effect of CO_2 on Fruit Crop Growth

Carbon dioxide (CO_2) is an important environmental factor that plays a major role in the growth and development of fruit crops as it is essential for photosynthesis. Plants utilize CO_2 along with water and sunlight to produce carbohydrates required for growth, flowering and fruit development. Increased CO_2 concentration generally enhances photosynthetic activity, resulting in better vegetative growth, higher biomass production and improved fruit yield. Elevated CO_2 levels also promote larger leaf area, better root growth and improved water use efficiency. In protected cultivation, CO_2 enrichment has shown positive effects on crops such as strawberry and grape by improving fruit size and productivity. However, excessive atmospheric CO_2 associated with climate change may indirectly affect fruit crops through increased temperature and irregular rainfall patterns, leading to poor flowering, reduced fruit set and lower fruit quality. Therefore, proper environmental management is necessary to utilize the beneficial effects of CO_2 for sustainable fruit production (Yadav *et al*., 2023).



Flow chart 1. Effect of elevated CO_2 on fruit crops (Balasooriya *et al*., 2019)

Interaction Among Environmental Factors

The growth and development of fruit crops are influenced by the combined interaction of environmental factors such as light, temperature, water, nutrients and carbon dioxide (CO_2). These factors collectively regulate important physiological processes including photosynthesis, respiration, transpiration, flowering and fruit development. Adequate light promotes photosynthesis, but its efficiency depends on suitable temperature and sufficient water supply. High temperature increases transpiration and water demand, while nutrient uptake is strongly affected by soil moisture and temperature conditions. Elevated CO_2 can enhance photosynthesis, but its benefits are limited under nutrient or water deficiency. Any imbalance among these factors negatively affects crop growth and productivity. For example, high temperature combined with low moisture may lead to flower drop and poor fruit development, whereas excessive rainfall can reduce nutrient availability and root respiration. Therefore, proper management of environmental factors through balanced irrigation, nutrient application and orchard management practices is essential for achieving higher yield and better fruit quality (Ali *et al*., 2021).

Conclusion

Eco-physiological factors such as light, temperature, water, nutrients and carbon dioxide (CO_2) significantly influence the growth, development and productivity of fruit crops. These factors regulate important physiological processes including photosynthesis, flowering, fruit set and fruit maturation, thereby affecting yield and fruit quality. Proper balance and interaction among environmental factors are essential for healthy plant growth and sustainable fruit production. Any imbalance may lead to stress conditions and reduced productivity. Therefore, scientific management practices such as efficient irrigation, balanced nutrition, canopy management and climate-resilient cultivation techniques are necessary to ensure higher yield, better fruit quality and long-term sustainability under changing climatic conditions.

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AI and Smart Composting Systems: A New Paradigm for Sustainable Agricultural Waste Management

Abstract

Composting is a vital biological process in sustainable farming that transforms organic waste into nutrient-rich manure. However, traditional composting methods tend to be slow, labor-intensive, and unreliable due to the difficulty in controlling environmental conditions and microbial activity. Recent progress in artificial intelligence (AI), the Internet of Things (IoT), and sensor technology has led to the development of smart composting systems, which offer a more efficient and precise way to manage organic waste. These systems employ sensors to continuously track critical parameters like temperature, moisture, oxygen levels, and gas emissions. The collected data are then analyzed using machine learning models such as Artificial Neural Networks (ANNs), Random Forests, and Support Vector Machines (SVMs) to forecast compost readiness and optimize process conditions. This real-time monitoring and adaptive management boost microbial efficiency, speed up decomposition, and enhance compost quality. Furthermore, combining AI with advanced microbiological methods, like metagenomics, provides insights into microbial succession and diversity, enabling targeted improvements in composting. Despite these benefits, challenges such as high startup costs, technical complexity, data reliance, and infrastructure constraints hinder widespread adoption, especially in developing areas. Overall, AI-powered smart composting systems are a promising advancement in agricultural microbiology, aiding in waste recycling, lowering environmental impacts, and promoting healthier soil. With ongoing research and supportive policies, these technologies could become key to sustainable, climate-resilient agriculture.

Keywords: Artificial Intelligence, Smart Composting, IoT, Agricultural Microbiology, Waste Management, Sustainable Agriculture

Introduction

Managing agricultural waste remains a significant global challenge, especially in countries such as India, where vast amounts of crop residues and organic waste are produced each year. Composting provides an environmentally friendly approach by converting organic material into useful soil amendments.

However, conventional composting methods rely heavily on manual oversight and are susceptible to environmental fluctuations. The integration of artificial intelligence and IoT technologies has transformed composting into a **precision-driven microbial process**. Smart composting systems utilize sensors, data analytics, and machine learning algorithms to optimize decomposition conditions, thereby improving efficiency and compost quality.

AI and IoT in Smart Composting Systems

Smart composting systems utilize sensor networks, cloud computing, and AI algorithms to oversee composting conditions. Sensors constantly gather data on temperature, moisture, oxygen, and gases, then send it to cloud platforms. There, AI models analyze the data and offer practical insights. Recent studies have demonstrated the effectiveness of machine learning models, including Random Forest, Artificial Neural Networks (ANN), and Support Vector Machines (SVM), in predicting compost maturity and optimizing microbial activity. These models help maintain optimal thermophilic conditions, which are crucial for pathogen elimination and rapid decomposition. For instance, IoT-enabled composting reactors developed in 2025 have shown improved efficiency by automating aeration and moisture control, reducing composting time significantly while enhancing nutrient retention.

Role of Microbial Dynamics

Microorganisms are essential drivers of composting. AI-driven systems offer more detailed understanding of microbial succession and activity throughout various composting stages. By examining environmental data, AI can forecast microbial behavior and optimize conditions as needed. Advanced techniques like metagenomics, combined with AI, enable researchers to pinpoint functional genes involved in cellulose and lignin breakdown. This synergy is advancing precision microbiome engineering, promoting specific microbial groups to improve composting efficiency.

Benefits of Smart Composting

Smart composting systems offer multiple advantages over traditional methods:

- **Enhanced decomposition rate:** Optimized environmental conditions accelerate microbial activity.
- **Improved compost quality:** Consistent monitoring ensures uniform nutrient composition.
- **Reduction in greenhouse gas emissions:** Controlled conditions minimize methane and nitrous oxide release.
- **Labor efficiency:** Automation reduces manual intervention.
- **Data-driven management:** Real-time insights enable better decision-making.

These benefits make smart composting an essential component of modern sustainable agriculture and circular bioeconomy models.

Challenges and Limitations

Despite its potential, the adoption of AI-driven composting systems faces several significant challenges. These limitations are particularly relevant in developing countries and small-scale farming systems.

1. High Initial Investment: The installation of smart composting infrastructure—including sensors, microcontrollers, communication devices, and AI software—requires substantial capital. Small and marginal farmers may find it difficult to afford such systems without financial support or subsidies.

2. Technical Complexity and Skill Gap: Operating AI-based systems demands technical expertise in data management, software operation, and system upkeep. Many farmers do not have the required training, which hinders adoption. Moreover, resolving hardware and software problems can be difficult in rural areas.

3. Data Availability and Quality: AI models rely on large datasets for training and accurate predictions. In many agricultural regions, especially in developing countries, **data scarcity and inconsistency** limit the effectiveness of these models. Poor-quality data can lead to incorrect predictions and suboptimal composting outcomes.

4. Connectivity and Infrastructure Issues: Smart composting systems depend on reliable internet connectivity for real-time data transmission and cloud-based analysis. Rural areas often face network instability, which disrupts system performance and reduces efficiency.

5. Maintenance and Durability of Sensors: Sensors in composting settings face harsh conditions like high temperatures, moisture, and microbial activity, which can cause them to wear out quickly. This results in higher maintenance costs and can reduce the system's reliability.

6. Energy Requirements: For sensors, data loggers, and communication systems to operate continuously, a reliable power supply is essential. This is especially challenging in regions with limited access to electricity.

7. Economic Viability at Small Scale: While smart composting is efficient at industrial or large-farm scales, its cost-effectiveness for small-scale farmers remains uncertain. The return on investment may not justify the initial expenditure without proper policy support.

8. Data Privacy and Security Concerns: With increasing reliance on cloud-based systems, concerns regarding **data ownership, privacy, and cybersecurity** are emerging. Farmers may hesitate to adopt technologies that require sharing operational data.

9. Limited Awareness and Adoption: Awareness about smart composting technologies is still low among farmers. Extension services and training programs are needed to promote adoption and demonstrate practical benefits.

Future Prospects

The future of AI-based composting systems is promising, driven by rapid technological advancements and increasing emphasis on sustainable agriculture. Key developments expected in the coming years include:

- **Low-cost and robust sensor technologies** for wider accessibility
- **Integration with mobile applications** for user-friendly monitoring
- **Development of explainable AI models** for better transparency
- **Use of renewable energy sources** such as solar power for system operation
- **Robotic automation** for compost turning and material handling

Conclusion

AI and smart composting systems represent a transformative approach to agricultural waste management. By integrating advanced technologies with microbial processes, these systems enhance efficiency, reduce environmental impact, and support sustainable farming practices. Although challenges such as high costs, technical complexity, and infrastructure limitations persist, ongoing research and technological innovations are expected to address these issues. With appropriate policy support and capacity building, smart composting can become a key component of future agricultural systems.

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The Role of Soil Physical Properties in Soil Health Management and Crop Productivity

Abstract

Soil physical architecture forms the fundamental grid that regulates agroecosystem functions and crop development. Soil health management has evolved to emphasize that mechanical and physical parameters—such as aggregate stability, bulk density, and variable porosity networks—are core drivers of chemical and biological feedback systems. This article comprehensively examines these foundational indicators and reviews advanced agronomic interventions—including deep subsoiling, conservation tillage, organic amendments, and hydrogel technologies—designed to remediate structural limitations and optimize crop yields in challenging agricultural environments.

Introduction

Modern agronomic research has fundamentally transitioned from single-variable nutrient management toward an integrated "soil health" paradigm. This framework recognizes soil as a dynamic, living ecosystem where physical, chemical, and biological dimensions are inextricably linked. While chemical fertilizers and microbiological abundance frequently dominate soil conservation strategies, their functional efficiencies are ultimately governed by the soil's physical framework.

The physical matrix acts as the primary hydro-mechanical engine of the rhizosphere. It dictates water infiltration, controls gas fluxes, regulates thermal energy, and sets mechanical boundaries for root elongation. Consequently, genetic crop yield potentials cannot be achieved unless the soil physical environment is preserved at an optimum state. Understanding and managing these physical indicators is an absolute necessity for sustaining global crop productivity under accelerating climate uncertainty.

Core Physical Indicators and Hydro-Mechanical Drivers

Aggregate Stability and Architecture

Soil structure is defined by the spatial arrangement of primary mineral particles (sand, silt, and clay) into stable structural clusters or peds. Water-stable aggregates (WSAs) serve as the primary defensive mechanism against erosion, mechanical breakdown, and surface sealing. The preservation of spheroidal macroaggregates (>250 µm) creates a stable network of continuous, open pores that facilitate rapid water movement and root proliferation. Conversely, in fields subjected to intensive, repeated tillage, macroaggregates collapse into sub-angular blocky or platy structures. This structural disintegration triggers surface crusting, drives accelerated run-off, and drastically restricts early crop emergence.

Bulk Density and Root Elongation

Bulk density (BD), calculated as the ratio of dry soil mass to its total volume, serves as a primary metric for assessing soil compaction and mechanical resistance. Normal, uncompacted mineral soils typically exhibit a bulk density of approximately 1.33 g/cm³. However, intensive heavy machinery traffic and repetitive conventional tillage drive compaction layers upward, exceeding threshold values of 1.40–1.60 g/cm³.

BD = M_dry / V_total

High bulk density restricts root elongation by increasing mechanical resistance within the soil matrix. This traps root systems within shallow surface horizons, causing severe crop vulnerability during subsequent dry spells.

RHIZOSPHERE STRUCTURAL COMPARISON
Low Bulk Density (~1.33 g/cm³) --> Well-aggregated, open pores --> Deep, robust taproot path
High Bulk Density (>1.60 g/cm³) --> Compacted, restrictive layer --> Shallow, deflected lateral roots (Hypoxia risk)

Porosity and Hydraulic Conductivities

Total soil porosity typically ranges between 30% and 60% and is inversely related to bulk density. However, agricultural functionality depends heavily on pore-size distribution. Macropores (>30 µm) govern gravitational drainage and maintain optimal soil aeration, which prevents root zone hypoxia and fuels respiration. Micropores (<30 µm) provide crucial microhabitats that retain plant-available water against gravity. Compacted soils suffer a selective destruction of macropores, which fundamentally reduces saturated hydraulic conductivity (K_sat), impedes water infiltration, and leads to prolonged waterlogging in fine-textured soils.

Synergistic Biogeochemical Feedback Loops

The physical architecture of a soil establishes the fundamental micro-environmental conditions that dictate its chemical and biological performance. Stable macroaggregates act as physical protective barriers that shield soil organic carbon (SOC) from premature microbial oxidation. When these aggregate structures break down via mechanical disruption, previously protected organic carbon fractions are exposed to rapid microbial decomposition.

This depletion of organic matter sets off a destructive cycle: the loss of binding agents destabilizes remaining aggregates, increases bulk density, and reduces water-holding capacity. Furthermore, poor physical aeration limits the aerobic microbial conversion of essential nutrient cycles (such as carbon, nitrogen, and phosphorus), turning a physical bottleneck into a systemic chemical fertility deficiency.

Strategic Agronomic Management for Structural Remediation

To alleviate physical limitations and optimize crop yields, targeted, site-specific agronomic strategies must be systematically implemented:

- **Deep Subsoiling and Chiseling:** In soils limited by restrictive subsurface hardpans, mechanical disruption using a chisel plough down to depths of 40–50 cm lowers penetration resistance and decreases bulk density. This remediation expands deep water storage and improves profile infiltration rates up to threefold.
- **Conservation Tillage and Residue Mulching:** Adopting no-till or reduced-tillage methods ensures that at least 30% of the soil surface remains covered by crop residues. This residue cover buffers the soil against the kinetic energy of raindrops, preventing surface crusting and maintaining long-term aggregate stability.
- **Organic Matter and Amendment Loading:** Applying farmyard manure (FYM) or compost introduces humic binding substances that anchor individual soil particles into resilient structural peds. This integration increases the available water-holding capacity (WHC) while lowering the bulk density of compacted agricultural horizons.
- **Hydrogels and Soil Conditioners:** Incorporating modern super-absorbent polymers, such as Pusa hydrogel, significantly improves structural stabilization in highly permeable sandy soils. These advanced polymers alter internal soil water tension, prolong moisture availability during dry

spells, and loosen tight structures to improve root exploration.

Conclusion

Soil physical properties form the irreplaceable structural foundation supporting overall soil health and long-term crop productivity. Quantitative variations in aggregate stability, bulk density, and pore networks dictate the biological habitats and hydrological fluxes across agricultural landscapes. Remediation of physical degradation requires moving away from continuous conventional tillage toward integrated conservation practices, organic amendments, and targeted subsoil shattering. Future soil science research must emphasize the validation of high-resolution spatial modeling and non-destructive imaging technologies to monitor and protect these physical structures under increasing global environmental strain.

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SUCCESS STORY OF SHRI. MAHADJI SHIRDAKAR: FROM TRADITIONAL FARMING TO A PROFITABLE AYURVEDIC ENTERPRISE

INTRODUCTION

Agriculture in the rainfed regions of Maharashtra is highly dependent on climatic conditions, market fluctuations, and available resources. Farmers with small landholdings often struggle to achieve sustainable income due to irregular rainfall, drought conditions, low productivity, and rising cultivation costs. In such situations, diversification and value addition in agriculture emerge as important pathways for improving farmers' livelihoods and ensuring economic stability. One such inspiring example is the success story of Shri. Mahadji Shirdakar from Dandegaon village of Hingoli district of Maharashtra State. Through determination, innovation, and proper technical guidance, he transformed himself from a traditional farmer facing economic hardships into a successful entrepreneur engaged in Ayurvedic value-added food production. His journey demonstrates how rural farmers can create profitable enterprises by combining traditional knowledge with scientific training and market-oriented approaches.

BACKGROUND OF THE FARMER

Shri. Mahadji Shirdakar belonged to a farming family where agriculture was the primary source of livelihood. Like many small and marginal farmers of the Marathwada region, his farming activities depended mainly on rainfall. Due to unpredictable weather patterns, climate variability, and declining profitability in conventional farming, he continuously faced financial instability.

The major challenges faced by him included:

- Irregular and uncertain rainfall
- Drought and unseasonal rains
- Low crop productivity
- Fluctuating market prices
- Limited irrigation facilities
- Small landholding
- Increasing cost of cultivation
- Lack of modern agricultural technologies

Despite his hard work, the returns from traditional farming were insufficient to meet family expenses and agricultural investments. Realizing that conventional agriculture alone could not provide sustainable income, Shri. Mahadji started searching for alternative livelihood opportunities.

SEARCH FOR NEW OPPORTUNITIES

During his exploration for income diversification, Shri. Mahadji came across the concept of value-added Ayurvedic food products. He developed interest in the preparation of Mohaphul Laddu, a traditional nutritious sweet prepared using natural and medicinal ingredients. He recognized that health-conscious consumers were increasingly demanding traditional and chemical-free food products with medicinal benefits.

The idea of producing Ayurvedic laddus appealed to him because:

- It required comparatively low investment.
- Raw materials were locally available.
- The product had good market demand.
- Traditional Ayurvedic foods were gaining popularity.
- Value addition could provide higher profit compared to raw agricultural produce.

This motivated him to learn scientific methods of preparation and establish a small-scale enterprise.

PROFESSIONAL TRAINING AND SKILL DEVELOPMENT

To acquire proper technical knowledge, Shri. Mahadji attended a specialized Ayurvedic Panchakarma training programme in Kerala. During the training, he learned about:

- Ayurvedic food preparation techniques
- Medicinal importance of herbs
- Nutritional values of natural ingredients
- Hygiene and quality maintenance
- Health-oriented food processing

After returning from Kerala, Shri. Mahadji contacted Krishi Vigyan Kendra, Hingoli for further technical support and practical guidance. Scientists and experts from KVK provided him training regarding:

- Preparation technology of Mohaphul Laddu
- Selection of quality ingredients
- Proper formulation and proportions
- Hygienic processing methods
- Packaging techniques
- Marketing strategies
- Entrepreneurial guidance

The continuous technical support from KVK strengthened his confidence and encouraged him to initiate the business on a commercial scale.

ESTABLISHMENT OF MOHAPHUL LADDU ENTERPRISE

After gaining technical knowledge and confidence, Shri. Mahadji started his first production unit for Mohaphul Laddu at village level. He prepared the first batch of approximately 50 kg laddus.

The total expenditure incurred for production included:

Particulars	Estimated Cost (Rs.)
Raw materials	15,000
Labour charges	5,000
Packaging and labeling	3,000
Miscellaneous expenses	2,000
Total Cost	**25,000**

Initially, the production cost ranged between Rs. 22,000 to Rs. 25,000 depending upon availability and cost of ingredients. To attract consumers and ensure convenient sales, he packed the laddus into half-kilogram packets. Attractive packaging improved product appeal and market acceptance.

MARKETING AND SALES

After completing the first production batch, Shri. Mahadji started marketing the product through:

- Local markets
- Grocery shops
- Ayurvedic medicine stores
- Farmer exhibitions
- Direct consumer sales
- Social contacts and word-of-mouth publicity

The response from consumers was highly encouraging. Customers appreciated the:

- Traditional taste
- Nutritional benefits
- Use of natural ingredients
- Ayurvedic value
- Hygienic preparation

ECONOMIC ANALYSIS

The enterprise proved economically profitable from the very first batch.

INCOME AND PROFIT FROM ONE BATCH

Particulars	Amount (Rs.)
Total Production Cost	32,000
Total Sales Income	50,000
Net Profit	18,000

The net profit earned from one production cycle was significantly higher compared to returns obtained from conventional farming practices. This encouraged Shri. Mahadji to continue and expand the business further.

EXPANSION OF THE ENTERPRISE

Encouraged by the profitability and growing consumer demand, Shri. Mahadji gradually expanded his enterprise. He reinvested the profits into:

- Increasing production capacity

- Purchasing improved equipment
- Better packaging materials
- Branding and labeling
- Expanding market reach

He also introduced variations in products by incorporating locally available seasonal ingredients and experimenting with different flavors to meet consumer preferences.

To widen market opportunities, he started collaborating with:

- Local retailers
- Urban health stores
- Ayurvedic shops
- Online customers
- Agricultural fairs and exhibitions

His products gradually gained recognition as healthy, authentic, and traditional Ayurvedic sweets.

CHALLENGES FACED DURING THE JOURNEY

Although successful, Shri. Mahadji faced several difficulties during the initial stages:

- Arranging investment capital
- Maintaining product consistency
- Procuring quality raw materials
- Building market trust
- Transportation and logistics
- Packaging and storage management

However, through continuous learning, technical guidance from KVK, and his dedication towards quality production, he successfully overcame these challenges.

SOCIAL IMPACT AND COMMUNITY DEVELOPMENT

The success of Shri. Mahadji Shirdakar has positively influenced the rural community of Dandegaon and surrounding villages.

His enterprise contributed towards:

Employment Generation

Local villagers received employment opportunities in processing, packaging, and marketing activities.

Promotion of Value Addition

Farmers became aware of the importance of processing and value addition for increasing farm income.

Encouragement for Entrepreneurship

Many rural youth and farmers became motivated to start small-scale food processing enterprises.

Support to Local Farmers

Procurement of raw materials from nearby farmers strengthened the local economy.

Awareness on Sustainable Livelihoods

Shri. Mahadji actively promotes diversification and sustainable agricultural practices among farmers.

He regularly shares his experiences and knowledge during village meetings, workshops, and farmer training programmes organized by Krishi Vigyan Kendra, Hingoli.

ROLE OF KRISHI VIGYAN KENDRA, HINGOLI

Krishi Vigyan Kendra, Hingoli played a crucial role in the success of Shri. Mahadji by providing:

- Technical guidance
- Entrepreneurial motivation
- Training on value addition
- Processing technologies
- Packaging and branding support
- Market linkage information
- Continuous advisory services

The timely support and scientific guidance from KVK enabled Shri. Mahadji to transform his traditional livelihood into a successful business enterprise.

CONCLUSION

The success story of Shri. Mahadji Shirdakar is an excellent example of how innovation, value addition, and scientific guidance can transform the lives of small and marginal farmers. By shifting from traditional farming to Ayurvedic value-added food processing, he created a sustainable and profitable livelihood model. His journey demonstrates that rural entrepreneurship, combined with local resources and traditional knowledge, can significantly improve farmers' economic conditions. The success of Mohaphul Laddu enterprise highlights the importance of diversification, skill development, and institutional support in rural development. Today, Shri. Mahadji Shirdakar stands as a role model for farmers across the region, inspiring others to adopt value addition and agri-based entrepreneurship for sustainable income generation and self-reliance.

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Sugarcane Ratooning and Production Constraints

ABSTRACT

Ratooning in sugarcane is an important agronomic practice in which a new crop is obtained from the underground stubble buds left after harvesting the plant cane. This system is widely adopted in sugarcane-growing regions due to its economic advantage, as it reduces the cost of cultivation by saving inputs related to seed cane, land preparation, and planting operations. Ratoon crops also contribute to extending the crushing period of sugar factories as they generally mature earlier than plant crops. However, ratoon productivity is often lower than that of plant cane due to several interacting constraints. This review highlights that ratoon yield and performance are influenced by genetic potential, environmental conditions, soil health, and agronomic practices. Key production constraints include environmental stresses such as low winter temperatures and moisture extremes, soil-related problems like compaction and nutrient depletion, and biotic stresses caused by diseases (smut, ratoon stunting, leaf scald) and insect pests (borers, pyrilla, mealy bugs, and scale insects). Crop-based limitations such as shallow rooting, early maturity, pith formation, and varietal limitations further reduce ratoon efficiency. In addition, cultural constraints such as small landholdings, piecemeal harvesting, and improper planting methods, along with socio-economic limitations like inadequate input use and poor management knowledge, significantly affect ratoon productivity. Despite these challenges, studies indicate that improvements in varietal selection, stubble management, balanced fertilization, irrigation scheduling, trash mulching, and integrated pest management can substantially enhance ratoon yields. Therefore, ratooning remains a crucial component of sustainable sugarcane production systems, provided that its constraints are effectively managed through integrated agronomic and technological interventions.

Keywords: Sugarcane, ratooning, constraints, stubble buds, yield decline, agronomy, productivity.

Introduction:

Ratooning is a practice of growing full crop of sugarcane from sprouts of underground stubble left in the field after harvest of the main crop. In sugarcane farming ratooning is an important aspect owing to its low cost of production when compared with main crop as it saves the cost of seedbed preparation, seed material and planting operations. Ratoons help in extending the crushing schedule of sugar factories as they mature earlier than the plant crop. However, most often ratoon crop yields are lower than the main (plant) crop due to soil compaction, decreased soil fertility under continuous sugarcane cropping and inefficient use of applied fertilizers. Therefore, small improvement in ratoon cane productivity would add considerably to overall sugarcane production in country.

Sugarcane is a long duration crop and its initial growth is slow. The lateral spread depends upon the production of tillers. Among the agronomic yield attributing characters, the number of millable canes per unit area with 40 per cent contribution rank first. Individual cane length, diameter and weight account for 27, 3 and 30 percent res. (Yadava, 1993.) Therefore, to obtain the maximum number of stalks per unit area, it is necessary to induce tillering in plants at an early stage. Moreover, the tiller number determines the level of nutrition to individual cane and thus associated traits. It follows that if desired optimum plant population could be maintain by suitable agro-techniques, the potential yield of sugarcane could easily be achieved.

Ratoon produces higher number of tillers than plant crop. If ratoon is initiated at optimum temperature (27^0), maximum tillering is attained during 110 to 125 days after ratooning. Within the verities, there is significant differences in the production of tillers and formation of millable canes. Around 80 % of the sprouted subterranean buds are located on the lower half of the stubble. Tillage operations either by the country plough or sub- soiler increase number of millable canes, average cane weight and finally cane yield.

Ratooning potential and performance:

A genotype whose ratoon crop shows higher percentage of its plant crop or a younger crops yield is said to have good ratooning ability, but unless yield is economically rewarding it may not be said to have commercial potential. Yield of ratoon crop in any environment is a function of the yield potential of the variety and its ratooning ability.

In India, sugarcane verities cultivated in the sub-tropics prior to the introduction of Co canes were not ratooned because of their susceptibility to pest and diseases. Incorporation of S. spontaneum genome in present day sugarcane verities has contributed to their ratooning potential. Ethirajan (1982) assessed ratooning ability by periodic harvests at four months intervals of above ground parts and estimating dry matter production. Such a ratoon index helps in identifying potential ratooners. Kapur et al. (1985) evaluated the ratio of performance of number of millable canes and cane weight in ratoon with respect to plant crop. Sundara et al. (1986) observed that higher plant cane yield, stalk population and sprouting of stubble buds were useful in selecting better ratooners. Tripathi et al. (1982) however, observed that genotypes giving higher cane yield in plant crop, with certain exceptions, invariably gave good ratoon yields.

Frequency of ratoons:

Ratoon cropping is an old, which has been practiced for many years, especially in tropics. Although, the origin of ratooning is probably not known for any particular crop, it might have begun when man would have noticed first regrowth of new shoots following cutting of certain crops. Thus, new crop produced without replanting. Also, earlier observations of grassland, regrowth following burning might have created an interest in utilizing regrowth of plants as basis for multiple harvesting from an original root system (Plucknett et al. 1970). It is of interest to mention that in East China Province of Fuigian, sugarcane planted in 1727 A. D. is still being grown as ratoon and the cane raised are still said to good in height and other characters even after two hundred eighty-three years of continuous cultivation. Apart from this exception, as many as eleven ratoons having been successfully taken by the farmers in Cuba. At present, almost in all the countries where sugarcane is a major crop, taking of at least two or even more ratoon crops are a normal practice. In Hawaii, Mauritius, Philippines and Cuba, 4 to 6 ratoons are quite common (Misra and Mathur, 1983). Sri Prafulla Chandara, a progressive farmer of Hosahalli Village in Shimoga district (Karnataka) has been successfully growing ratoon sugarcane of Co 449 and Co 740 varieties continuously for the past 44 years from a single planting which was done during 1968 on two hectors. His average cane productivity for three decades vacillated more than 100 tonnes/ha which is much higher than the average national cane yield (81 t/ha).

Rooting in ratoon:

Initially ratoon starts functioning on old stubble roots, which are especially a, Rope system of the plant crop (Hunsigi, 1982). Rope roots are those, which grows vertically downwards and from strands consisting of 15-20 roots. These develop strongly on the cane, which have wild blood (*Saccharum spontaneum*) than the noble tropical (*Saccharum officinarum*). However, it is a controversial matter to say that roots of the old sugarcane stool continue to function even after the harvest of the crop (Plucknett, et al. 1970). Convincing evidences are available to show that the old root system ceases to function soon after harvest. Additional evidence was supplied by time lapse cineraphy of ratooned plants using a wind box technique. Rapid deterioration of the old root system and rapid growth of new root system resulted following harvest. The transition period between the decay of stubble roots and initation of new shoot roots, however, depends on the soil and climatic condition and might vary from 6 to 8 weeks. Ratoon roots are shallower than the plant crop because shoots of ratoon originate from higher level than the plant crop. These also became sparer in successive ratoon crops.

Hunsigi (1982) described a detailed examination of the root system of the first ratoon crop of Co 62175 in red soils of Mandya, which was one by the method of evans using a jet of water. During the frist 3 to 4 weeks after stubble shaving, more than 90 % of the root system comprised stubble roots. The lateral spread of the stubble root was 1.76meters and was about 1 meter deep. Tracer technique was used at IISR (1976) to study the rooting behavior of Co 1148 in its first ratoon crop.

Ratoon cane production constraints:

The state-wise site-specific constraints in breaking yield plateau of sugarcane relate to wide disparity as well as declining trend in total fertilizer consumption (87.6 kg/ha) for all crops. Also, water logging, late planting and ratooning under which sugarcane is grown are a feature of reduced nutrient use efficiency and decreased factor productivity. In India different constraints are faced in various states by sugarcane growers.

1. **Environmental constraints:**

These are mainly temperature and soil moisture induced constraints. In subtropics, the harvesting of sugarcane starts during peak of the winters which witness low to very low temperature. Stubble bud gets exposure to such odd ambience and usually yield gaps. Late harvesting too dries out the bottom buds of stubble and reduces s plant population.

2. **Soil based production constraint:**

The compactness of the soil mainly under multi-ratooning system and build- up of weed flora and pest contribute to the loss of productive capacity of sugarcane growing soils under long term monoculture. It is recognized as a component of the productivity plateau and occurs n all sugarcane growing areas. The shallow root system of the ratoons reduces nutrient quenching ability and eventually makes the ratoon more sensitive to moisture stress and more demanding for available nutrients. Because of faulty and frequent irrigation, weeds along with their associated problem create menace to proper plant growth and reduce number of millable canes.

3. **Biotic Constraints:**

Ratoon cane is subjected to biotic stress like smut, grassy shoot, ratoon stunting and leaf scald diseases. The insect – pest like root borer, top borer, stalk borer, pyrilla, mealy bug and scale insects are major pests causing damages to the crop.

4. **Crop based production constraint:**

Short life span- The maturity in the ratoon crop sets in prior to that of plant crop. Under identical growing conditions, it has been observed that under subtropical climatic conditions, the normal growth and vigour in both plant and ratoons.

Root system- sugarcane roots are short and die out quickly with little scope for substantial lateral growth, thus occupying smaller soil volume with limited foraging capacity and more prone to lodging. Moreover, ratoon crop results due to stubble buds which are closer to ground surface, the surface coverage shrinks further reducing the ratoons crop rendering them to become surface feeder. Arrowing and pith formation- Arrowing is characterized by cessation of growth and in case of ratoons, it sets in early than plant crop. Ratoons are also reported to have more pith than plant crop and thus cause less cane weight.

Varietal constraints- Sugarcane varieties having good ratooning potential under low/ high temperature conditions are not available in plenty.

5. **Cultural Constraints:**

1. **Small holdings:**

Small holding sizes and socio-economic conditions of sugarcane farmers affect the adoption of improved mechanical devices and timely completion of cultural operations.

Holding size in India

% Growers	Holding size
5.4	< 0.5 ha
58.00	0.5 to 5.0 ha
20.7	5.0 to 10.0 ha
15.9	Others

2. **Piecemeal harvesting:**

Sprouting of stubble buds occurs only at its favorable temperature. In case of sugarcane, the harvesting is mainly demand driven and procedural, without considering its impact on subsequent ratoons. An early winter harvested plant crop may result in to more gaps. Similarly harvesting of over matured canes during high temperature and desiccating winds in subtropical region render the bottom buds dry quickly and cause gaps. Piecemeal harvesting of plant cane creates problems in carrying out the cultural operations timely and the crop fails to obtain symmetry till its maturity. The planting methods of sugarcane exhibit considerable impact in subsequent ratoon yields. Ratoons of ring pit and trench method planted canes harvested close to the ground level by sharp edged chopper give higher ratoon yield over flat method of planting. Harvesting of cane leaving 4-6 inches above the ground portion give rise to poor ratoon crop.

6. **socio-economic constraints**

Adequate and balanced use of inputs is essential to obtain desired ratoon crop yield. Since sugarcane is grown under highly diverse situations, poor socio-economic conditions and ignorance about the actual requirement of the ratoon cane for its nutrition and plant protection and other critical inputs for specific conditions result in low ratoon cane productivity. Constraints for low productivity Shukla et al. (2013c) discussed the constraints sugarcane growers face in different regions of India (Table 1). Water logging has been considered a severe issue in the country's north-central and eastern parts. However, early and late droughts also adversely affected crops in rain-fed situations. In Punjab and Rajasthan states, salinity and drought were the critical issues affecting the crop yield. In Uttar Pradesh, the eastern part faces waterlogging. However, in the western part, late planting of sugarcane water wheat harvest has been the talk of the town. In Gujarat, high ground water table and sodicity were the pertinent issues. In Madhya Pradesh, Odisha, and Andhra Pradesh, inadequate irrigation facilities also adversely affected crop yield. However, a few critical issues are discussed below.

Conclusions

Ratooning is a fundamental and widely practiced system in sugarcane cultivation that offers significant economic and operational advantages by reducing production costs and enabling multiple harvests from a single planting. It also supports the sugar industry by extending the crushing season and ensuring continuous cane supply. However, the productivity of ratoon crops is generally lower than plant cane due to a combination of environmental, soil-based, biotic, crop-based, cultural, and socio-economic constraints.

The review clearly indicates that yield decline in ratoon crops is not due to a single factor but results from the interaction of multiple limitations, including soil compaction, reduced fertility, pest and disease buildup, unfavourable climatic conditions during harvesting, shallow rooting systems, and inadequate agronomic management. Additionally, constraints such as small farm holdings, delayed harvesting practices, improper stubble management, and limited access to improved technologies further reduce ratoon efficiency, particularly in developing regions.

Despite these challenges, substantial improvement in ratoon productivity is possible through integrated management strategies. These include the use of high ratooning potential varieties, proper harvesting techniques, stubble shaving, balanced nutrient management, efficient irrigation practices, trash mulching, and effective control of pests and diseases. Strengthening extension services, improving farmer awareness, and promoting mechanization and timely field operations are also essential for enhancing productivity.

In conclusion, ratooning remains a vital component of sustainable sugarcane production systems. Addressing its production constraints through scientific, technological, and socio-economic interventions can significantly improve cane yield, enhance sugar recovery, and increase profitability for farmers while ensuring long-term sustainability of sugarcane-based agro-industries.

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Nature's Carbon Sponge: Using Bamboo to Beat the Urban Heat Island Effect and Global Warming

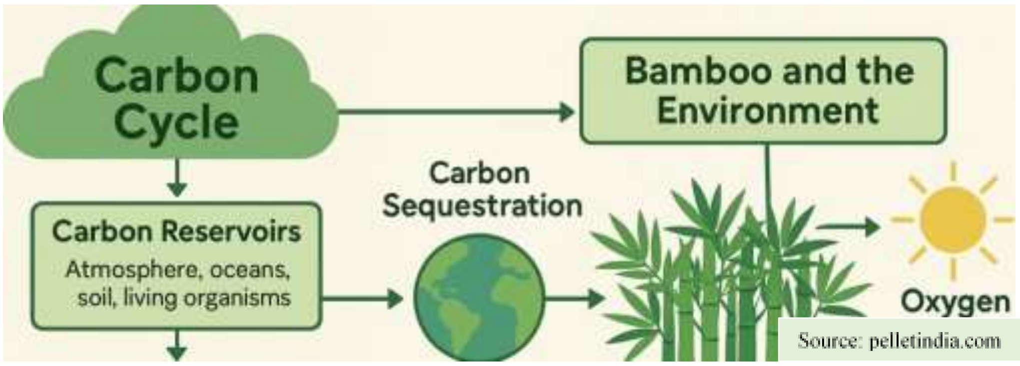
Introduction

Anthropogenic activities have pushed atmospheric carbon dioxide levels to roughly 420 ppm, intensifying the devastating impacts of global warming. Terrestrial ecosystems—specifically forest vegetation, which accounts for 77.1% of the global terrestrial carbon reservoir—are our frontline defense, absorbing CO_2 through assimilation. However, to meet the fast-approaching targets of international climate conventions, we need natural solutions that work on an accelerated timeline. Often termed "Green Gold," this grass from the subfamily Bambusoideae is an ecological powerhouse capable of massive carbon offsetting, rapid environmental restoration, and sustainable socio-economic development.

The Ultimate Carbon Sponge

Bamboo operates at biological hyper-speed. While traditional timber requires 20 to 50 years to mature, bamboo reaches harvestable maturity in just 3 to 5 years. Certain species can even grow up to 91 centimeters in a single day. Globally, bamboo covers 36 million hectares (about 3.2% of the world's forest area). India is a major producer with 11.4 million hectares, while Ethiopia holds Africa's largest natural bamboo forest at 1 million hectares.

This rapid growth drives immense carbon capture. On average, a hectare of bamboo absorbs about 17 tonnes of carbon per year—sequestering two to four times more carbon than traditional pine or fir forests of a similar size. Crucially, when mature poles are selectively harvested, bamboo's extensive underground rhizome system remains intact. This prevents the release of belowground carbon, which typically occurs when timber plantations are clear-felled and allows the plant to immediately send up new shoots.



Source: pelletindia.com

Cooling the Concrete Jungle: The Physics of Transpiration

Beyond global carbon metrics, bamboo offers immediate localized relief. Expanding cities create Urban Heat Islands (UHIs)—zones where asphalt, concrete and steel absorb and re-radiate thermal heat, making cities dangerously hot. Bamboo combats the UHI effect through the thermodynamics of transpiration. As a bamboo grove pulls water from the soil and evaporates it through microscopic leaf pores (stomata), the liquid changes to vapor.

This phase change requires massive energy, defined by the latent heat formula:

$$Q = mLv$$

Where Q is the heat energy absorbed, m is the mass of the evaporating water and Lv is the latent heat of vaporization of water.

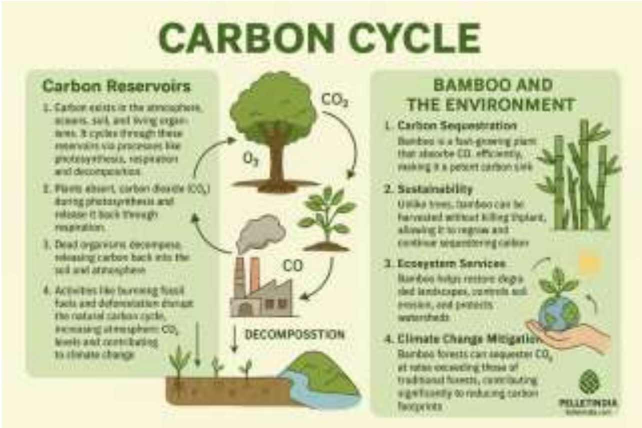
To fuel this evaporation, the water strips sensible heat from the ambient air, converting it into latent heat. Due to its dense canopy and hyper-rapid growth, bamboo requires a constant, massive water flow. By transpiring thousands of gallons into the air, it acts as a solar-powered evaporative cooler that actively lowers ambient city temperatures.

Industrial Marvel: Locking Carbon in Products

To maximize carbon sequestration, harvested bamboo must not be burned. Instead, it should be transformed into durable goods, safely locking away over 90% of its stored carbon. Utilized in over 1,500 industrial applications, bamboo's lightweight, high tensile strength, and flexibility make it an excellent substitute for high-emission materials like steel and concrete. Its industrial footprint includes:

- Wood & Building: Bamboo flooring, particle boards, bridges and laminates replace high-emission concrete and steel.
- Textiles: Breathable clothing, blankets and towels offer a sustainable alternative to resource-heavy cotton.
- Bio-energy: Bamboo briquettes offer a renewable alternative to fossil fuels.
- Biochar: When heated in the absence of oxygen (pyrolysis), bamboo transforms into biochar—a highly stable form of carbon that can remain locked in the soil for hundreds of years while simultaneously improving agricultural soil fertility.

By replacing high-emission materials with bamboo, we prevent further greenhouse gas emissions while keeping atmospheric carbon safely locked inside everyday items.



The Underground Network: Soil Restoration

Bamboo's resilience is practically legendary. It thrives in an incredibly wide spectrum of environments and can survive in degraded, organic-poor or overgrazed soils. Its dense, fibrous root systems grip the earth firmly, which controls soil erosion, prevents landslides and safeguards vital watersheds. When planted on degraded land, the presence of bamboo and the accumulation of its decaying leaf litter significantly improve the consistency, structure, and biological properties of the soil. Remarkably, research on bamboo ecosystems reveals that up to 67% to 81% of its carbon storage capacity is locked safely underground within the soil, roots and rhizomes.

The Double-Edged Sword: Ecological Risks

However, nature requires balance. Wielding this "super-grass" requires absolute precision, as it can be a double-edged sword when planted outside its native ecosystems. For instance, in Mediterranean regions like Italy, the introduction of fast-growing *Phyllostachys edulis* (Moso bamboo) for carbon sequestration has raised serious environmental concerns. While it removes substantial atmospheric carbon, it is an alien species in Europe that can seriously alter local plant and animal biocoenosis, ultimately reducing native biodiversity and increasing the risk of pathogen attacks.

Furthermore, to achieve rapid growth rates in non-native, drier climates, bamboo requires significantly more water and fertilizer than indigenous agricultural systems. If left unchecked, its aggressive rhizomes can suffocate surrounding native forest species. Therefore, strict containment strategies—such as installing underground root barrier panels—are essential to prevent bamboo from becoming an invasive ecological threat.

A Blueprint for Net-Zero

For developing nations, hitting net-zero targets means deploying bamboo strategically. Key steps include integrating bamboo into agroforestry systems, empowering local smallholder farmers, and utilizing selective harvesting to maintain continuous carbon uptake. Furthermore, formalizing these efforts through rigorous accounting standards—such as the Verified Carbon Standard (VCS)—allows bamboo-based projects in the Clean Development Mechanism (CDM) to provide critical climate finance to developing economies. By carefully navigating the balance between aggressive afforestation and native biodiversity protection, bamboo can serve as a cornerstone for modern climate mitigation.

Conclusion

Bamboo is a dynamic, highly efficient engine for climate intervention. It's phenomenal growth rates, robust carbon sequestration capacity and ability to cool urban heat islands offer an actionable pathway to global net-zero emissions. Its subterranean network restores degraded lands, while its durable industrial applications permanently lock away harvested carbon.

However, its implementation must be carefully managed. To harness its benefits without triggering ecological imbalances, policymakers must prioritize site-specific cultivation and sustainable silvicultural practices. By balancing its aggressive growth with rigorous ecological stewardship, we can transform this ancient grass into a cornerstone of our modern climate survival strategy.

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Invasive Insect Pests in India: A Growing Agricultural Threat

Introduction

Indian agriculture is facing a serious challenge from invasive insect pests that are rapidly spreading across different agroecosystems. These pests are non-native organisms introduced accidentally or intentionally into new geographical regions where they establish, multiply rapidly, and cause severe economic damage due to the absence of effective natural enemies (Muniappan, 2022). In recent years, several invasive insect pests such as fall armyworm, tomato pinworm, rugose spiralling whitefly, papaya mealybug, and invasive thrips have emerged as major threats to Indian agriculture (Shashank et al., 2018). Globalization, increased international trade, movement of agricultural commodities, climate change, and intensive cultivation practices have accelerated the spread of invasive pests in India (Paini et al., 2016). These pests not only reduce crop yield and quality but also increase pesticide dependence and production costs, thereby affecting farmer profitability and ecological sustainability.

Why Invasive Insect Pests are Dangerous

Invasive insect pests possess several biological advantages that help them establish quickly in new regions. Most invasive pests have high reproductive potential, short life cycles, wide host ranges, and remarkable adaptability to diverse environmental conditions (Early et al., 2016). In addition, the absence of natural enemies in newly invaded areas allows these pests to multiply unchecked.

Farmers often fail to recognize new invasive pests during the early stages of infestation. As a result, delayed management leads to severe outbreaks and heavy crop losses. Excessive pesticide application against these pests also contributes to insecticide resistance, environmental contamination, and destruction of beneficial insects (Desneux et al., 2010).

Major Invasive Insect Pests in India

1. Fall Armyworm (*Spodoptera frugiperda*)

Fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith), is one of the most destructive invasive pests affecting Indian agriculture today. Native to tropical and subtropical regions of the Americas, the pest was first reported in India during 2018 from maize fields of Karnataka (Sharanabasappa et al., 2018; Sahoo and Pradhan, 2022). Since then, it has rapidly spread across almost all maize-growing regions of the country.

FAW is highly polyphagous and attacks more than 350 plant species including maize, sorghum, sugarcane, rice, and millets (Montezano et al., 2018). The larvae feed voraciously on leaves and produce characteristic window-pane symptoms and whorl damage in maize crops. Severe infestation may lead to complete destruction of young plants.

Economic studies have shown that FAW infestation significantly increases cultivation costs due to repeated pesticide applications and yield losses (Prakash et al., 2024).

Management Strategies

- Installation of pheromone traps
- Regular field scouting
- Conservation of parasitoids and predators
- Use of *Bacillus thuringiensis*-based biopesticides
- Need-based insecticide application
- Destruction of crop residues

2. South American Tomato Pinworm (*Tuta absoluta*)

Tuta absoluta (Meyrick), commonly known as tomato pinworm or tomato leaf miner, is another devastating invasive pest threatening tomato cultivation in India. The pest originated in South America and was first detected in India around 2014–15 (Shashank et al., 2015).

The larvae mine leaves, stems, flowers, and fruits, causing extensive damage and making tomato fruits unmarketable. Under severe infestation, yield losses may reach 80–100% if timely management practices are not adopted (Desneux et al., 2010).

The hidden feeding behaviour of larvae inside plant tissues makes management difficult. Continuous tomato cultivation and excessive pesticide use have further aggravated the problem.

Important Management Practices

- Pheromone trap installation
- Removal of infested plant parts
- Crop sanitation
- Biological control using parasitoids
- Sticky traps
- Integrated Pest Management (IPM)

3. *Thrips parvispinus*: An Emerging Invasive Threat

Recently, *Thrips parvispinus* Karny has emerged as a serious invasive pest of chilli, capsicum, papaya, and ornamental crops in India (Thorat et al., 2022). The pest damages crops by rasping and sucking plant tissues, resulting in leaf curling, bronzing, flower drop, and poor fruit development.

The rapid multiplication rate and concealed feeding behaviour of thrips make management extremely difficult. Many farmers rely heavily on chemical insecticides, which often fail to provide effective control due to resistance development.

Recommended Management

- Blue sticky traps
- Field sanitation
- Conservation of natural enemies
- Neem-based biopesticides
- Removal of alternate weed hosts
- Judicious insecticide use

4. Rugose Spiralling Whitefly (*Aleurodicus rugioperculatus*)

The rugose spiralling whitefly, *Aleurodicus rugioperculatus* Martin, has become an important invasive pest of coconut, banana, ornamental plants, and several fruit crops in India (Selvaraj et al., 2017). The pest produces copious amounts of honeydew, which promotes black sooty mould development on leaves, thereby reducing photosynthetic activity.

The pest spreads rapidly under warm and humid climatic conditions and has caused serious concern among coconut growers in southern India.

Table 1. Important Invasive Insect Pests Reported in India

Pest	Native Region	Major Host Crops	Nature of Damage
Spodoptera frugiperda	Americas	Maize, sorghum, sugarcane	Defoliation and whorl damage
Tuta absoluta	South America	Tomato	Leaf mining and fruit boring
Thrips parvispinus	Southeast Asia	Chilli, ornamentals	Curling and bronzing
Aleurodicus rugioperculatus	Central America	Coconut, banana	Honeydew and sooty mould
Paracoccus marginatus	Mexico/Central America	Papaya, mulberry	Sap sucking and stunting

Sustainable Management Approaches

- Yellow sticky traps
- Release and conservation of parasitoids
- Spraying fish oil rosin soap
- Pruning heavily infested leaves
- Avoidance of indiscriminate insecticide application

Role of Biological Control and IPM

Biological control has emerged as one of the most promising eco-friendly approaches for invasive pest management. Natural enemies such as parasitoids, predators, and entomopathogenic microorganisms help suppress invasive pest populations without causing environmental pollution (Heimpel and Mills, 2017). Integrated Pest Management (IPM), which combines monitoring, cultural practices, biological control, and need-based pesticide application, is essential for sustainable invasive pest management.

Conclusion

Invasive insect pests are rapidly emerging as a major challenge to Indian agriculture and food security. Climate change, global trade, and intensive farming practices are likely to increase future invasions. Early detection, strict quarantine measures, farmer awareness, and promotion of biological control and IPM strategies are essential for minimizing economic losses and protecting agroecosystems. Sustainable and eco-friendly management practices will play a crucial role in safeguarding Indian agriculture from these silent invaders.

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Plasma-Activated Water: A New Frontier in Food Processing

Introduction

Plasma-treated (or plasma-activated) water (PAW) has recently emerged as a promising, eco-friendly technology for food processing, offering a chemical-free alternative for microbial decontamination and shelf-life extension. Generated by exposing water to non-thermal plasma, PAW acquires reactive oxygen and nitrogen species (ROS/RNS), an increased oxidation–reduction potential, and a slightly acidic pH, which collectively contribute to its strong antimicrobial activity. In food processing, PAW is increasingly applied for surface disinfection of fresh produce, meats, seafood, and food-contact surfaces, where it effectively reduces spoilage microorganisms and foodborne pathogens without significantly altering sensory or textural properties. Beyond microbial safety, studies have demonstrated additional benefits such as reduction of pesticide residues, enhancement of seed germination, and support for meat-curing processes, highlighting PAW's versatility from farm to processing line. Given the growing demand for clean-label and sustainable technologies in the food industry, the application of plasma-treated water represents a significant step toward safer, greener, and more efficient food processing systems.

Source: *www.Google.com*

What is plasma-activated water?

Non-thermal plasma is a partially ionized gas (the "fourth state of matter") generated by applying high-voltage electricity to a gas (often air or an inert gas) at near-ambient temperature. When this plasma interacts with water either by contacting the liquid surface, bubbling through it, or treating it in a nearby gas phase—reactive species diffuse into the water, turning it into plasma-treated or plasma-activated water.

Key reactive species formed include reactive oxygen species (ROS) such as hydrogen peroxide and superoxide, and reactive nitrogen species (RONS) such as nitrites and nitrates, which are responsible for most of PAW's biological effects.

Changes in water properties

Plasma treatment alters several measurable properties of the water:

- pH: The pH usually decreases, making the water slightly acidic due to formation of nitric and nitrous acids from dissolved nitrogen oxides.
- Conductivity and ions: Electrical conductivity increases because of added ions (especially nitrate and nitrite), which also act as plant-available nutrients.
- Oxidation–reduction potential (ORP): ORP rises, indicating strong oxidative capacity that helps inactivate pathogens and organic contaminants.

These changes are typically transient and depend on treatment time, power, gas composition, and water source (distilled, tap, or nutrient-rich).

How is it produced?

Common plasma systems used for water treatment include:

- Plasma jet: A stream of plasma gas is directed onto or into the water.
- Dielectric-barrier discharge (DBD) or corona discharge: High-voltage electrodes generate plasma above the liquid or in a gas gap, transferring reactive species to the water surface.
- Remote or bubbling configuration: Plasma is generated in a separate chamber and the activated gas is then bubbled through water.

By varying voltage, pulse frequency, gas flow, and exposure time, researchers can tune the concentration of ROS/RONS and the application-specific properties of PAW.

Applications

Plasma-activated water is being explored in several sustainability-oriented fields:

- Water purification and sanitation: Cold plasma can degrade organic pollutants, heavy metals (e.g., iron, arsenic), and pathogens in groundwater or wastewater without strong chemical residuals.
- Agriculture and plant growth: PAW can act as a mild fertilizer (due to nitrate/nitrite) and as a growth-promoting or pathogen-suppressing irrigation solution for crops and cut flowers.
- Food safety and processing: PAW is used to disinfect fruits, vegetables, equipment, and packaging surfaces, reducing bacteria, fungi, and biofilms with minimal chemical residues.
- Biomedical and medical uses: Plasma-activated liquids are investigated for wound disinfection, sterilizing medical instruments, and even selective cancer-cell-killing under controlled conditions.

Advantages and limitations

Advantages:

- Operates at low temperature, so it can treat heat-sensitive products or living tissues.
- Can be "on-demand" and localized, reducing storage and transport of chemicals.
- Often leaves fewer toxic residues compared with conventional chemical disinfectants.

Limitations:

- Effects are usually short-lived; the active species decay over time, so PAW is often used freshly prepared.
- Performance depends strongly on water quality, equipment design, and operating parameters, which complicates standardization.

Conclusion

Plasma-activated water (PAW) represents a transformative, sustainable technology in food processing, leveraging non-thermal plasma-generated ROS/RNS for effective microbial decontamination, pesticide reduction, and quality preservation across fresh produce, meats, and equipment surfaces. Despite challenges like transient reactivity and process optimization, its chemical-free, low-temperature operation positions PAW as a viable clean-label alternative to traditional methods, paving the way for safer, greener food systems with further research into scalability and standardization.

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HEALTHY SOIL, HEALTHY PLATE: WHERE NUTRITION TRULY BEGINS

Abstract
Healthy soil is the foundation of nutritious food and human well-being, though its role in food quality is often overlooked. This article provides an overview of how soil health influences crop nutrition, food quality, and human health through the soil–plant–human continuum. Healthy soils rich in nutrients, organic matter, and microbial diversity support plant growth and improve nutritional quality. Essential minerals such as zinc, iron, selenium, calcium, and magnesium move from soil into crops and ultimately into human diets, influencing growth, immunity, and health. The article also highlights the effects of soil on food quality, safety, and flavor, while discussing soil degradation, contamination, hidden hunger, and sustainable management practices for ensuring food security and improved nutrition.

Introduction: Food Begins Beneath Our Feet

When we think about nutritious food, we often focus on vegetables, fruits, grains, or supplements, rarely considering the soil beneath them. Yet, nutrition begins underground in a living system rich in minerals, organic matter, microbes, water, and air. Healthy soil forms the foundation of food quality by supplying essential nutrients that move from soil to plants and eventually to human diets. For centuries, farming communities recognized that fertile land produced healthier crops and healthier people. However, modern agriculture increasingly emphasized yield over soil health, contributing to hidden hunger despite record food production.

Figure 1: The Soil–Plant–Human Continuum: Investigating the Impact of Soil Health on Nutritional Quality, Food Security, and Human Well-Being

According to the World Health Organization, nearly two billion people suffer from micronutrient deficiencies even when calorie intake is sufficient. Nutrient-poor soils often produce nutrient-deficient crops, affecting human health and well-being. Therefore, understanding the connection between soil and nutrition is essential for improving food quality, combating malnutrition, ensuring food security, and building a healthier future.

Understanding Healthy Soil

Before understanding how soil shapes nutrition, we must first understand what makes soil healthy. Although the terms *soil* and *dirt* are often used interchangeably, they are fundamentally different. Dirt is lifeless material, whereas soil is a living, dynamic ecosystem capable of supporting plants, animals, and humans while maintaining environmental quality. Healthy soil is far more than a medium for anchoring plant roots; it is a complex system where minerals, organic matter, water, air, and living organisms interact continuously to sustain life. Several characteristics define healthy soil. It contains adequate nutrients in plant-available forms, sufficient organic matter to improve fertility, balanced pH for proper nutrient uptake, and good aeration and water-holding capacity. Healthy soil also supports rich biological activity, with billions of microorganisms that recycle nutrients and maintain soil fertility while minimizing contamination from harmful substances. Importantly, soil is not merely inert matter—it is a living ecosystem. A single teaspoon of healthy garden soil contains more microorganisms than there are people on Earth. These microscopic organisms drive nutrient cycling, improve soil structure, and play an essential role in producing healthy, nutritious food.

Soil as the Foundation of Plant Nutrition

Plants are remarkable natural chemists that convert sunlight, water, and carbon dioxide into energy through photosynthesis. However, sunlight alone cannot produce healthy and nutritious crops. Plants rely on soil to obtain essential mineral nutrients required for growth, development, and food quality. Through their roots, they absorb at least 17 essential elements, including macronutrients, secondary nutrients, and micronutrients. Macronutrients such as nitrogen, phosphorus, and potassium promote plant growth, root development, energy transfer, and resistance to diseases. Secondary nutrients like calcium, magnesium, and sulfur support cell structure, chlorophyll formation, and protein synthesis. Micronutrients, including zinc, iron, copper, boron, and selenium, though needed in small quantities, are vital for plant and human health. Beneficial fungi called mycorrhizae often assist plants in nutrient uptake. These nutrients move into grains, fruits, vegetables, and seeds, becoming part of human diets. Therefore, healthy soil ensures healthy crops and ultimately supports human nutrition and well-being.

From Soil Nutrients to Human Nutrition

The relationship between soil health and human health is measurable, predictable, and, in many cases, preventable. Although food reaches people through farms, markets, and kitchens, many of the minerals essential for human survival begin their journey in the soil. Plants absorb nutrients from the soil through their roots, and these nutrients are transferred into grains, fruits, vegetables, and pulses consumed by humans. When soils are deficient in essential nutrients, crops grown in those soils often become nutrient-poor, eventually contributing to deficiencies in human diets. This direct relationship forms the basis of the soil–plant–human health continuum, emphasizing that human nutrition fundamentally begins beneath the soil surface.

One of the most significant examples of this connection is zinc deficiency, one of the world's most widespread micronutrient disorders. Soils lacking sufficient zinc frequently produce cereals with reduced zinc concentrations. Since cereals constitute staple foods for much of the global population, zinc deficiency becomes common, especially among children and pregnant women. Zinc plays a critical role in enzyme activity, immune system functioning, wound healing, cellular growth, and normal development. According to the World Health Organization (WHO), zinc deficiency contributes to over 400,000 child deaths annually, particularly in regions where dietary zinc intake remains inadequate. Children suffering from zinc deficiency commonly experience stunted growth, weakened immunity, delayed development, and increased vulnerability to infectious diseases.

Iron deficiency presents another major challenge linked to soil fertility. Iron-deficient soils often produce crops containing lower iron concentrations, increasing the risk of anemia, chronic fatigue, reduced work productivity, impaired cognitive development in children, and higher maternal mortality. Despite widespread supplementation and food fortification programs, iron deficiency anemia remains the most prevalent nutritional disorder globally, affecting more than 1.6 billion people, especially women and children dependent on cereal-based diets.

Selenium deficiency further illustrates the importance of soil chemistry in human health. Selenium levels differ considerably among regions due to geological and environmental variations. In countries such as China, Finland, and New Zealand, selenium-poor soils historically resulted in crops with very low selenium content, increasing susceptibility to weakened immunity, cardiovascular diseases, thyroid dysfunction, and poor antioxidant defense. Conversely, selenium-rich soils support stronger immunity and healthier populations.

Other soil-derived nutrients are equally essential. Calcium-deficient soils may lower the nutritional quality of vegetables and legumes, indirectly affecting bone strength, muscle function, and nerve signaling. Magnesium depletion in soils can reduce food quality and influence hundreds of enzyme-mediated reactions in the human body. Copper deficiency interferes with iron metabolism and immune function, while boron affects plant reproduction and indirectly influences crop nutritional value.

This global challenge is often described as “hidden hunger,” where people consume enough calories but remain deficient in vital micronutrients. Nearly two billion people worldwide suffer from deficiencies of iron, zinc, iodine, and vitamin A. Therefore, sustainable solutions such as balanced fertilization, micronutrient management, biofortification, organic matter restoration, and biologically active soils are essential for producing nutrient-rich crops and healthier populations.

Does Soil Affect Food Taste and Quality?

Beyond providing basic nutrition, soil strongly influences the sensory qualities of food, including flavor, aroma, texture, sweetness, and overall eating experience. The noticeable difference between a tomato grown in fertile garden soil and one produced commercially often reflects the role of soil in determining food quality. Scientifically, soil affects taste and aroma through several interconnected mechanisms. Nutrient availability regulates the production of volatile organic compounds that create distinctive flavors and fragrances in crops. Potassium, for example, enhances sugar synthesis and aromatic compounds in fruits, while balanced soil moisture helps maintain desirable sugar-to-acid ratios essential for flavor development. Soil microorganisms further contribute by producing compounds that plants transform into flavor-related molecules.

A clear example can be observed in aromatic rice varieties of Southeast Asia. Basmati rice from India and Pakistan, jasmine rice from Thailand, and other premium rice types develop their characteristic fragrance only when cultivated in specific soils; the same genetic variety grown elsewhere often produces inferior aroma and taste. Likewise, tea quality is heavily influenced by soil properties such as acidity, mineral composition, and organic matter, explaining differences between Darjeeling and Assam tea. The French concept of *terroir* captures this relationship, emphasizing how soil, climate, and farming practices together create distinctive food qualities, making healthy soils essential not only for nutrition but also for flavor and food diversity.

The Hidden Workforce: Soil Microorganisms

Beneath the soil surface exists a vast hidden community of microorganisms that continuously supports soil fertility and plant growth. Healthy soil contains billions of bacteria, fungi, protozoa, nematodes, and other microbes that together form the soil food web, carrying out essential biological functions beyond the ability of plants alone. One of their most critical roles is nutrient cycling. Although nitrogen constitutes nearly 78% of Earth’s atmosphere, plants cannot use atmospheric nitrogen directly. Beneficial bacteria such as *Rhizobium*, associated with leguminous crops, and free-living *Azotobacter* convert atmospheric nitrogen into plant-available forms, naturally improving soil fertility and reducing fertilizer dependence. Similarly, mycorrhizal fungi help overcome phosphorus limitations by extending thread-like structures beyond plant roots, enabling access to phosphorus and water unavailable in surrounding soil. Nearly 80% of terrestrial plants depend on such associations. Other microorganisms decompose organic matter, solubilize phosphorus, suppress diseases, and stimulate growth. However, excessive tillage, monocropping, and chemical overuse can damage these beneficial microbial communities, making soil biological restoration essential for sustainable agriculture and human nutrition.

Soil Degradation: A Threat to Nutritious Food

Agricultural soils worldwide are degrading at an alarming pace despite growing awareness of soil health. The United Nations estimates that nearly one-third of global soils are moderately to highly degraded, while around 24 billion tons of fertile topsoil are lost annually through erosion. Since topsoil contains most nutrients, organic matter, and beneficial microorganisms, its loss directly reduces soil fertility and crop quality. Continuous harvesting without balanced nutrient replenishment causes nutrient depletion, gradually lowering productivity. Excessive use of synthetic fertilizers, especially nitrogen, may worsen soil degradation through acidification, microbial imbalance, and nutrient dilution, where crops appear productive but contain fewer minerals. Additional threats include salinity, declining organic matter, heavy metal contamination, and climate change–driven erosion, droughts, and floods. Consequently, higher yields may not always ensure healthier, nutrient-rich food.

Soil Contamination and Food Safety

From a food science perspective, soil acts as both a source of nutrients and a potential pathway for contaminants into food. While healthy soil supplies essential minerals, contaminated soils may transfer harmful substances into crops through the same soil-to-plant pathway. Heavy metals are among the most serious concerns. Cadmium, a toxic metal and known carcinogen, can accumulate in crops such as leafy vegetables, potatoes, and grains, often originating from phosphate fertilizers containing cadmium impurities. Lead contamination, though reduced after the phaseout of leaded gasoline, persists in urban and roadside soils and poses severe risks to children, particularly affecting cognitive development. Arsenic presents another challenge, especially in flooded rice-growing systems where paddy rice absorbs arsenic more efficiently, increasing chronic exposure risks in rice-consuming populations. Pesticide residues may also persist in soils and enter root and leafy vegetables. Since soil-derived contaminants become integrated into plant tissues, they cannot easily be removed through washing or cooking. ***The message is clear: safe food starts with safe soil.*** Regular soil testing, contamination prevention, and responsible land management are essential to protect food quality and human health.

Building Healthy Soil for Healthy Food

The encouraging reality is that degraded soils can be restored through proper management and sustainable agricultural practices. Healthy soil develops gradually through continuous interaction among farmers, soil organisms, and the surrounding environment. One of the first steps in soil restoration is soil testing, which helps determine nutrient status, soil pH, organic matter content, and possible contamination. Understanding soil conditions allows farmers to apply nutrients more precisely, preventing both deficiencies and excessive fertilizer use. Balanced fertilization is equally important for maintaining productivity and soil health. Nutrients should be supplied in appropriate amounts and combinations rather than through indiscriminate fertilizer application. Combining synthetic fertilizers with organic sources such as compost, farmyard manure, crop residues, and biofertilizers improves nutrient efficiency and long-term sustainability. Organic amendments restore soil organic matter, improve water retention, and stimulate beneficial microbes. Cover crops reduce erosion and enrich soil fertility, while crop rotation balances nutrient demands and suppresses pests. Conservation agriculture and biofortification further strengthen soil health, ultimately producing resilient crops and more nutritious food for future generations.

Soil Health and Food Security

With the global population projected to approach 10 billion by 2050, ensuring adequate and nutritious food for all presents a major challenge. Climate change, water scarcity, and shrinking agricultural land further intensify this problem, making soil health essential for long-term food security. Healthy soil contributes to food security in several ways. First, it improves crop productivity, often producing 10–30% higher yields than degraded soils due to better fertility, structure, and biological activity. Second, healthy soils enhance nutritional quality, producing crops richer in essential vitamins and minerals, thereby helping address hidden hunger. Third, soils rich in organic matter provide climate resilience by storing more water during droughts and improving drainage during heavy rainfall, reducing crop failure risks. Fourth, healthy soils reduce dependence on expensive external inputs such as fertilizers, pesticides, and irrigation, lowering farming costs and environmental impacts.

Finally, healthy soils sustain rural livelihoods by maintaining long-term agricultural productivity. Therefore, investing in soil health through research, farmer education, and sustainable management practices is not merely an agricultural priority—it is essential for public health, climate resilience, and global food security.

Conclusion

The journey from farm to nutrition begins beneath our feet—in healthy soil. The nutritional quality, flavor, and safety of food largely depend on soil health, which supports plant growth, nutrient availability, and microbial activity. Healthy soil nourishes crops, and crops, in turn, nourish people. However, soil degradation, contamination, and poor management increasingly threaten food quality and human nutrition. Sustainable practices such as balanced fertilization, organic matter management, crop rotation, and soil conservation can restore degraded soils and improve food systems. Protecting soil health is therefore not only an agricultural responsibility but also a public health necessity. Simply put, ***healthy soil and healthy food are inseparable—nutrition truly begins in the soil.***

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Integration of GIS and Remote Sensing Technologies in Precision Horticulture for Soil Health Enhancement

Abstract

Precision horticulture uses data-driven approaches to improve productivity and sustainability, yet challenges like soil degradation, inefficient inputs, and spatial variability persist. Integrating GIS and remote sensing (RS) enables advanced, site-specific soil health management through monitoring and mapping of key parameters. This review analyses their role, applications, and limitations using existing literature. Findings show that GIS–RS supports accurate assessment of soil moisture, nutrients, and organic carbon, aiding decisions on fertilization and irrigation. Despite costs and complexity, emerging AI and IoT technologies are improving accessibility. Overall, GIS–RS integration enhances resource efficiency, soil quality, and long-term sustainability in horticultural systems.

Keywords: Precision horticulture, GIS, Remote sensing, Soil health, Spatial variability, Sustainable agriculture

Introduction

Horticulture, encompassing the production of fruits, vegetables and ornamental crops, plays a vital role in ensuring global food security, improving nutritional quality, and supporting economic development. However, the sustainability and productivity of horticultural systems are strongly influenced by soil health, which governs nutrient availability, water retention, and overall plant growth. In recent years, increasing concerns over soil degradation, climate variability, and inefficient resource use have highlighted the need for advanced, sustainable management approaches. Precision horticulture, a specialized branch of precision agriculture, has emerged as a transformative solution to these challenges (Khot, 2018). It involves the application of advanced technologies such as Global Positioning Systems (GPS), Geographic Information Systems (GIS), remote sensing, and sensor-based tools to monitor spatial variability and optimize input use. This approach enables farmers to apply the "right input, at the right place, at the right time," thereby improving resource-use efficiency and minimizing environmental impacts (Sangeetha *et al*., 2024). Remote sensing technologies such as satellites, UAVs, and aerial imaging enable multi-scale assessment of agriculture. Using multispectral and hyperspectral data, they monitor vegetation health, soil moisture, nutrients, and degradation, supporting early stress detection and timely management interventions (Rai *et al*., 2023). Integrating GIS with remote sensing improves decision-making in precision horticulture by enabling spatial analysis, soil variability mapping, and site-specific management. By combining soil, crop, and climate data, it supports precise input use, enhances soil fertility, reduces overuse, and promotes sustainable production (Panotra *et al*., 2025). Recent advances in geospatial analytics, artificial intelligence, and data fusion techniques have further improved the accuracy of soil health assessment and prediction.

Modern approaches can analyze complex soil parameters such as moisture, nutrient content, and organic matter with high precision, enabling proactive soil management and long-term sustainability (Saki *et al*., 2024). Despite progress, the integration of GIS and remote sensing for soil health in horticulture remains limited. This study reviews their roles, applications, and future potential in enhancing soil health and sustainability within precision horticulture systems.

3. Concept of Precision Horticulture

Precision horticulture refers to the application of advanced information and communication technologies to optimize crop production through site-specific management of field variability. It involves dividing agricultural fields into distinct management zones and applying inputs such as water, fertilizers, and pesticides according to localized requirements, thereby improving efficiency and sustainability (Khot, 2018). This approach integrates GIS, remote sensing, IoT sensors, and Variable Rate Technology (VRT) to enable data-driven decisions and real-time crop monitoring. GIS supports spatial analysis, while remote sensing tracks crop and soil conditions. IoT provides real-time data, and VRT optimizes input use. Studies show these technologies can reduce water use by 20–50% and fertilizer use by 15–30% without affecting yield, promoting sustainable horticulture (Panotra *et al*., 2025). Furthermore, the integration of GIS and remote sensing plays a crucial role in enabling site-specific crop management and improving resource-use efficiency (Sangeetha *et al*., 2024).

Table 1. Components of Precision Horticulture

Component	Function	Benefit
GIS	Spatial mapping	Decision support
Remote sensing	Data collection	Crop monitoring
Sensors (IoT)	Real-time data	Precision control
VRT	Input optimization	Cost reduction

4. Soil Health and Its Importance in Horticulture

Soil health is defined as the capacity of soil to function as a living system that sustains plant productivity, maintains environmental quality, and promotes biological activity. It is a critical factor in horticulture as it directly influences crop growth, nutrient cycling, and water dynamics. Healthy soils support robust root development, enhance nutrient availability, and improve resilience against environmental stresses (Timilsina *et al*., 2025). Soil health is evaluated using physical, chemical, and biological indicators like texture, pH, nutrients, and microbial activity. In precision horticulture, GIS and remote sensing enable spatial monitoring of these factors, supporting targeted management. Tools like NDWI help estimate soil moisture, improving irrigation efficiency and reducing water waste(Sangeetha *et al*., 2024). Additionally, remote sensing and sensor-based approaches support soil mapping and monitoring, contributing to sustainable soil management practices and enhanced productivity (Timilsina *et al*., 2025).

Table 2. Soil Health Indicators

Category	Indicators	Importance
Physical	Texture, bulk density	Root growth
Chemical	pH, NPK, EC	Nutrient availability
Biological	Microbial biomass	Soil fertility

5. GIS Technology in Agriculture

Geographic Information Systems (GIS) are powerful tools that integrate spatial and non-spatial data to support decision-making in agriculture. In horticulture, GIS enables the collection, storage, analysis, and visualization of data related to soil properties, crop conditions, weather patterns, and topography. This integration allows farmers and researchers to identify spatial variability within fields and develop precise management strategies (Mulla, 2013). Applications of GIS include soil fertility mapping, land suitability analysis, irrigation planning, and the development of decision support systems (DSS). By generating prescription maps, GIS facilitates the implementation of variable rate technologies, ensuring that inputs are applied efficiently and only where needed. This not only enhances productivity but also minimizes environmental impacts such as nutrient leaching and soil degradation. Research indicates that GIS-based decision support systems significantly improve resource-use efficiency and agricultural productivity when combined with remote sensing and GPS technologies (Sangeetha *et al*., 2024; Panotra *et al*., 2025).

6. Remote Sensing in Soil and Crop Monitoring

Remote sensing is a key technology in precision horticulture that enables the acquisition of information about crops and soils without direct physical contact. Using satellite, aerial, and ground-based sensors, remote sensing provides real-time and large-scale data on crop health, soil moisture, nutrient status, and environmental conditions. This technology plays a vital role in crop monitoring, yield prediction, irrigation management, and early detection of pests and diseases. By analyzing spectral reflectance from plants, remote sensing can identify subtle changes in crop conditions that are not visible to the naked eye, allowing timely intervention. The use of multispectral and hyperspectral imaging further enhances the accuracy of crop assessment and stress detection. Remote sensing has been widely recognized for its ability to improve decision-making and optimize resource use in agriculture (Sishodia *et al*., 2020).

6.1 Key Vegetation Indices: Vegetation indices derived from remote sensing data are essential tools for assessing crop health and soil conditions. Among these, the Normalized Difference Vegetation Index (NDVI) is the most widely used indicator of crop vigor and biomass, while the Normalized Difference Water Index (NDWI) is used to assess soil and plant water status. The Soil Adjusted Vegetation Index (SAVI) is particularly useful in areas with sparse vegetation, as it minimizes the influence of soil brightness. These indices enable the identification of stress zones, monitoring of crop growth, and delineation of management zones for precision farming. Research has shown that NDVI is extensively used for monitoring vegetation health and correlating crop parameters such as yield, chlorophyll content, and water stress, making it a fundamental tool in precision horticulture (Giovos *et al*., 2021; Sishodia *et al*., 2020).

7. Types of Remote Sensing Platforms

Remote sensing platforms include satellite-based, UAV (drone), and ground-based systems, each offering unique benefits for agricultural monitoring. Satellites like Landsat and Sentinel provide large-scale, multi-temporal data for regional analysis but with limited resolution. UAVs offer high-resolution imagery for precise field-level monitoring of crop health and yield. Ground-based sensors supply real-time, localized data on soil and weather conditions. Integrating these platforms creates a comprehensive monitoring system, improving accuracy, decision-making, and productivity. Studies show that combining multiple remote sensing sources enhances the effectiveness of precision agriculture practices and supports more efficient, data-driven farm management (Fakhar & Khalid, 2023).

Table 3. Types of Remote Sensing Platforms in Precision Horticulture

Platform Type	Description	Key Features	Examples	Applications in Horticulture
Satellite-Based	Sensors mounted on satellites orbiting Earth	Large-scale coverage, periodic data	Landsat, Sentinel	Regional soil mapping, crop monitoring, climate analysis
UAV-Based (Drones)	Low-altitude aerial platforms	High-resolution imaging, flexible use	Multirotor drones, fixed-wing UAVs	Field-level monitoring, disease detection, yield estimation
Ground-Based	Sensors placed within or near fields	Real-time, high accuracy data	Soil moisture sensors, EC sensors	Soil moisture monitoring, nutrient assessment, irrigation management

8. Integration of GIS and Remote Sensing

The integration of GIS and remote sensing (RS) is central to precision horticulture, enabling efficient data fusion, analysis, and decision-making. Remote sensing provides large-scale data on crop health, soil moisture, and environmental conditions via satellites and UAVs, while GIS manages and visualizes this spatial information. The workflow includes data acquisition, preprocessing, and extraction of indicators like vegetation indices, followed by integration into GIS for mapping and analysis. This supports identification of field variability and creation of prescription maps for site-specific management. Overall, GIS–RS integration improves input efficiency, enhances productivity, and strengthens precision-based agricultural decision-making systems (Sangeetha *et al*., 2024; Fakhar & Khalid, 2023).

9. Applications in Precision Horticulture

The application of precision technologies in horticulture has transformed traditional farming into a data-driven system that enhances productivity and sustainability. One of the primary applications is soil fertility mapping, where GIS and remote sensing are used to assess spatial variability in soil nutrients and develop targeted fertilization strategies. Variable rate fertilization allows farmers to apply nutrients according to site-specific requirements, reducing waste and improving efficiency. Irrigation scheduling is another critical application, where remote sensing indices such as NDWI help monitor soil moisture and optimize water use (Halder *et al*., 2024; Mulla, 2013). Additionally, remote sensing plays a vital role in pest and disease detection by identifying stress patterns in crops through spectral analysis, enabling early intervention. Yield prediction is also facilitated through the integration of remote sensing data, GIS models, and machine learning techniques, allowing farmers to forecast production and plan accordingly. These applications collectively contribute to improved resource-use efficiency, reduced environmental impact, and enhanced crop yields (Rai *et al*., 2023; Giovos *et al*., 2021).

10. Challenges and Limitations

Despite its benefits, precision horticulture adoption faces key challenges. High initial costs of technologies like drones, sensors, and GIS tools limit access for smallholder farmers. Technical complexity requires specialized skills for data analysis and interpretation, while lack of awareness and training further restricts use. Additionally, managing large volumes of data from sensors and remote sensing systems demands strong storage and processing capabilities. These economic, technical, and infrastructural barriers significantly hinder widespread adoption, particularly in developing regions where resources, expertise, and digital infrastructure remain limited, slowing the transition to advanced, data-driven agricultural practices (Panotra *et al*., 2025; Fakhar & Khalid, 2023).

11. Future Perspectives

The future of precision horticulture lies in the integration of emerging technologies that enhance automation, accuracy, and scalability. The combination of Artificial Intelligence (AI) with GIS and remote sensing is expected to revolutionize agricultural decision-making by enabling predictive analytics, automated crop monitoring, and intelligent recommendation systems. IoT-based real-time monitoring systems will allow continuous tracking of soil, crop, and environmental parameters, improving responsiveness and efficiency (Khot, 2018; Panotra *et al*., 2025). Climate-smart agriculture supported by precision technologies helps farmers adapt to climate variability and reduce environmental impacts. Big data analytics enables integration of diverse datasets for better crop and resource management, making precision horticulture more efficient, accessible, and sustainable for future smart farming systems (Duff *et al*., 2021; Rai *et al*., 2023).

Conclusion

The integration of GIS and remote sensing (RS) is transforming precision horticulture, especially in soil health management. These geospatial tools enable accurate monitoring and mapping of soil moisture, nutrients, and organic carbon across space and time, supporting site-specific practices like variable rate fertilization, optimized irrigation, and targeted amendments. This improves resource efficiency and crop productivity. The addition of AI, machine learning, and IoT enhances data analysis, predictive modeling, and real-time decision-making. However, high costs, technical complexity, and limited access for smallholders remain challenges. Addressing these through supportive policies, training, and user-friendly technologies is essential for wider adoption. Overall, GIS–RS integration promotes sustainable and climate-resilient horticulture.

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Artificial Intelligence Driven Crop Disease Surveillance: Opportunities and Challenges for Smallholder Farmers

Abstract

Crop diseases significantly impact agricultural productivity and food security worldwide. Advances in AI, particularly ML and DL, have enabled automated disease detection using computer vision, sensors, and cloud platforms, achieving accuracies above 90–98% in controlled settings. This review evaluates AI-based crop disease surveillance, its relevance to smallholder farmers, and key challenges such as limited data, high costs, and low digital literacy. It also explores future directions, including explainable AI, edge computing, and mobile-based solutions for resource-limited environments. While AI offers transformative potential for sustainable agriculture, inclusive adoption will require supportive policies, affordable technologies, and improved accessibility for smallholder farming communities.

Keywords: Artificial intelligence, crop disease detection, deep learning, smallholder farmers, precision agriculture, CNN, digital agriculture.

1. Introduction

Crop diseases remain a major constraint on global agricultural productivity and food security, causing significant yield losses and economic damage worldwide. Recent estimates indicate that plant diseases are responsible for **10–40% reductions in crop yields annually**, posing a serious threat to sustainable food systems, particularly in developing countries where smallholder farmers dominate agricultural production (Shahane *et al*., 2025). Smallholder farmers are highly vulnerable due to limited access to inputs, resources, and expert guidance, making timely disease detection essential for reducing losses and protecting livelihoods. Traditional methods like manual inspection and lab diagnostics are slow, labor-intensive, and subjective, and in resource-poor areas, lack of expertise further delays detection, enabling diseases to spread unchecked rapidly (Dianambika *et al*., 2025). These limitations highlight the need for more efficient, scalable, and accessible approaches to crop disease surveillance. In this context, **artificial intelligence (AI)** has emerged as a promising solution for transforming agricultural practices through data-driven decision-making and precision farming. Advances in **machine learning (ML) and deep learning (DL)** particularly convolutional neural networks (CNNs) have enabled automated and highly accurate detection of plant diseases from image data. Studies report that such models can achieve **accuracy levels exceeding 90%** under controlled conditions, significantly outperforming traditional approaches (Dianambika *et al*., 2025). Furthermore, the integration of AI with **remote sensing technologies, Internet of Things (IoT) devices, and unmanned aerial vehicles (UAVs)** has enhanced the capability for real-time, large-scale crop monitoring, enabling early detection and targeted intervention strategies (Lebrini & Gotor, 2024). Despite advances, adoption of AI-based crop disease systems among smallholders remains low due to high costs, limited digital access, poor-quality datasets, and lack of technical skills.

Table 1. Key Components of AI-Driven Crop Disease Surveillance Systems

Component	Technologies Used	Function	Relevance to Smallholder Farmers
Data Acquisition	RGB cameras, UAVs, hyperspectral imaging, IoT sensors	Collect crop images and environmental data	Low-cost mobile cameras and basic sensors improve accessibility
Data Processing	Image pre-processing, segmentation, feature extraction	Enhance data quality and prepare inputs for models	Automated pre-processing reduces need for technical expertise
Modeling	CNN, SVM, Random Forest, YOLO, Vision Transformers	Detect and classify diseases, predict outbreaks	Lightweight models enable use on mobile devices
Deployment	Mobile apps, cloud platforms, edge computing	Provide real-time alerts and recommendations	Mobile-based tools support on-field decision-making
Data Acquisition	RGB cameras, UAVs, hyperspectral imaging, IoT sensors	Collect crop images and environmental data	Low-cost mobile cameras and basic sensors improve accessibility

Many models are tested in controlled settings, limiting real-world applicability, highlighting a gap between innovation and practical implementation that requires more holistic evaluation (Shahane *et al*., 2025; Susheel & Rajkumar, 2023). This study examines AI-driven crop disease surveillance, focusing on opportunities and challenges for smallholder farmers. It reviews technologies, assesses suitability in resource-limited settings, identifies adoption barriers, and suggests future research to improve scalability, affordability, usability, and promote inclusive, sustainable agricultural solutions.

2. Conceptual Framework of AI-Driven Crop Disease Surveillance

AI-driven crop disease surveillance shifts farming from reactive to proactive management by combining sensors, data analytics, and predictive models for early detection and decision-making. This integration improves crop monitoring, reduces losses, and supports sustainable productivity, especially in smallholder farming systems **(Nkwocha *et al*., 2025; Kusharki *et al*., 2025)**.

2.1 Components of AI-Based Systems: AI-driven crop disease surveillance systems operate through an integrated, multi-layered architecture comprising data acquisition, data processing, modeling, and deployment. The **data acquisition layer** collects crop images using RGB cameras, hyperspectral imaging, and unmanned aerial vehicles (UAVs), along with environmental parameters (e.g., temperature, humidity and soil moisture) through IoT-enabled sensors. These diverse datasets form the basis for accurate disease detection (Shahane *et al*., 2025). The system processes data through noise reduction, segmentation, and feature extraction, then applies ML/DL models like SVM, RF, CNNs, YOLO, and Vision Transformers for accurate disease detection. Deployment via mobile and cloud platforms enables real-time diagnosis, alerts, and continuous monitoring, improving early detection and reducing crop losses (Kusharki *et al*., 2025; Shahane *et al*., 2025).

2.2 Machine Learning Vs Deep Learning Approaches: Machine learning (ML) and deep learning (DL) techniques form the core analytical components of AI-based crop disease detection systems, differing in their computational complexity, data requirements, and performance outcomes. Traditional ML approaches rely on handcrafted features extracted from images, whereas DL models automatically learn hierarchical features directly from raw data, enabling superior performance in complex classification tasks. Deep learning models, particularly CNN-based architectures, have demonstrated significantly higher accuracy in plant disease detection compared to traditional ML approaches, owing to their ability to capture complex spatial patterns and non-linear relationships **(Shahane *et al*., 2025; Liao, 2025)**.

2.3 Data-Driven Early Warning Systems: Data-driven early warning systems enable predictive crop management by integrating weather, soil, and historical data to forecast disease outbreaks. Using machine learning, they identify conditions favorable for disease development and provide timely alerts, supporting proactive interventions and reducing potential crop losses **(Nkwocha *et al*., 2025; Kusharki *et al*., 2025)**.

3. AI Technologies for Crop Disease Detection

3.1 Convolutional Neural Networks (CNNs): CNNs are widely used for plant disease detection due to their strong image analysis, achieving over 90–98% accuracy in controlled settings. Advanced models like ResNet, EfficientNet, and MobileNet improve efficiency and real-time performance, though accuracy may drop under variable field conditions (Shahane et al., 2025; Liao, 2025).

3.2 Transformer and Hybrid Models: Recent AI advances include transformer-based and hybrid models that combine CNNs with attention mechanisms to improve robustness and generalization. They capture contextual relationships and handle noise and lighting variations effectively. Architectures like CNN–Transformer and Vision Transformers perform well in complex agricultural settings, especially with multimodal data (Kusharki *et al*., 2025; Liao, 2025).

3.3 Smartphone-Based Applications: Smartphone-based AI apps enable farmers to capture crop images and receive instant disease diagnosis and recommendations. Powered by lightweight models, they are low-cost, accessible, and user-friendly, making them ideal for smallholders. Offline and edge capabilities further improve usability in rural areas with limited internet access (Kusharki *et al*., 2025).

3.4 Drone and Remote Sensing Technologies: Drone and satellite remote sensing enables large-scale, non-invasive crop monitoring for early disease detection. Using NDVI, hyperspectral/multispectral, and thermal imaging, these systems identify crop stress and disease patterns across fields and regions efficiently. These technologies can detect subtle physiological changes in plants before visible symptoms appear, enabling proactive disease management (Nkwocha *et al*., 2025). The integration of UAVs with AI models further enhances detection accuracy by combining spatial, spectral, and environmental data, supporting predictive analytics and large-scale surveillance (Shahane *et al*., 2025).

4. Opportunities for Smallholder Farmers

4.1 Early Disease Detection and Yield Improvement: AI technologies enable early and accurate detection of crop diseases, allowing farmers to take timely preventive measures and reduce yield losses. Deep learning models, particularly convolutional neural networks (CNNs), can identify

Table 2. AI Technologies for Crop Disease Detection

Technology	Key Models/Tools	Advantages	Limitations	Relevance to Smallholders
CNNs	ResNet, EfficientNet, MobileNet	High accuracy, strong image analysis	Sensitive to environmental variation	Mobile deployment possible
Hybrid/Transformers	ViT, CNN-Transformer	Robust to noise, better generalization	High computational cost	Limited but growing applicability
Smartphone Apps	Mobile CNN models	Low cost, real-time diagnosis	Depends on image quality	Highly suitable
Drones & Remote Sensing	UAVs, NDVI, hyperspectral	Large-scale monitoring, early detection	High cost, technical complexity	Limited access but high potential

disease symptoms at early stages, improving decision-making and overall crop productivity **(Shahane *et al*., 2025)**. Compared to traditional methods, AI-based systems provide faster, more consistent, and scalable diagnosis, which is especially valuable in regions with limited access to agricultural experts **(Nkwocha *et al*., 2025)**.

4.2 Reduction in Pesticide Use: AI-based systems support targeted disease management by identifying specific infections and affected areas. This enables precise application of pesticides, reducing excessive chemical use and minimizing environmental impact. Such approaches contribute to sustainable agricultural practices while lowering input costs for farmers **(Kusharki *et al*., 2025)**.

4.3 Accessibility Through Mobile Technologies: Mobile-based AI applications provide cost-effective and user-friendly solutions for smallholder farmers. These tools allow farmers to capture crop images and receive real-time disease diagnosis and recommendations. Lightweight models and offline capabilities further improve accessibility in rural areas with limited internet connectivity, bridging the gap between advanced technologies and field-level implementation **(Kusharki *et al*., 2025; Liao, 2025)**.

5. Challenges and Limitations

5.1 Data Availability and Quality: AI models require large, diverse, and high-quality datasets for effective training. However, limited availability of annotated agricultural datasets, particularly for rare diseases and diverse environmental conditions, affects model performance and generalization in real-world scenarios (Shahane *et al*., 2025; Kusharki *et al*., 2025).

5.2 Environmental Variability: AI model performance can decline under real-world conditions due to environmental variability such as lighting changes, complex backgrounds, and inconsistent image quality. Models trained on controlled datasets often struggle to adapt to diverse field environments, reducing their reliability in practical applications **(Liao, 2025; Shahane *et al*., 2025)**.

5.3 Digital Literacy and Adoption Issues: Limited digital literacy and technical knowledge among farmer's present significant barriers to the adoption of AI technologies. Many smallholder farmers lack familiarity with mobile applications and digital tools, highlighting the need for training programs, user-friendly interfaces, and extension services to support effective implementation **(Kusharki *et al*., 2025)**.

Table 3. Opportunities and Challenges of AI in Smallholder Farming

Aspect	Opportunities	Challenges	Implications
Disease Detection	Early diagnosis, improved yield	Reduced accuracy in field conditions	Need for robust models
Pesticide Use	Targeted application, reduced chemicals	Risk of misclassification	Requires high precision
Accessibility	Mobile-based solutions	Digital literacy gaps	Training required
Infrastructure	Scalable AI systems	High cost, limited connectivity	Need low-cost solutions
Data	Improved prediction	Limited datasets	Need diverse data collection

6. Case Studies and Applications

6.1 AI in Horticultural Crops: CNN-based AI models are widely used for disease detection in crops like tomato, potato, and rice, achieving over 95% accuracy under controlled conditions. Advanced models such as ResNet, VGG, and MobileNet improve efficiency, while multi-crop models show over 97% accuracy, demonstrating scalability across agricultural systems (Mohanty *et al*., 2016; Too *et al*., 2019; Gülmez, 2024; Jagan *et al*., 2025).

6.2 Field vs Controlled Conditions: AI models achieve high accuracy in controlled settings but often perform poorly in real field conditions due to lighting variations, background complexity, occlusion, and inconsistent image quality. This limits generalization, highlighting the need for robust, adaptive, and field-ready models to ensure reliable real-world performance (Mohanty *et al*., 2016; Too *et al*., 2019; **Gülmez, 2024)**.

7. Future Perspectives

7.1 Explainable AI (XAI): Explainable AI (XAI) improves transparency by showing how AI models make predictions, helping users understand results. This builds trust among farmers and stakeholders, making AI systems more reliable, user-friendly, and suitable for critical agricultural decision-making (Kaleeswari & Sundarrajan, 2024).

7.2 Federated Learning: Federated learning enables decentralized training by allowing users to share insights, not raw data, preserving privacy. It improves model performance using diverse datasets and addresses data scarcity and privacy challenges, making it a promising approach for agricultural AI systems (Jagan *et al*., 2025; Kaleeswari & Sundarrajan, 2024).

7.3 Scalable Solutions for Smallholders: Low-cost, scalable, and user-friendly AI solutions are key to wider adoption among smallholder farmers. Emphasizing lightweight models, mobile platforms, offline use, and farmer training can bridge the gap between advanced AI technologies and practical, real-world agricultural applications (Gülmez, 2024; Kaleeswari & Sundarrajan, 2024).

Conclusion : AI-driven crop disease surveillance is transforming agriculture by enabling early detection, reducing losses, and supporting data-driven decisions through machine learning, deep learning and remote sensing. However, adoption among smallholder farmers is limited by data scarcity, high costs, environmental variability and low digital literacy. Addressing these challenges requires affordable, scalable, and user-friendly solutions such as mobile platforms and edge AI systems. Advances in explainable AI and federated learning can further improve transparency, trust and data privacy. Collaborative efforts among developers, policymakers, and farmers are essential to ensure inclusive, practical and sustainable implementation of AI technologies in agriculture.

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EMPOWERING AGRIBUSINESS STARTUPS: GOVERNMENT INITIATIVES AND SUPPORT

Summary
This article reviews major Government of India initiatives supporting agribusiness startups. It covers policy support, financial assistance, infrastructure development, incubation programmes and flagship schemes such as MANAGE-CIA, Bharat-VISTAAR, Pradhan Mantri Mudra Yojana (PMMY) and Startup India Seed Fund Scheme. The impact on job creation, farmer income and rural entrepreneurship is also discussed.

Introduction The history of agriculture is as old as the history of humankind. As humankind evolved, so did agriculture. Before systematic cultivation, humans were hunters and gatherers. Although wild grains were gathered in the Middle Stone Age (280,000 to 50–25,000 years ago), domestication of plants for food began only about 10,000 years ago. Wheat, barley, peas, lentil, chickpea, flax, rice and potato were among the earliest cultivated crops in the Eastern Mediterranean region. Agriculture later spread worldwide. In India, intensification started along the Indus River during the Bronze Age (Pandey and Kumari, 2021).

After the discovery of sea routes, crops moved across continents. Potato travelled from the Americas to Europe, while wheat, barley and rice moved from the Mediterranean to the Americas. Agriculture intensified further during the British Agricultural Revolution (17th–19th centuries) through crop rotation, fertilisers and irrigation. India faced severe challenges after independence in 1947. Today, India is a net exporter of food and one of the world's top producers of nearly 17 agricultural commodities, thanks to the efforts of its farmers and policy reforms. The Indian Government recognises the role of "agribusiness" and "entrepreneurship" in enhancing farm incomes and creating employment opportunities. The Committee on Doubling Farmers' Income emphasised secondary agriculture and post-production activities. The Government's holistic policy approach has encouraged youth to become agripreneurs. Agripreneurship applies entrepreneurial principles to agriculture to increase financial gains, productivity and innovation (Trivedi and Patel, 2024). It plays a vital role in job creation, raising farmer incomes and rural development (Sonkar and Yadav, 2024). Government initiatives have been foundational in shaping the agribusiness startup ecosystem in India, especially by improving access to finance.

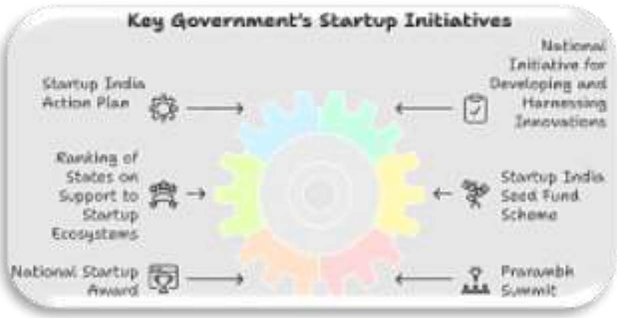
Role of Government Initiatives in Promoting Agribusiness

Policy Formulation and Implementation: Government departments focus on agripreneurship to create a business-friendly climate for farming. New policies and action plans are needed, especially for women agripreneurs (Aggarwal et al., 2004).

Financial Assistance and Schemes: The government provides financial support through programmes focused on small businesses and rural artisans, including Women's Development Programs (WDCs), Mahila Kisan Sashakti Karan Pariyojna (MKSP), ARVIND and MAHIMA.

The 2020 economic package allocated funds for beekeeping, herbal agriculture, dairy infrastructure and micro-food businesses (Singh et al., 2023).

Developing Infrastructure: Investments are made in rural roads, market yards, storage and cold-storage facilities. The Scheme for Agro-Marine Processing and Development of Agro-Processing Clusters (SAMPADA) aims to expand food-processing capacity.



Supporting Agri-Entrepreneurship Development: Rashtriya Krishi Vikas Yojana (RKVY) and RKVY-RAFTAAR provide financial support and incubation environments for innovative agripreneurship.

Establishing Agri-Business Incubators: Incubators offer technical, financial, marketing support, training, mentoring, seed funding and investor linkages. Programmes such as RKVY-RAFTAAR, Startup India and Atal Innovation Mission (AIM) back these incubators.

Addressing Challenges and Removing Barriers: The government is simplifying procedures and creating single-window mechanisms to reduce bureaucracy and improve ease of doing business.

Promoting Public-Private Partnerships (PPP): PPP models deliver high-tech and digital services to farmers while avoiding duplication of efforts.

Key Initiatives

MANAGE-CIA Agribusiness Incubation Programme: A government-supported programme under RKVY-RAFTAAR that provides mentoring, grant funding and incubation support. Startups with minimum viable products can receive grant-in-aid up to ₹25 lakh.

Bharat-VISTAAR: Virtually Integrated System to Access Agricultural Resources – an AI-driven multilingual platform that integrates AgriStack with ICAR package of practices and delivers real-time personalised advisories to farmers.

Pradhan Mantri Mudra Yojana (PMMY): Launched in 2015, it offers collateral-free loans up to ₹10 lakh to micro and small enterprises (Shishu: up to ₹50,000; Kishor: ₹50,000–₹5 lakh; Tarun: ₹5 lakh–₹10 lakh). Over 45 crore loans have been sanctioned.

Startup India Seed Fund Scheme (SISFS): Provides up to ₹20 lakh to early-stage startups for prototype development and market entry.

Impact on Agribusiness Startups

Significant increase in the number of agriculture companies nationwide. • Youth now view entrepreneurship as a viable career option. • Adoption of automation, data analytics and mobile applications has improved productivity. • Creation of jobs in production, processing, marketing and services, reducing rural-urban migration. • Stronger agricultural value chains and better price realisation for farmers.

Conclusion: Government initiatives have revolutionised agribusiness entrepreneurship in India by addressing funding, technology and infrastructure challenges. Agriculture startups are driving innovation, job creation and higher productivity. However, issues of awareness, implementation efficiency, regional disparities and sustained support still remain. A more comprehensive strategy with better coordination and continuous assistance is needed to unlock the full potential of these efforts.

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Nanopore Sequencing: A Revolutionary Tool for Dairy and Food Safety Diagnosis

Introduction

Milk is a daily staple for millions of Indian families, but hidden microbial contamination can turn this nutritious food into a health risk. Traditional detection methods are slow, costly, and often take several days, which delays diagnosis and increase the chance of unsafe milk consumption. This delay costs lives, especially for pregnant women, elderly people, and children whose immune systems are weak. Now imagine a technology so advanced that it can identify exactly which bacteria is causing disease in your cow's milk within six hours, tell you which antibiotics will work against it, and send the results directly to your smartphone. This is not science fiction. This technology exists today and is called nanopore sequencing. Nanopore sequencing belongs to what scientists call third-generation sequencing technology. Unlike older methods that required complex laboratory equipment, expensive reagents, and highly trained scientists, nanopore sequencing is portable, affordable, and can be used in field conditions. The MinION device, the smallest nanopore sequencer from Oxford Nanopore Technologies, is about the size of a smartphone and weighs only 90 grams. You can carry it in your pocket, plug it into a laptop or even a smartphone, and sequence DNA from bacteria found in milk samples right at the farm. This portability is revolutionary because it means we can diagnose diseases where they occur, not send samples to distant laboratories and wait days for results it is a promising tool for India's expanding dairy sector, where faster diagnosis can mean safer dairy products and better disease control.

What is Nanopore Sequencing and How Does It Work?

To understand nanopore sequencing, let's first understand what DNA is and why sequencing helps us identify bacteria. Every living organism, including bacteria, has DNA inside its cells. Different bacteria have slightly different DNA sequences, just like different people have different fingerprints. If we can read the DNA sequence of a bacterium, we can identify exactly which species it is, what diseases it can cause, and even which antibiotics it is resistant to.Traditional DNA sequencing methods work by breaking DNA into small pieces, copying them many times, and then trying to figure out the sequence. These methods are slow, expensive, and require sophisticated laboratory equipment. Nanopore sequencing works on a completely different principle This is like having a molecular machine that can read the genetic code of any bacterium directly, without needing to copy it millions of times. Imagine a tiny pore that only one strand of DNA can pass through it at a time. This pore is called a nanopore, and it's made of a protein. When you apply an electrical voltage across this nanopore, electric current flows through it. Now, when a single strand of DNA passes through the nanopore, each nucleotide in the DNA sequence (A, T, G, C) blocks the electric current differently.

By measuring these tiny changes in electrical current, the device can "read" the DNA sequence in real time without needing sophisticated infrastructure and skill

Applications in Food Safety and Pathogen Detection

Nanopore sequencing has enormous potential for food safety in the dairy industry. Milk and dairy products can be contaminated with various pathogens that cause foodborne illnesses in humans. Common foodborne pathogens include *Listeria monocytogenes*, *Salmonella species*, *Escherichia coli* O157:H7, *Campylobacter*, *Staphylococcus aureus*, and *Brucella* species. These bacteria can contaminate milk at the farm through contaminated udders, manure, or equipment, or during processing through poor hygiene practices.

Traditional methods for detecting foodborne pathogens in milk involve culture on selective media, biochemical tests, and serological tests. These methods take 24-72 hours for preliminary results and several more days for confirmatory identification. During this time, contaminated products may already be distributed and consumed, causing outbreaks of foodborne illness. Even when contamination is detected, it is often too late to prevent illness.

Nanopore sequencing can detect these pathogens much faster. By sequencing the entire genome of bacteria in a milk sample, you can identify not just which species is present, but which specific strain it is. This is critical for outbreak investigation. When people get sick from contaminated food, health authorities need to identify the source of contamination quickly to prevent more people from getting sick. With nanopore sequencing, you can compare the genome of bacteria from sick patients with bacteria from milk samples, dairy equipment, or farm environments. If the genomes match exactly, you know you have found the source of the outbreak. This can be done in hours instead of days, significantly limiting the scope of the outbreak. Another important application is monitoring the microbiome of dairy products. Many dairy products, especially fermented products like yogurt, cheese, and lassi, contain beneficial bacteria called probiotics that provide health benefits to consumers. However, these products must be made with the right strains of bacteria, and contamination with harmful bacteria must be prevented. A study using nanopore sequencing for probiotic development showed that the technology could sequence the genomes of lactic acid bacteria used in dairy fermentation at 75% lower cost and much faster than traditional methods. This helped food companies assess the safety of their probiotic strains, verify their identity, and ensure consistent quality in their products.

Nanopore Sequencing for Bovine Mastitis Diagnosis: Bovine mastitis is the most common and economically important disease in dairy animals worldwide. In India, mastitis affects millions of dairy cows and buffaloes, causing enormous economic losses The disease is caused by various bacteria, including *Escherichia coli*, *Staphylococcus aureus*, *Streptococcus uberis*, *Klebsiella pneumoniae*, and many others. The problem is that different bacteria cause mastitis, and they require different treatments. If you use the wrong antibiotic, the infection will not cure, the animal will continue to suffer, and the bacterium may become resistant to that antibiotic. Nanopore sequencing identified the causative bacteria with high accuracy within approximately 6 hours from the time of sample collection. When the major causative bacteria of bovine mastitis identified farmer could start the right treatment almost immediately instead of waiting several days. The study also showed that nanopore sequencing could identify bacteria that are difficult to grow in culture, which means it can detect infections that would be missed by traditional methods. This information can help develop better prevention strategies, identify high-risk farms, and monitor the spread of dangerous bacteria across regions.

Antimicrobial Resistance Surveillance in Dairy: Antimicrobial resistance (AMR) is one of the most serious public health threats facing the world today. When bacteria become resistant to antibiotics, infections become harder or impossible to treat, leading to prolonged illness, increased mortality, and higher healthcare costs. Dairy animals are often given antibiotics to treat infections such as mastitis, respiratory diseases, and reproductive problems. When bacteria in dairy animals develop resistance to these antibiotics, they can transfer to humans through consumption of contaminated milk, direct contact with animals, or through environmental contamination.

Traditional methods for detecting antibiotic resistance involve testing bacteria against different antibiotics in culture, which takes days and only tests a limited number of antibiotics. With nanopore sequencing, you can sequence the entire genome of a bacterium and identify all the antibiotic resistance genes it carries in a single test these providing insights that traditional methods cannot provide in single run and help for better surveillance and discourage indiscriminate use of antibiotic.

Conclusion: Nanopore sequencing is emerging as a powerful tool for improving dairy health and food safety. Its main strength lies in speed, allowing pathogens to be detected far earlier than with conventional methods. For Indian dairy systems, this means quicker diagnosis of mastitis and other infections, more targeted treatment, less antibiotic misuse, and better milk quality. It also helps cooperatives, laboratories, and processing units strengthen quality control and respond faster to contamination events. For farmers, it can reduce losses and support healthier animals; for consumers, it offers safer milk and greater confidence in dairy products. As this technology becomes more accessible, it has the potential to reshape dairy diagnostics and make disease management more efficient, practical, and reliable.

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The Invisible Threat: Non-Typhoidal Salmonella in the Indian Dairy Value Chain

Introduction

Dairy producers usually focus on mastitis-causing microbes because they directly impact animal health and milk yield, but another serious threat hides in the food chain: Non-Typhoidal Salmonella (NTS). Unlike typhoid strains (*Salmonella* ***typhi,*** *Salmonella Paratyphi* A) that mainly infect humans, NTS represents a large group of zoonotic bacteria that migrate between animals, food, and people. The World Health Organization consider NTS as one of the deadliest foodborne bacterial pathogen, leading an estimated 93 million enteric infections and over 155,000 deaths globally every year.

In India, this problem is getting worse as milk production expands to fulfil increasing local demand and export target. For dairy farmers, processors, and cold-chain operators, the real task is not only producing more milk, but also preventing contamination throughout dairy supply chain from milking to storage to final consumer. If Salmonella enters the milk chain, it can damage public health, compromise product quality, and create serious financial burden.

NTS includes many serotypes such as *Salmonella enterica* serotype Newport *Salmonella enterica* serotype Heidelberg *Salmonella enterica* **serotype Weltevreden** (India), but *Salmonella typhimurium* and *Salmonella enteritidis* are some of the most frequent in foodborne outbreaks. Although these organisms are often associated with poultry and eggs, they are also found in raw milk, processed milk, and traditional dairy products in Indian dairy systems, particularly in areas where temperature control, water quality, and hygiene are compromised.

How it enters in milk

Salmonella is commonly enter through the digestive track and reaches the dairy environment through feces. Bacteria can infiltrate the milk supply if cows are milked in unclean conditions, if teats are not thoroughly cleaned, or if milking instruments are contaminated or If the milk is not promptly chilled, even a tiny contamination can become significant because most of the country follow zero tolerance policy for it.

Why it spreads fast

India's high ambient temperature accelerates ***Salmonella*** growth in warm milk during transport. What starts as minor farm contamination rapidly multiplies before reaching processing facilities. This rapid proliferation is driven by *Salmonella's* robust, redundant metabolic networks and advanced stress response systems, which allow the pathogen to adapt and thrive effortlessly in shifting environments. Consequently, maintaining immediate cooling, strict hygienic handling, and swift cold-chain movement is absolutely critical to suppress this resilient bacteria and safeguard the supply.

Risk in traditional dairy products

Paneer, khoya, peda, and other milk-based desserts are particularly susceptible due to their moisture content, high nutrient content, and frequent manual handling. Salmonella can survive or infect food after processing if contaminated water is utilized, equipment is not cleaned, or workers handle products improperly. Because of this, conventional dairy products require the same level of food safety regulation as mass-produced goods.

2. Drivers of Emergence: The Silent Carrier Phenomenon

The way Non-Typhoidal Salmonella spreads across a herd makes it so harmful and elusive.

The Healthy Shedder

NTS rarely results in obvious udder injury in cows, in comparison to mastitis bacteria. Adult cattle who are infected frequently exhibit no symptoms. As "silent carriers," they release millions of live cells into their excrement while harboring the bacteria in their digestive tract. Farmers are fully ignorant that an extremely deadly disease is circulating through the farm yard since the animal appears healthy and its milk seems perfect.

Poor On-Farm Sanitation

Gaps in daily sanitation are correlated with an increase in NTS in intensive dairy setups. Drying dung crusts form when farms neglect to thoroughly cleaning before using milking machines or neglect to do routine pre-milking teat washing.

Cross-Contamination Sources

Salmonella is quite robust bacteria; it can live for months in moist soil, unclean feeding stations, and stagnant water troughs. The disease is continuously reintroduced into the herd's surroundings via rats, farm dogs, and wild birds that drink from shared water sources.

3. The True Significance: Global Fatalities and Human Impact

The phrase "food poisoning" frequently brings up images of a slight stomach upset, but NTS infection (Salmonellosis) is a very different kind of illness.

Acute Gastrointestinal Attack

The germs penetrate the human intestinal lining within 6 to 72 hours of consuming contaminated raw milk or inadequately managed dairy products. This causes extreme nausea, watery, occasionally bloody diarrhoea, severe cramping in the abdomen, and sudden start of high fever. The severe fluid loss can be crippling, even though healthy adults usually recover in a few days.

The Invasive Disease and Vulnerable Population

The elderly, those with weakened immune systems, small children and preganant womens are highly susceptible of NTS. Invasive Non-Typhoidal Salmonella (NTS) is a disease that occurs in around 5% of instances when the bacteria completely exit the intestine and enter the circulation. This causes potentially lethal consequences like meningitis, septic arthritis, and bacteremia (blood poisoning), which have an alarmingly high case fatality rate in underdeveloped nations.

4. The Burning Concern: Multidrug-Resistant (MDR) *Salmonella*

Multidrug Resistance (MDR) defined as resistance to three or more different classes of antibiotics simultaneously. A clear trend toward Multidrug Resistance (MDR), has been observed in recent laboratory analyses of Indian dairy and livestock Salmonella isolates.

Over decades of record break livestock production, the systematic misuse of antibiotics as routine preventative treatments has forced Salmonella to evolve robust survival mechanisms to dodge antibotics and become MDR salmonella.

5. Field Action Plan: Blocking *Salmonella* at the Source

An MDR strain of Salmonella bridges the gap between the human hospital bed and the dairy farm when it contaminates the milk supply. When a consumer infected with MDR strain, normal, empirical hospital treatments are ineffective, leading to a protracted sickness, exorbitant medical expenses, and an increased chance of death.

It takes an unwavering dedication to everyday clean milk production and careful temperature control to eradicate non-typhoidal Salmonella.

Implement Strict Pre-Milking Sanitation: Never milk a cow whose teats are damp or unclean. Clean every teat with a special sanitizing solution, remove any organic material, and use fresh, single-use paper towels to properly dry the skin.

Safe Clean Water and Feed Supplies: Water troughs need to be cleaned, disinfected, and scrubbed every week because they are a significant hotspot for the spread of Salmonella. Make sure feed stockpiles are raised and shielded from domestic pets, rats, and birds.

Set Up a Rigid Cold Chain supply: When temperatures go below 7°C, Salmonella fails to grow. Freshly drawn raw milk should be transferred to a Bulk Milk Cooler (BMC) and chilled to 4°C within two hours of leaving the udder. Maintaining constant chilling of the milk guarantees that the bacterial population won't blow up even in the event of a little contamination.

Adopt Strict Pasteurization Standards: Never give raw milk that hasn't been cooked or pasteurized to people. To ensure that all live bacterial cells are completely destroyed before the milk reaches packaging lines, make sure commercial pasteurizers are tuned correctly (72ºc for 15 seconds).

Stick to Reasonable Antibiotic Use: Avoid giving antibiotics without a valid diagnosis from a licensed field veterinarian. Use diagnostic methods, such as antibiotic sensitivity testing, extensively to make sure that medication is administered precisely when needed, hence slowing the spread of AMR.

Conclusion: Non-Typhoidal Salmonella may be an invisible foe, but it can be controlled with basic, disciplined cleanliness. The Indian dairy industry can protect customers, maintain its market reputation, and guarantee that every glass of milk spilled nationwide is pure, nourishing, and completely safe by viewing the farm floor as a crucial starting point for human food safety.

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Kefir: A New-Age Fermented Milk Product and Its Significance for the Indian Dairy Sector

Introduction

The dairy product consumption pattern in india is changing fast. Consumers no longer consume milk only for basic nutrition such as a source of protein, fat, and calcium; many now want foods that also support digestion, immunity, lifestyle wellness, and preventive health. This shift has opened the door to a new generation of dairy products that are not just nutritious but also functional. Among these, Russian traditional fermented milk *kefir* is now popular as one of the most exciting functional dairy drink of the present era. Although it has old traditional roots, *kefir* feels new in today's indian market because it fulfill modern consumer need in probiotics, gut health, and natural fermentation. For Indian readers, *kefir* may still sound unfamiliar compared with *dahi*, *lassi*, *chaas*, *shrikhand* or yogurt. Yet it deserves attention because it blends the science of beneficial bacteria with the legacy of fermented dairy with the science of beneficial microbes. In simple words, *kefir* is a fermented milk drink produced by mixing *kefir* grains to milk. These grains are not cereal grains; they are soft, gelatinous clusters made up of bacteria, yeasts, proteins, and polysaccharides living together in a symbiotic association. When added to milk, they ferment lactose and produce a mildly sour, slightly yeasty, and sometimes lightly fizzy beverage with a refreshing taste.

What Makes *Kefir* Different

Kefir is more than just drinking yogurt or curd. Its uniqueness lies in its microbial diversity. Lactic acid bacteria, yeasts, and frequently acetic acid bacteria found in kefir grains work together to form traditional kefir. According to studies, kefir grains are a complex microbial consortium that is dominated by lactic acid bacteria and supported by yeasts and other microorganisms that help produce flavor, gas, preservation, bioactive compounds and beneficial substances. Kefir is different from regular fermented milk products, which are mostly manufactured with a few chosen bacterial starter cultures. In yogurt, fermentation is usually driven by defined bacteria, while in *kefir* both bacteria and yeasts collaborate. As a result, kefir has a more nuanced flavor, a more dynamic microbiological profile, and a wider market perception as a "functional food." That is one of the main reasons kefir is becoming more and more popular worldwide.

Why *Kefir* Is Significant in This Era

Today's food market prioritizes natural fermentation, live cultures, and wellness-related goods, which is why kefir has grown important. According to scientific reviews, kefir has garnered increasing attention globally due to the presence of many bioactive substances and health-promoting bacteria. It is being explored more and more as a probiotic-enriched or functional fermented meal with possible advantages for lactose digestion, gut microbial balance, and overall metabolic health.

Another factor contributing to kefir's growing popularity is its compatibility with contemporary urban lifestyles. Consumers today demand foods that combine convenience with authenticity, while also offering tangible health benefits. As a ready-to-drink fermented beverage, kefir fits well within this evolving market, finding applications as a cultured dairy drink, flavored functional beverage, premium dairy product, and wellness-oriented food.

What differentiates kefir apart from many other probiotic foods is the remarkable complexity of its microbial ecosystem. Unlike conventional probiotic products that typically contain selected bacterial strains, kefir is produced through the activity of kefir grains, which harbor a naturally occurring symbiotic community of lactic acid bacteria, acetic acid bacteria, and yeasts embedded within a unique polysaccharide matrix known as kefiran. This distinctive consortium contributes not only to kefir's characteristic sensory properties but also to its broad spectrum of bioactive metabolites and potential health-promoting effects. The simultaneous presence of both beneficial bacteria and yeasts creates a dynamic fermentation system rarely found in other probiotic dairy foods.

Consequently, kefir's appeal extends beyond its nutritional value. In many markets, it has emerged as a symbol of informed and health-conscious consumption, attracting consumers who are looking for natural, functional foods supported by both tradition and scientific interest.

Nutritional and Functional Value of *Kefir*

Kefir derives its value not simply from fermentation, but from the remarkable microbial interactions that occur during the process. As milk ferments, lactose is converted into lactic acid, improving preservation and making the product easier to digest. At the same time, the yeasts naturally present in kefir grains generate small amounts of carbon dioxide, ethanol, and aromatic compounds such as esters and aldehydes, which contribute to kefir's lightly sparkling texture and distinctive flavor. What truly distinguishes kefir from most other probiotic foods is the presence of a naturally occurring consortium of bacteria and yeasts living together within a matrix of kefiran, a unique exopolysaccharide produced during fermentation. This microbial diversity results in a wide range of metabolites, including bioactive peptides, organic acids, vitamins, and other compounds that enhance the nutritional and functional profile of the beverage.Growing scientific interest in kefir stems from evidence linking its consumption with improved lactose utilization and a variety of potential health benefits, including antimicrobial, immunomodulatory, antihypertensive, hypocholesterolemic, and antidiabetic effects. Its unique microbial composition has also attracted attention for supporting gut microbial balance and host immunity.

Kefir and the Global Dairy Landscape

Around the world, kefir has evolved from a traditional fermented beverage of the Caucasus region into a globally recognized functional dairy product. Rising consumer interest in probiotics, gut health, and naturally fermented foods has driven its expansion into mainstream dairy markets across North America, Europe, Asia, and the Middle East. No longer confined to specialty health-food shelves, kefir is increasingly positioned alongside yogurt and other cultured dairy beverages as part of the growing functional foods segment.

This trend holds particular significance for India, which is not only the world's largest milk producer but is also emerging as an important player in the global dairy trade. As the Indian dairy industry moves beyond conventional liquid milk markets toward value-added and health-oriented products, kefir presents a promising opportunity for product diversification and innovation. Growing urbanization, rising health awareness, expanding retail networks, and increasing demand for premium dairy beverages have created a favorable environment for novel fermented products. For a country with a vast dairy resource base and ambitions to strengthen its presence in high-value dairy markets, kefir represents both a commercial opportunity and a pathway toward greater diversification of the dairy product portfolio.

How *Kefir* Could Disrupt the Indian Dairy Sector

India is currently grappling with a sharp rise in lifestyle disorders, metabolic syndromes, and chronic gastrointestinal issues. In this shifting health climate, basic sustenance is no longer enough; consumers are actively seeking functional foods that offer targeted health benefits. This creates a massive opening for the dairy sector. *Kefir*, a complex fermented milk beverage, can disrupt the market not by replacing fluid milk or *dahi* overnight, but by fundamentally changing how value is created. *Kefir* introduces a new logic: milk can be processed into a scientifically backed lifestyle product carrying premium pricing and strong market differentiation. This opens three distinct transformations across the industry:

- **Premium Value Addition:** Selling pasteurized milk yields highly restricted margins. Converting that same milk into kefir allows dairy startups, A2 milk brands, and progressive farms to enter an elite functional segment, escaping commodity price wars and capturing significantly higher margins.
- **Strategic Market Positioning:** While consumers thoroughly understand *dahi* and *lassi*, kefir occupies a distinct niche as a "next-generation probiotic." It directly appeals to health-conscious urban professionals and fitness enthusiasts, driving a segmented market split between mass affordability and premium functional nutrition.
- **Technological Advancement:** Manufacturing consistent kefir requires strict control over live starter cultures, precise fermentation temperatures, and flawless cold-chain management. Mastering these parameters systematically upgrades a dairy's expertise in advanced bio-fermentation, benefiting the entire fermented dairy ecosystem.

By shifting from simple volume to targeted wellness, the Indian dairy industry can address pressing public health challenges while unlocking a highly profitable, resilient future

Current Indian Scenario

Kefir is building an early footprint in India, driven by specialized farms and boutique dairy brands. Rather than a mass staple, retail positioning frames it strictly as a premium health beverage, focusing on gut wellness and easy digestion.

This creates a distinct dual landscape of market opportunities and structural bottlenecks:

- **The Catalyst:** Growing urban awareness around the gut microbiome, alongside the expansion of e-commerce platforms, allows premium health products to easily connect with motivated consumers.
- **The Barrier:** Broad consumer awareness remains low. High pricing, cold-chain dependencies, and a tendency to confuse kefir with traditional *dahi* or buttermilk slow down widespread adoption.

A primary operational hurdle is flavor acceptance. Authentic kefir possesses a sharp, sour, and slightly effervescent (fizzy) profile that contrasts with the smooth, familiar taste of Indian curd or sweetened yogurt drinks. To bridge this gap, domestic dairies must localize the product. Introducing mild fruit fusions or tailored flavor profiles will be essential. Lasting market disruption in India rarely comes from replicating a western concept exactly; success relies on localizing the product to match domestic palates without diluting its bioactive health benefits.

Opportunities for Indian Dairy Farmers and Startups

In India, where public health initiatives continuously battle under-nutrition and infectious diseases like tuberculosis, kefir serves as a practical, high-impact tool for nutritional support. While never a replacement for targeted medical treatment, its unique matrix of high-quality proteins, vital micro-nutrients, and live beneficial microbes offers an affordable, bio-available booster for immune health and gut recovery. Integrating this functional food into regional dairy nutrition strategies could provide a powerful, food-based layer of defense for vulnerable populations.

On the commercial front, kefir gives progressive dairy farmers a direct entry point into profitable niche markets. Smaller operations can bypass low-margin wholesale pools by converting fresh milk into artisanal kefir, supplying urban wellness stores, local cafés, or direct-to-home subscription networks. It serves as a natural product extension for farms already built around premium narratives like organic certified, A2, or goat milk.

For agile dairy startups, this beverage acts as an open canvas for product innovation. Brands are not locked into a single format; they can easily pivot between plain, fruit-flavored, low-fat, or high-protein variants to match evolving consumer trends. This extreme adaptability allows businesses to position kefir at the profitable intersection of daily dairy, modern fitness, and preventive health. Even if its total processing volume remains a fraction of the conventional *dahi* or fluid milk market, its high-margin profile makes it an influential, resilient category for the modern dairy entrepreneur.

Conclusion

Kefir may be old in origin, but it operates like a modern breakthrough because it aligns perfectly with today's consumer demands: live probiotics, gut health, natural fermentation, and clean-label nutrition. Its true value extends far beyond its dense microbial profile or documented health benefits; it acts as a catalyst that reframes how milk is processed, marketed, and valued. While still a niche segment within India, kefir has the structural potential to steer the broader dairy industry toward higher innovation, sophisticated value addition, and specialized functional foods.

For domestic processors and dairy farmers, this beverage represents an opportunity rather than a market threat. It challenges producers, researchers, and entrepreneurs to look past the traditional view of milk as a basic wholesale commodity, reimagining it as a bio-active platform for targeted human nutrition. If integrated strategically into current production lines, kefir can easily become one of the definitive products driving the next phase of dairy diversification and long-term economic relevance across the country.

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Climate-Smart and Welfare-Centred Livestock Systems: Pathways for Sustainable Development

Livestock systems are increasingly recognized not merely as production enterprises, but as integrated socio-ecological systems critical for food security, nutrition, livelihoods, ecosystem services and climate resilience. Globally, livestock support over one billion people and contribute significantly to agricultural economies, while in India they remain central to smallholder farming and rural development. Yet the sector faces a "triple challenge": meeting growing demand for animal-source foods, reducing environmental footprints, and ensuring animal welfare under accelerating climate change (Billoto F et al., 2024)

Sustainable livestock development now requires a shift from productivity-driven models toward climate-smart, welfare-centred and One Health-oriented systems. Traditional mixed crop–livestock systems already embody many sustainability principles through nutrient recycling, manure use, crop residue feeding and livelihood diversification. Strengthening such circular systems, rather than replacing them with purely industrial models, is vital for resilience (Kebreab E et al., 2026)

Animal welfare has emerged as a cornerstone of sustainability rather than a separate ethical concern. Guided by standards of the World Organisation for Animal Health (WOAH), welfare encompasses nutrition, health, behaviour, housing and mental well-being. Good welfare improves productivity through better fertility, disease resistance and stress tolerance. This becomes especially important under climate stress, where heat waves impair milk yield, reproduction and immunity. Thus welfare and adaptation are increasingly inseparable.

Climate change poses profound threats to livestock through heat stress, feed and water scarcity, altered vector ecology and emerging disease risks, including zoonoses. At the same time, livestock contribute to greenhouse gas emissions, particularly methane and nitrous oxide. The response, however, is not to view livestock simply as a problem, but to transform systems through climate-smart livestock approaches that integrate adaptation, mitigation and productivity (Hristov, A. N., et al. 2025)

Key adaptation strategies include heat-resilient housing, shade and cooling systems, drought-tolerant fodder, resilient indigenous breeds and early warning systems. Mitigation measures include precision feeding, improved digestibility, methane-reducing feed additives, better manure management and biogas systems. Many of these interventions simultaneously enhance welfare, efficiency and environmental performance (Hossein-Zadeh, N. G., et al. 2026)

A major opportunity lies in adopting circular bioeconomy models, where livestock waste becomes a resource rather than a liability. Manure-to-biogas systems, integrated crop–livestock farming and nutrient recycling reduce emissions while improving soil fertility and rural energy security. Such models are particularly relevant for India's smallholder systems (Swastika, D. K. S., et al., 2024)

Digital technologies are accelerating this transformation. Precision livestock farming using sensors, AI, wearable devices and computer vision enables real-time monitoring of animal health, welfare and productivity. These tools can detect heat stress, lameness, disease and behavioural changes early, improving both management and resilience. Combined with climate forecasting and disease surveillance, digital livestock systems strengthen preparedness under One Health framework (Jiang, B., et al. 2023)

The One Health perspective is fundamental to sustainable livestock development. Better welfare and husbandry reduce disease risks, antimicrobial dependence and zoonotic spillover potential. Sustainable livestock systems thus contribute not only to productivity but also to public health, ecosystem health and antimicrobial resistance containment.

These transformations align strongly with the United Nations Sustainable Development Goals, contributing to poverty reduction, food security, climate action, biodiversity conservation and responsible production. For India, policy pathways include climate-smart livestock missions, indigenous breed conservation, digital livestock initiatives, methane-smart strategies and welfare-sensitive governance reforms (Zhang, T., et al. 2024).

The future of livestock lies not in maximizing output at ecological cost, but in optimizing productivity, welfare and resilience together. This requires moving from livestock production to livestock stewardship. Sustainable livestock systems must be viewed as part of the solution to climate change, not merely contributors to it (FAO and WHO).

As emphasized by the Food and Agriculture Organization, sustainable livestock transformation is central to resilient food systems. The challenge before policymakers is therefore not whether livestock systems should change, but how rapidly they can be redesigned to support a humane, climate-resilient and sustainable future.

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Integrated Fish Farming: A Sustainable Approach for Enhanced Agricultural Productivity

Abstract

Integrated Fish Farming (IFF) is an innovative and sustainable farming system that combines aquaculture with agriculture and livestock enterprises to maximize productivity, improve resource utilization, and increase farm income. Unlike conventional fish farming, integrated systems utilize the waste generated from one farming component as an input for another, thereby reducing production costs, minimizing environmental pollution, and promoting ecological balance. This integrated approach has gained significant importance in recent years due to increasing pressure on land resources, climate change, and the need for sustainable food production. Fish farming can be integrated with crops, poultry, ducks, pigs, cattle, horticulture, and biogas production, creating a circular farming system that generates multiple outputs from the same unit of land.

1. Introduction

Fish farming has become one of the fastest-growing food production sectors worldwide. However, traditional aquaculture often requires high inputs of feed, fertilizers, and water. Integrated Fish Farming (IFF) addresses these challenges by combining fish culture with other agricultural activities, enabling efficient recycling of nutrients and farm residues.

The concept of integrated farming is based on the principle that "the waste of one enterprise becomes the resource of another." Animal manure enriches pond water with nutrients, stimulating the growth of plankton, which serves as natural food for fish. Pond water rich in organic matter can subsequently be used to irrigate crops, enhancing soil fertility.

Integrated Fish Farming is particularly suitable for small and marginal farmers because it allows diversified production, reduces financial risk, and provides year-round employment opportunities.

2. Principles of Integrated Fish Farming

The success of integrated fish farming depends on effective resource recycling and efficient management of different farm enterprises.

Major Principles

- Efficient recycling of nutrients
- Maximum utilization of available land and water
- Diversification of farm enterprises
- Reduction in production costs
- Sustainable utilization of natural resources
- Conservation of soil fertility
- Enhanced farm profitability
- Reduced environmental pollution

A properly designed integrated farming system creates a balanced ecosystem where each component supports the productivity of others.

3. Components of Integrated Fish Farming

Integrated fish farming involves combining aquaculture with one or more agricultural enterprises.

a) Fish-Crop Integration

Fish ponds provide nutrient-rich water for irrigation, while crop residues can be utilized as supplementary fish feed or compost.

Benefits include:

- Improved soil fertility
- Reduced fertilizer requirement
- Efficient water utilization
- Increased crop yield

b) Fish-Duck Farming

Duck farming is one of the most successful integrated systems.

Ducks:

- Feed on insects and aquatic weeds.
- Stir pond water, increasing oxygen circulation.
- Drop manure directly into ponds.
- Reduce the requirement of artificial fertilizers.

Generally, 200–300 ducks per hectare are sufficient for maintaining pond fertility.

c) Fish-Poultry Integration

Poultry droppings serve as an excellent organic fertilizer for fish ponds.

Advantages include:

- Continuous nutrient supply
- Enhanced plankton production
- Lower feed costs
- Additional income from eggs and meat

d) Fish-Pig Farming

Pig manure contains high levels of nitrogen and phosphorus, promoting natural fish food production.

Major advantages:

- Efficient nutrient recycling
- Higher fish productivity
- Reduced fertilizer expenses
- Increased farm profitability

e) Fish-Horticulture System

Fruit trees and vegetables are cultivated on pond embankments.

Suitable crops include:

- Banana
- Papaya
- Mango
- Guava
- Drumstick
- Lemon
- Coconut

This system maximizes land utilization while providing additional farm income.

4. Resource Recycling in Integrated Fish Farming

One of the most significant advantages of integrated farming is nutrient recycling.

Examples include:

Farm Component	Resource Generated	Utilization
Poultry	Manure	Pond fertilization
Ducks	Droppings	Natural fish feed production
Piggery	Organic waste	Pond nutrient enrichment
Fish Pond	Nutrient-rich water	Crop irrigation
Crop Residues	Plant waste	Compost and fish feed
Biogas Plant	Slurry	Organic fertilizer

This continuous recycling significantly reduces waste generation and external input requirements.

5. Advantages of Integrated Fish Farming

Integrated fish farming offers numerous economic, environmental, and social benefits.

Economic Benefits

- Higher farm income
- Multiple income sources
- Reduced production costs
- Better utilization of family labor
- Increased employment opportunities
- Improved financial stability

Environmental Benefits

- Recycling of organic wastes
- Reduced environmental pollution
- Conservation of water resources
- Improved soil fertility
- Enhanced biodiversity
- Lower dependence on chemical fertilizers

Social Benefits

- Improved nutritional security
- Increased protein availability
- Better livelihood opportunities
- Sustainable rural development
- Enhanced food security

6. Types of Integrated Fish Farming Systems

Several models of integrated fish farming are practiced depending on local conditions.

Common Models

- Fish + Duck Farming
- Fish + Poultry Farming
- Fish + Pig Farming
- Fish + Dairy Farming
- Fish + Rice Farming
- Fish + Vegetable Farming
- Fish + Horticulture
- Fish + Biogas System
- Fish + Mushroom Cultivation
- Multi-enterprise Integrated Farming

Selection of the appropriate model depends on climate, land availability, water resources, and market demand.

7. Management Practices

Successful integrated fish farming requires careful planning and management.

Pond Management

- Maintain proper pond depth.
- Ensure adequate dissolved oxygen.
- Monitor water quality regularly.
- Remove aquatic weeds.
- Prevent disease outbreaks.

Fish Stocking

Healthy fingerlings should be stocked at recommended densities.

Common species include:

- Rohu (*Labeo rohita*)
- Catla (*Catla catla*)
- Mrigal (*Cirrhinus mrigala*)
- Common Carp
- Grass Carp
- Silver Carp

Composite fish culture is widely practiced because different species occupy different ecological niches.

Feeding Management

Fish feed may consist of:

- Rice bran
- Mustard oil cake
- Groundnut cake
- Agricultural by-products
- Natural plankton
- Kitchen waste (where appropriate)

Balanced feeding improves growth and feed conversion efficiency.

8. Challenges in Integrated Fish Farming

Although integrated fish farming has numerous benefits, farmers may encounter several constraints.

Major Challenges

- Initial investment requirements
- Limited technical knowledge
- Disease transmission among enterprises
- Water scarcity
- Market fluctuations
- Poor infrastructure
- Lack of quality fingerlings
- Climate variability
- Limited institutional support

Training, extension services, and scientific management can help overcome these challenges.

9. Future Prospects

Integrated fish farming has enormous potential to support sustainable agriculture, especially in developing countries. Increasing demand for fish, rising production costs, and concerns regarding environmental sustainability have accelerated interest in integrated farming systems.

Future developments are expected in:

- Precision aquaculture
- IoT-based water quality monitoring
- Biofloc integration
- Recirculating aquaculture systems (RAS)
- Solar-powered aeration
- Climate-smart farming practices
- Organic aquaculture
- Digital farm management

10. Conclusion

Integrated Fish Farming is a scientifically sound and economically viable farming system that promotes efficient utilization of natural resources while minimizing environmental impacts. By integrating aquaculture with livestock, crops, and horticulture, farmers can enhance productivity, diversify income sources, and improve food security. The recycling of nutrients within the farm reduces production costs, improves soil health, and conserves water resources. Although certain management challenges exist, appropriate planning, technical guidance, and government support can make integrated fish farming a cornerstone of sustainable agricultural development. As the global demand for food continues to rise, integrated farming systems offer a practical pathway toward resilient, profitable, and environmentally responsible agriculture.