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SUSTAINABLE AGRICULTURE

Climate Resilience, Technology and Food Security

Editors:

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Sustainable Agriculture: Climate Resilience, Technology and Food Security

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PREFACE

Agriculture stands at a critical crossroads in the twenty-first century, shaped by the pressing challenges of climate change, resource degradation, and a rapidly growing global population. The book *Sustainable Agriculture: Climate Resilience, Technology and Food Security* emerge as a timely and comprehensive contribution to understanding and addressing these interconnected issues. It aims to explore innovative pathways that ensure agricultural productivity while preserving ecological balance and securing livelihoods.

Climate variability, extreme weather events, declining soil health, and water scarcity have significantly impacted agricultural systems worldwide. These challenges demand a shift from conventional practices to sustainable and climate-resilient approaches. This volume highlights the importance of adaptive strategies such as climate-smart agriculture, conservation practices, agroecology, and integrated farming systems that enhance resilience while minimizing environmental impacts.

The role of technology in transforming agriculture is another central theme of this book. Advances in precision farming, remote sensing, artificial intelligence, biotechnology, and digital agriculture are revolutionizing how food is produced, monitored, and distributed. By integrating traditional knowledge with modern innovations, sustainable agriculture can become more efficient, resource-conscious, and inclusive.

Food security remains a global priority, especially in the context of climate uncertainty and socio-economic disparities. This book emphasizes the need for equitable access to nutritious food, sustainable supply chains, and policies that support smallholder farmers and marginalized communities. It underscores that achieving food security is not merely about increasing production, but also about ensuring sustainability, accessibility, and resilience.

This edited volume brings together diverse perspectives from researchers, academicians, and practitioners, offering valuable insights into sustainable agricultural practices and policies. It is hoped that this book will serve as a useful resource for students, scholars, policymakers, and stakeholders committed to building a resilient and sustainable agricultural future.

- Editors

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AI-DRIVEN PRECISION IRRIGATION FOR CLIMATE-RESILIENT AGRICULTURE

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Abstract

Climate change has intensified water scarcity, altered rainfall distribution and increased the frequency of extreme weather events, posing significant challenges to agricultural sustainability. Efficient water management is therefore a critical component of climate-resilient agriculture. Artificial Intelligence (AI)-driven precision irrigation has emerged as a transformative approach to optimize water use efficiency and enhance crop productivity under dynamic climatic conditions. This chapter examines the integration of AI technologies, including machine learning algorithms, Internet of Things (IoT)-based sensors, remote sensing, and decision support systems, in irrigation management. AI-enabled irrigation systems enable real-time monitoring of soil moisture, climatic parameters and crop water requirements, enabling site-specific, timely irrigation decisions. These technologies significantly reduce water wastage, improve irrigation efficiency and support sustainable agricultural practices. The chapter also explores various AI models for irrigation scheduling, predictive analytics for water demand forecasting and automation technologies in irrigation systems. Case studies demonstrating the application of AI-based irrigation in different agro-ecological regions are discussed. Despite its advantages, the adoption of AI-driven irrigation faces challenges, including high upfront costs, technical complexity and limited access for smallholder farmers. The chapter highlights prospects, including the integration of big data, cloud computing and low-cost smart technologies for wider adoption. AI-driven precision irrigation represents a promising pathway for achieving sustainable and climate-resilient agricultural systems.

Keywords: Climate Change, Precision Irrigation, Artificial Intelligence, Iot, Water Use Efficiency, Climate Resilience, Smart Agriculture.

Introduction

Climate change has emerged as one of the most critical challenges affecting global agriculture. Rising temperatures, erratic rainfall patterns, increased frequency of droughts, floods and heat waves are significantly influencing crop productivity and water availability. Agriculture is highly sensitive to climatic variability, as it relies heavily on natural resources such as soil and water. Among these, water scarcity has become a major limiting factor in sustaining agricultural production systems. Globally, agriculture accounts for approximately 70% of freshwater withdrawals, making it the largest consumer of water resources (FAO, 2021). Inefficient irrigation practices, coupled with climate-induced water stress, have exacerbated the problem of water scarcity. Traditional irrigation methods often lead to over-irrigation, resulting in water wastage, nutrient leaching and reduced water use efficiency (Zhang *et al.,* 2023).

In recent years, precision irrigation has gained prominence as an effective strategy to optimize water use in agriculture. Precision irrigation involves the application of water in precise amounts based on crop requirements, soil conditions and weather parameters. The integration of Artificial Intelligence (AI) into precision irrigation systems has further enhanced their efficiency and effectiveness. AI-driven irrigation systems utilize real-time data and predictive analytics to make informed decisions, thereby improving water use efficiency and crop productivity (Kumar *et al.,* 2024). AI technologies such as machine learning, deep learning and data analytics enable the processing of large volumes of data from sensors, satellites and weather stations. These technologies facilitate accurate prediction of crop water requirements and support decision-making in irrigation management. As a result, AI-driven precision irrigation has emerged as a key component of climate-resilient agriculture, contributing to sustainable water management and enhanced agricultural productivity (Liakos *et al.,* 2018).

Concept of precision irrigation

Precision irrigation focuses on delivering water based on crop-specific requirements by integrating soil, weather, and plant data. It is a key component of precision agriculture, which aims to improve resource use efficiency and crop productivity through the use of advanced technologies. Traditional irrigation practices are typically based on fixed schedules or farmer experience, which often do not account for spatial and temporal variability in soil moisture, crop growth stage and weather conditions. This can result in inefficient water use, leading to either water stress or waterlogging in crops (Li *et al.,* 2024).

To gather data in real time, precision irrigation systems make use of cutting-edge technologies including remote sensing tools, weather monitoring systems, and soil moisture sensors. The best watering schedule is then determined by analyzing this data. Precision irrigation guarantees effective water delivery by taking into account variables including evapotranspiration, soil properties, and crop water requirements (Jones, 2004). According to studies, precision irrigation can maintain or even increase crop yields while reducing water use by 20–50% (Zhang *et al.,* 2023). Additionally, by reducing leaching losses and increasing fertilizer usage efficiency, precision irrigation helps to enhance nitrogen management.

The integration of AI into precision irrigation systems has further improved their performance. AI-based systems can analyze complex datasets, identify patterns and provide predictive insights, enabling more accurate and efficient irrigation management (Jha *et al.,* 2019). Thus, precision irrigation serves as a vital tool in achieving sustainable and climate-resilient agriculture.

Artificial Intelligence in Agriculture

Artificial Intelligence (AI) refers to the use of computational algorithms and models that enable machines to perform tasks that typically require human intelligence. In agriculture, AI is increasingly being used to enhance decision-making, improve efficiency and optimize resource utilization. AI technologies such as machine learning, deep learning and computer vision are widely applied in various agricultural operations, including crop monitoring, disease detection, yield prediction and irrigation management. These technologies enable the analysis of large datasets generated from multiple sources, such as sensors, satellites, drones and weather stations (Liakos *et al.,* 2018). Machine learning algorithms play a crucial role in AI-driven agriculture by identifying patterns and relationships within data. For instance, these algorithms can predict crop water requirements based on historical weather data, soil moisture levels and crop growth stages. Such predictive capabilities are essential for efficient irrigation management (Kumar *et al.,* 2022).

The integration of AI with the Internet of Things (IoT) has further expanded its applications in agriculture. IoT devices, such as soil moisture sensors and weather stations, continuously collect data, which is processed by AI systems to provide real-time insights. This integration enables automated and data-driven decision-making, reducing the need for manual intervention (Jaiswal and Kumar, 2025). Moreover, AI-based decision support systems (DSS) assist farmers in making informed decisions regarding irrigation scheduling, fertilizer application and pest management. These systems enhance farm productivity while minimizing resource wastage. Recent advancements in AI, including cloud computing and big data analytics, have further improved the scalability and efficiency of agricultural systems. AI-driven technologies are therefore playing a pivotal role in transforming traditional agriculture into a more sustainable and climate-resilient system (Elshaikh *et al.,* 2024).

Table 1: Comparison of Traditional vs AI-Based Precision Irrigation

Parameter	Traditional Irrigation	AI-Driven Precision Irrigation
Irrigation scheduling	Fixed/manual	Real-time, data-driven
Water use efficiency	Low	High
Decision-making	Based on experience	AI-based predictive models
Resource utilization	Less efficient	Optimized
Crop yield	Variable	Improved
Labor requirement	High	Low (automated)
Cost savings	High	Significant reduction
Environmental impact	High footprint	Low footprint

AI-Driven Precision Irrigation Systems

AI-driven precision irrigation systems represent an integration of advanced digital technologies with irrigation management to optimize water use efficiency under dynamic climatic conditions. These systems combine sensor networks, machine learning algorithms, remote sensing tools and automation technologies to provide real-time, site-specific irrigation decisions. The adoption of such systems is increasingly important in the context of climate variability, where traditional irrigation practices fail to respond to rapid environmental changes.

IoT Based Sensor Networks

The Internet of Things (IoT) forms the backbone of AI-driven irrigation systems. IoT-based sensor networks are deployed across agricultural fields to continuously monitor soil and environmental parameters. These sensors collect data on:

- Soil moisture content
- Soil temperature
- Air humidity
- Solar radiation
- Wind speed

Soil moisture sensors, such as capacitance and tensiometric sensors, provide accurate information on water availability in the root zone. This real-time data enables precise irrigation scheduling and prevents both over-irrigation and water stress. Wireless sensor networks (WSNs) facilitate communication between sensors and central control systems, enabling seamless data transmission. The integration of IoT sensors with cloud platforms allows for real-time monitoring and remote access to field data. Studies have demonstrated that IoT-based irrigation systems can reduce water consumption by up to 30–50% while maintaining crop yield (Jaiswal and Kumar, 2025).

Table 2: Types of sensors used in precision irrigation

Sensor Type	Parameter Measured	Role in Irrigation
Soil moisture sensor	Soil water content	Determines irrigation timing
Temperature sensor	Air/soil temperature	Affects evapotranspiration
Humidity sensor	Relative humidity	Influences crop water needs
Rain gauge	Rainfall	Adjusts irrigation schedule
Anemometer sensor	Wind speed	Influences evapotranspiration
NDVI sensors (remote sensing)	Crop health	Detects stress conditions

Table 3: Technical Specifications of Soil Moisture Sensors

Sensor Category	Working Principle	Accuracy	Cost	Suitability for AI Systems
Tensiometric	Measures soil water tension	High	Low	Limited; requires high maintenance.
Capacitance (FDR)	Dielectric constant measurement	Moderate	Medium	High; easy to integrate with IoT.
TDR	Signal travel time	Very High	High	Best for research-grade AI data.
Neutron Probe	Radioactive attenuation	Extremely High	Very High	Low, regulated and non-automated.

Sensor Calibration and Data Integrity

The efficacy of AI-driven irrigation is fundamentally predicated on the accuracy of the input data, adhering to the principle of "Garbage In, Garbage Out" (GIGO). While modern IoT sensors provide high-frequency monitoring, the raw signals typically measured as capacitance, voltage, or resistance must be precisely converted into standardized agronomic units, such as Volumetric Water Content (VWC) or Soil Water Potential.

Addressing Soil Variability

Factory-set calibrations are often based on specific mineral soil standards. In practice, variations in soil texture, bulk density and salinity significantly alter the dielectric properties of the medium. Without site-specific calibration, AI models may receive skewed data, leading to erroneous irrigation scheduling.

Table 4: Calibration Parameters for Different Soil Textures

Soil Texture	Field Capacity (%)	Permanent Wilting Point (%)	Calibration Sensitivity
Sand	10–15	3–6	High (Fast drainage)
Loam	25–30	10–15	Moderate
Clay	40–50	20–25	Very High (Salinity interference)

Calibration Methodologies

- **Physical Ground-Truthing:** The gravimetric method remains the golden standard, where soil core samples are oven-dried to correlate physical water loss with electronic sensor outputs.
- **Algorithmic Correction:** Advanced AI systems now employ "self-calibrating" routines that use historical data trends and neighborhood-based cross-referencing to detect sensor drift or hardware degradation, ensuring long-term data reliability.

- **Systemic Impact:** Proper calibration ensures that the AI model operates within the "Managed Allowed Depletion" (MAD) zone, preventing from50 both anaerobic conditions (waterlogging) and permanent wilting points.

Edge computing: Decentalized intelligence in the field

While cloud-based platforms offer extensive computational power for deep learning, they often face challenges related to latency, bandwidth costs and connectivity in remote agricultural landscapes. Edge Computing addresses these limitations by shifting data processing from centralized servers to the "edge" of the network—the local gateway or the sensor nodes themselves (O'Grady and O'Hare, 2024).

- **Latency and Real-Time Response:** Precision irrigation requires immediate action when specific thresholds are met. Edge computing allows for near-instantaneous decision-making, such as triggering an emergency shut-off during a pipe burst or adjusting flow rates in response to sudden micro-climatic shifts, without waiting for a round-trip to a cloud server.
- **Bandwidth Optimization:** Continuous transmission of raw environmental data consumes significant energy and bandwidth. Edge devices filter and process this data locally, transmitting only high-value "event-driven" information or daily summaries to the cloud. This architecture is essential for battery-powered IoT deployments in large-scale farming.
- **Operational Autonomy:** By hosting lightweight machine learning models (often referred to as *TinyML*) locally, irrigation systems can remain fully functional during network outages. This decentralized approach ensures that the "intelligence" of the system is resilient to external infrastructure failures.
- **Security and Privacy:** Processing data at the source minimizes the volume of sensitive field data traversing public networks, providing an inherent layer of data security for agricultural enterprises.

Table 5: Comparison of Cloud vs. Edge Computing

Feature	Cloud Computing	Edge Computing
Latency	High (Server response delay)	Ultra-Low (Local processing)
Connectivity	Requires a stable Internet	Operates offline/locally
Processing Power	Massive (Deep Learning)	Limited (Lightweight ML/TinyML)
Data Cost	High (Transmitting raw data)	Low (Transmitting summaries only)
Deployment	Centralized	Distributed across fields

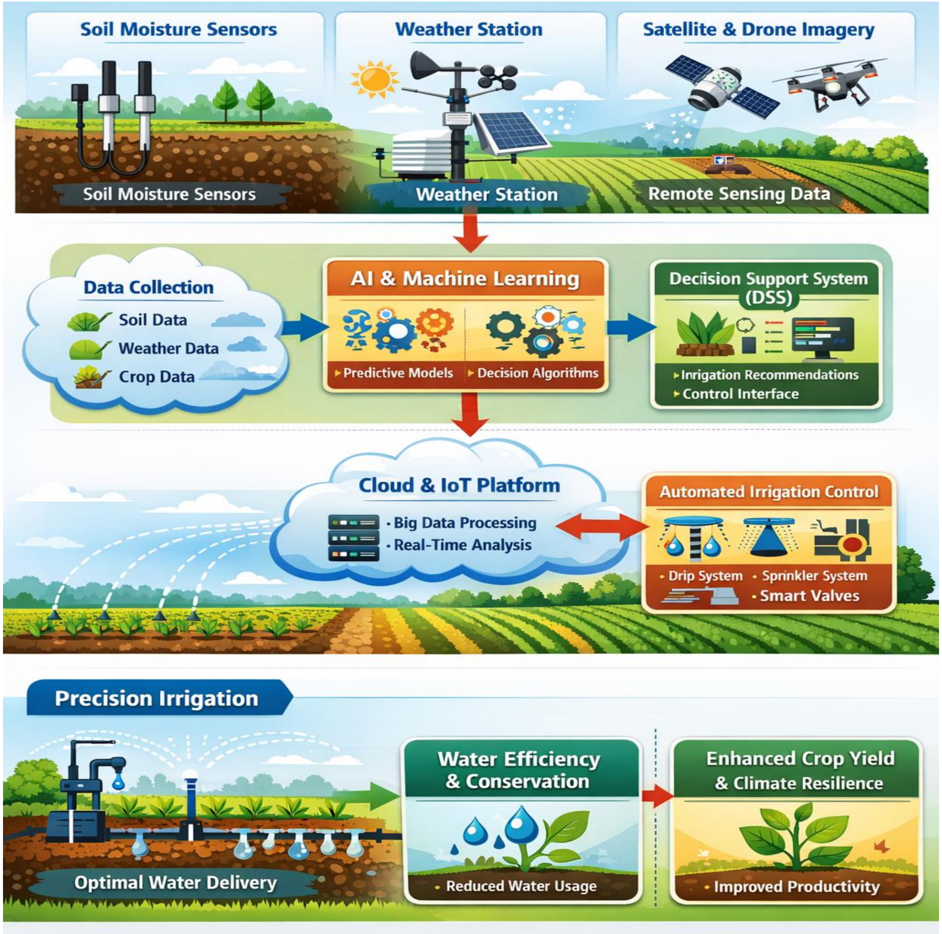

Figure 1: Integrated AI-Based Precision Irrigation System for Smart Water Management

Machine Learning and Predictive Analytics

Machine learning (ML) algorithms play a crucial role in analyzing large datasets generated by sensor networks and weather stations. These algorithms identify patterns and relationships between environmental variables and crop water requirements.

Commonly used ML models in irrigation include:

- Artificial Neural Networks (ANN) – predict evapotranspiration and water demand
- Support Vector Machines (SVM) – classifies irrigation needs
- Random Forest Algorithms - handles nonlinear relationships in weather and soil data
- Deep Learning Models - analyzes images/satellite data for crop stress forecasting
- XGBoost – high accuracy in classifying irrigation types and scheduling
- Linear Discriminant Analysis – efficient water requirement forecasting

These models are trained using historical and real-time data to predict irrigation needs. For example, ANN models can estimate evapotranspiration rates based on climatic parameters, enabling precise water application.

Predictive analytics also supports water demand forecasting, allowing farmers to anticipate irrigation requirements under future climatic scenarios. Research indicates that ML-based irrigation scheduling improves water use efficiency by 20–40% compared to conventional methods (Kim and AlZubi, 2024).

Table 6: AI Algorithm Selection for Irrigation Tasks

AI Model Type	Specific Application	Primary Advantage
Random Forest	Soil Moisture Prediction	Handles non-linear data and outliers well.
CNN (Deep Learning)	Crop Stress Detection	Processes UAV/Satellite imagery for wilting.
LSTM (RNN)	Weather Trend Forecasting	Remembers historical climate patterns.
Fuzzy Logic	Automated Valve Control	Handles "if-then" logic for simple hardware.

Table 7. AI techniques used in machine learning

AI Technique	Application	Benefit
Machine Learning	Irrigation scheduling	Accurate prediction
Deep Learning	Crop stress detection	Early warning
Neural Networks	Water demand forecasting	High precision
Decision Support Systems	Farm decision-making	Improved efficiency

Evapotranspiration-Based Irrigation Modelling

Accurate estimation of crop water requirements is essential for efficient irrigation management, particularly under climate variability. Evapotranspiration (ET) is a key parameter used to quantify water loss from soil and plant surfaces. In AI-driven precision irrigation systems, evapotranspiration-based models are widely used to determine irrigation scheduling and optimize water application. Crop evapotranspiration (ETc) is estimated using reference evapotranspiration (ET_o) and crop coefficient (Kc), which varies with crop type and growth stage.

$ETc = Kc \times ET_0$

Where:

ETc is the crop evapotranspiration.

Kc is the crop coefficient (dimensionless).

ET_0 is the reference evapotranspiration (mm/day).

AI models integrate real-time data from weather stations, soil moisture sensors and satellite observations to dynamically estimate ET_o and Kc values. This allows for the precise calculation of crop water requirements and enables automated irrigation decisions. The use of evapotranspiration-based approaches improves water use efficiency, reduces over-irrigation, and enhances crop productivity under changing climatic conditions (Allen *et al.,* 1998; Zhang *et al.,* 2023).

Table 8: Parameters Used in Evapotranspiration-Based Irrigation Scheduling

Parameter	Description	Unit	Importance of Irrigation
ET_0 (Reference Evapotranspiration)	Rate of evapotranspiration from a reference surface (grass)	mm day^{-1}	Forms the baseline for crop water requirement
Kc (Crop Coefficient)	Factor representing crop-specific water use	Dimensionless	Adjusts ET_0 based on crop type and growth stage
ETc (Crop Evapotranspiration)	Actual crop water requirement ($ET_0 \times Kc$)	mm day^{-1}	Determines irrigation quantity
Soil Moisture Content	Water available in the root zone	% or m^3 m^{-3}	Helps decide irrigation timing
Effective Rainfall (Pe)	Portion of rainfall available to crops	mm	Reduces irrigation requirement
Irrigation Efficiency (Ei)	Efficiency of the irrigation system	%	Determines the actual water applied

Remote sensing and Geospatial Technologies

Remote sensing technologies, including satellite imagery and unmanned aerial vehicles (UAVs), provide spatial information on crop health, soil moisture and evapotranspiration. These technologies enable large-scale monitoring of agricultural fields.

Key applications include:

- Detection of water stress zones
- Monitoring vegetation indices such as NDVI
- Estimation of crop water requirements
- Mapping soil moisture variability

AI algorithms process remote sensing data to generate irrigation maps and recommendations. The integration of Geographic Information Systems (GIS) further enhances spatial analysis and decision-making. Remote sensing-based irrigation management is particularly useful in large-scale farming systems, where field-level monitoring is challenging. Studies have shown that UAV-based monitoring improves irrigation efficiency and crop productivity (Agrawal and Arafat, 2024).

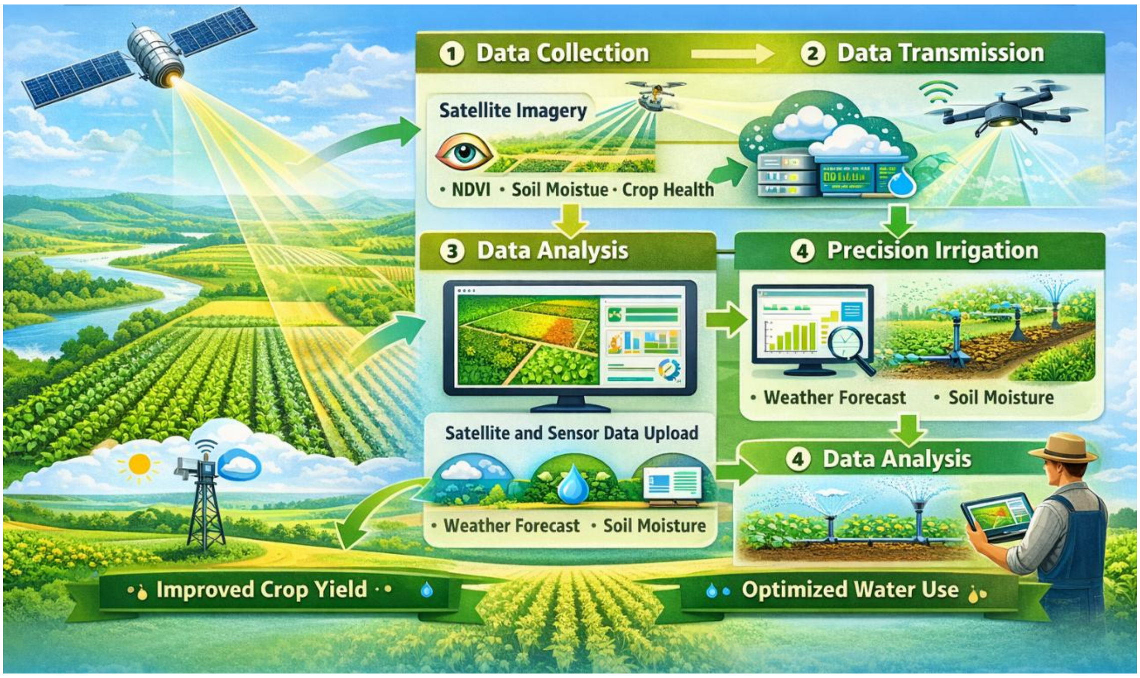

Figure 2: Operational Framework of Remote Sensing-Based Irrigation Decision Support System

Decision Support Systems (DSS)

Decision Support Systems (DSS) are AI-powered platforms that integrate data from multiple sources and provide actionable recommendations for irrigation management. DSS tools use advanced algorithms to process inputs such as:

- Soil moisture data
- Weather forecasts
- Crop growth stages
- Historical irrigation data

These systems generate irrigation schedules and recommendations tailored to specific field conditions. DSS platforms often include user-friendly interfaces, enabling farmers to make informed decisions without requiring advanced technical knowledge. Cloud-based DSS platforms allow real-time data processing and remote access, making them highly efficient for large-scale agricultural operations. Studies have reported that DSS-based irrigation systems significantly enhance water use efficiency and reduce operational costs (Dong *et al.,* 2024).

Automation and Smart Control Systems

Automation is a key feature of AI-driven irrigation systems. Smart controllers use AI algorithms to regulate irrigation systems based on real-time data. These controllers can:

- Automatically turn irrigation systems on/off
- Adjust water flow rates
- Control irrigation duration

Integration with drip and sprinkler systems enables precise water delivery directly to the root zone. Automation reduces labour requirements and minimizes human errors in irrigation management. Advanced systems also incorporate **feedback mechanisms**, where sensor data continuously updates the irrigation schedule. This dynamic adjustment ensures optimal water application under changing environmental conditions.

Integration of AI with Climate Data

AI-driven irrigation systems increasingly integrate climate data to enhance decision-making. Weather forecasting models provide information on rainfall, temperature and humidity, which are used to adjust irrigation schedules.

Climate-based irrigation models help in:

- Avoiding irrigation before rainfall events
- Adjusting water application during heat stress
- Managing irrigation under drought conditions

The integration of climate data improves the resilience of irrigation systems to climate variability and extreme weather events.

Application of AI in Irrigation

The application of AI in irrigation management has transformed traditional farming practices into data-driven systems. AI technologies enable precise, efficient and sustainable water management, which is essential for climate-resilient agriculture.

Intelligent Irrigation Scheduling

AI-based irrigation scheduling is one of the most significant applications in precision agriculture. Traditional scheduling methods rely on fixed intervals, whereas AI systems use real-time data to determine optimal irrigation timing and quantity.

AI models consider multiple factors, including:

- Soil moisture levels
- Crop growth stage
- Weather conditions
- Evapotranspiration rates

These systems dynamically adjust irrigation schedules, ensuring that crops receive the exact amount of water required. This reduces water wastage and enhances crop productivity. Studies indicate that AI-based scheduling can reduce irrigation water use by up to 40% while maintaining yield levels (Elshaikh *et al.,* 2024).

Water Demand Forecasting

Water demand forecasting is crucial for efficient resource planning, especially in water scarce regions. AI models use historical climate data, soil characteristics and crop information to predict future water requirements.

Forecasting models help farmers:

- Plan irrigation schedules in advance
- Optimize water allocation
- Prepare for drought conditions

Machine learning algorithms improve the accuracy of water demand predictions by continuously learning from new data. This enhances the reliability of irrigation planning under uncertain climatic conditions.

Automated Irrigation System

Automation in irrigation systems reduces manual intervention and enhances efficiency. AI-controlled systems integrate sensors, actuators and control units to automate irrigation processes.

These systems can:

- Trigger irrigation based on soil moisture thresholds
- Adjust water application rates
- Shut down irrigation during rainfall

Automation ensures timely irrigation and reduces labour costs. It also minimizes human errors, leading to more efficient water management.

Integration with the Microirrigation System

AI technologies are widely integrated with micro-irrigation systems such as drip and sprinkler irrigation. These systems provide precise water delivery directly to the plant root zone.

Benefits of AI-integrated micro-irrigation include:

- Reduced water losses due to evaporation and runoff
- Improved nutrient use efficiency (fertigation)
- Enhanced crop growth and yield

Research shows that combining AI with drip irrigation significantly improves water productivity and resource efficiency (Hamdaoui *et al.,* 2024).

Real time Monitoring and Control

AI-enabled irrigation systems provide real-time monitoring of field conditions through mobile applications and dashboards. Farmers can access data on:

- Soil moisture status
- Weather conditions
- Irrigation schedules

Real-time monitoring allows immediate adjustments to irrigation practices, improving responsiveness to environmental changes. Cloud-based platforms enable remote control of irrigation systems, allowing farmers to manage irrigation operations from anywhere.

Climate Risk Management

AI plays a critical role in managing climate risks in agriculture. By analyzing climate data and predicting extreme weather events, AI systems help farmers adapt their irrigation practices.

Applications include:

- Adjusting irrigation during heat waves
- Managing water during drought conditions
- Preventing waterlogging during heavy rainfall

AI-based climate risk management enhances the resilience of agricultural systems and reduces crop losses.

Integration with the Smart Farming System

AI-driven irrigation is often integrated with other smart farming technologies, such as:

- Precision nutrient management
- Crop health monitoring systems
- Farm management software

This integration creates a holistic approach to farm management, improving overall efficiency and sustainability. Smart farming systems enable data-driven decision-making, which is essential for modern agriculture under climate change scenarios (Kumar *et al.,* 2024).

Table 9: Benefits of AI-driven precision agriculture

Aspect	Impact
Water use efficiency	Increased by 20–50%
Crop productivity	Improved yield
Energy consumption	Reduced
Environmental impact	Lower groundwater depletion
Climate resilience	Enhanced adaptation capacity

Challenges and limitations

Despite its advantages, AI-driven precision irrigation faces several challenges:

- High initial investment costs
- Lack of technical knowledge among farmers
- Limited infrastructure in rural areas
- Data availability and quality issues

Smallholder farmers often face barriers in adopting advanced technologies due to financial and technical constraints.

Conclusion

AI-driven precision irrigation brings a significant advancement in sustainable agriculture. It transforms sustainable agriculture by leveraging sensors, ML models and ET parameters for optimal water management. By optimizing water use and improving crop productivity, these technologies also contribute to climate-resilient farming systems addressing the key challenges in water scarce regions. Despite challenges, continued technological innovation and policy support can facilitate widespread adoption.

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BIOFUMIGATION IS AN ECO-FRIENDLY SOLUTION FOR SOIL HEALTH AND DISEASE MANAGEMENT IN SUSTAINABLE HORTICULTURE

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Abstract

Biofumigation is an eco-friendly agricultural practice that utilizes biocidal compounds released from Brassicaceous plants to suppress soil borne pathogens. Brassicaceae family Species Brassica, Raphanus are the most widely used plants for biofumigation. These plants contain glucosinolates, which produce biocidal compounds, such as isothiocyanates, following enzymatic hydrolysis, with scientifically proven fungicidal effects. In addition to the release of compounds in the soil, complementary mechanisms, such as the supply of nutrients and organic matter and improvement of the soil structure. In the past several studies on the use of brassica residues in biofumigation have been published, showing promising results in the management of soil pathogens (fungi and oomycetes, bacteria), This chapter discusses the mechanisms, benefits, and applications of biofumigation, as well as its challenges and future prospects in sustainable agriculture.

Keywords: Brassica spp., Soil Pathogens, Glucosinolates, Isothiocyanates, Green Manure.

Introduction

Brassica species are a unique type of cover crop that produce compounds, glucosinolates (GSLs), which help in the suppression of certain soil borne pathogens. The management of soil-borne plant pathogens is a major constrain in vegetable crop production (Dixon & Tilston *et al.,* 2010). Biofumigation method is a 'natural' alternative to chemical fumigation if they can be successfully incorporated into vegetable crop rotations to manage soilborne diseases. Brassica species represents sustainable technique for soil disinfection and soil fertility, productivity. Utilizing biofumigant cover crops can be an effective tool enhancing yield by suppressing soil borne diseases in horticultural production systems, which offers growers a solution that does not involve the use of synthetic chemicals for disease control. Some resting stages of soilborne diseases can survive for many years even in the absence of a suitable host and remain dormant until conditions are favourable resulting in the development of symptoms on the plant. The soil borne pathogen *Sclerotium rolfsii* can survive for 3-4 years, *Sclerotinia sclerotiorum generally* survive in the soil for 3-8 years *Macrophomina phaseolina* has been shown to survive in the soil for between 2 and 15 with variable sclerotial survival from region to region dependent on both environmental and biological conditions (Kator *et al.,* 2015). Improving soil health is one such control option to support microbial communities to help fight micro-organisms that are deleterious to plant health. Since the 1980s, the use of natural soil fumigation through plant-based volatile compounds targeting known plant pathogens—such as fungi, bacteria, and nematodeshas become increasingly recognized. This practice, known as biofumigation, utilizes the natural release of bioactive compounds from certain plants to suppress soil-borne pathogens, offering an eco-friendly alternative to traditional chemical fumigants. Biofumigation is effective at controlling phytopathogens that cause disease in plants (fungi, oomycetes, nematodes, and bacteria).

Biofumigation

The term "biofumigation" was first coined by J.A. Kirkegaard. It refers to growing, macerating / incorporating certain Brassicaceae family species into the soil, leading to the release of isothiocyanate compounds (ITCs) through the hydrolysis of glucosinolate (GSL) compounds contained in the plant tissues which leads to suppression of soil-borne pests pathogens (Kirkegaard *et al.,* 1993).

Brassica Cover Crops for Managing Soil Borne Diseases in Vegetable Production Systems

Interest in Brassica biofumigation Cover Crops for managing soil borne diseases in has increased recently in vegetable production system due to prohibition of several synthetic pesticides and soil fumigants. Methyl bromide is classic example soil fumigation, its prohibition led to limitations in some production sectors, such as vegetables, flowers, and seedlings (Epstein, 2014). Since the 1990s, studies have investigated alternative proposals or techniques that may be used to replace fumigation with synthetic chemical compounds (Kierkegaard *et al.,* 1993). Soil borne pathogens can bring major constraints to vegetable crop production and their suppression often relies on synthetic chemicals that can be ineffective and/or expensive (Baker *et al.,* 1996).

The challenge from a disease management in vegetable crop production reducing disease inoculum in the soil, enriching soil health so that crops are able to become more resilient to soil borne pathogens. An integrated approach utilizing biofumigant cover crops can be an effective tool in the management of soilborne diseases in horticultural production systems. Brassica species, such as mustard, radish and have been shown to suppress soil borne diseases such as basal rot (*Sclerotium rolfsii*), Onion white rot (*Sclerotium cepivorum*), charcoal rot (*Macrophomina phaseolina*) and white mould (*Sclerotinia sclerotiorum*) (Larkin *et al.,* 2010)

How Power of Biofumigation Process Works in Brassica Plants

Brassica species naturally produce a group of glucosinolates (GSLs) chemicals. Through the process of incorporation, once glucosinolates are released from the plant cells and with the addition of irrigation water, glucosinolates are converted by the enzyme myrosinase into isothiocyanates (ITCs), gases that are toxic to various soilborne pathogens and pests. isothiocyanates that gives mustard and radish its biofumigation power. The isothiocyanate that is produced by mustard is called “Allyl isothiocyanate” (AITC). AITC is a compound that is very similar to the compound that is contained in the commercial fumigant Vapam®.

Commonly used biofumigant crops and their respective GSLs and ITCs (Rosa *et al.,* 1997)

Common Name	GSL	ITC
Black mustard (Brassica nigra)	Sinigrin	2-propenyl-ITC (= allyl-ITC)
Brown mustard (Brassica juncea)	Sinigrin	2-propenyl-ITC (= allyl-ITC)
Radish (Raphanus sativus)	Glucoraphenin	4-methylsulfinyl-3-butenyl--ITC

Best time of incorporation into feild

The concentration and type of GSLs will vary between varieties, as does the type of ITCs produced from the GSLs. The highest concentration of glucosinolates presents in mustard and radish approximately 25% flowering which is also seasonally dependant. Biofumigant crops will flower earlier in summer and later in winter due to the temperature affecting the speed of growth. The brassica varieties were flowering between 5-10 weeks when grown in summer and 9-14 weeks when grown in winter which is the recommended timing for incorporating biofumigants. Irrigation or rolling helps to seal the gas in the soil so that they are most effective in suppressing soil borne pathogens (Rosa *et al.,* 1997).

Fumigation vs. Biofumigation

Fumigation and biofumigation are both strategies for controlling soilborne pests and pathogens, but they differ in their mechanisms, environmental impact, and sustainability.

Aspect	Fumigation	Biofumigation
Source	Synthetic chemicals (e.g., methyl bromide, metam sodium)	Natural compounds from decomposing Brassicaceous plants and organic matter
Mode of Action	Releases toxic gases that kill pests and pathogens	Produces biocidal compounds (e.g., isothiocyanates) through enzymatic hydrolysis
Effectiveness	Highly effective but may leave residues	Variable effectiveness depending on plant species and soil conditions
Environmental Impact	Can be toxic, contributes to ozone depletion and pollution	Eco-friendly, improves microbial diversity soil health
Sustainability	Non-renewable and subject to regulatory restrictions	Renewable, sustainable, and enhances soil fertility

There are multiple benefits to using biofumigants in vegetable cropping systems, including:

- ITCs effectively suppress soil borne pathogens,
- Good biomass production, Organic amendments enhance microbial diversity and soil structure.
- Minimizes reliance on synthetic chemicals and fumigants.
- Decomposed plant material adds organic matter, reducing soil degradation. Improves soil conditions leads to better plant growth and productivity.

- Reducing top soil loss through erosion from the summer rains
- Biofumigant cover crop minimizes and manages the impact of soil borne diseases
- Reducing the use of harsh harmful and potential fungicides when controlling soil borne diseases

Limitations Despite its advantages, biofumigation faces several challenges:

- Efficacy depends on plant species, soil type, and environmental conditions.
- Large quantities of plant material are needed for effective fumigation.
- Proper incorporation and soil sealing are essential for optimal ITC release.
- Farmers need education and technical support for implementation.

Conclusion

Overall biofumigation presents a sustainable and effective strategy for managing soil-borne diseases and improving crop yields. Continued research is essential to optimize its application across various crops and soil types. Biofumigation is a promising, sustainable agricultural strategy that balances soil health, pest control, and environmental safety. Its adoption can reduce reliance on synthetic fumigants while promoting biodiversity and long-term soil fertility. Continued research and farmer education will be crucial in optimizing and expanding the use of biofumigation in modern agriculture.

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POLLEN MICROFOSSILS AS EARLY WARNING INDICATORS OF AGRICULTURAL COLLAPSE: LESSONS FROM PAST CIVILIZATIONS

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Abstract

Economic models, satellite vegetation indicators, and short-term climate projections are the mainstays of contemporary agricultural early warning systems. The deep time perspective required to identify a gradual, systemic decline toward collapse is rarely incorporated. This chapter shows how pollen microfossils—more especially, cereal pollen, weed indicators, and forest taxa offer a measurable, empirical foundation for agricultural vulnerability and resilience. Using case studies of the Hohokam, Akkadian Empire, Indus Valley, and Classic Maya, We demonstrate that long-term reductions in crop pollen frequently occurred decades or even millennia before social collapse. We suggest a "pollen early warning framework" that combines real-time automated pollen monitoring using machine learning and bioaerosol sensors with fossil criteria (such as a >40% decline in wheat pollen sustained over 50 years). Taphonomy, taxonomic resolution, and separating climate from human origins are among the difficulties. However, including palynology into food security planning provides a special, underutilized tool for developing agriculture that is climate resilient.

Keywords: Pollen Microfossils, Agricultural Collapse, Early Warning Indicators, Climate Resilience, Food Security, Palynology, Machine Learning.

1.Introduction: The Blind Spot in Modern Food Security

Weather forecasts, satellite imaging, and economic indicators are major components of modern agricultural early warning systems. These instruments track present circumstances, but they don't have a long-term standard by which to gauge genuinely extraordinary stress. It is impossible to tell the difference between a typical poor crop and the start of a systemic collapse without knowing how agricultural systems responded to previous climate shocks. A direct, high-resolution record of crop abundance and vegetation change spanning decades or millennia is provided by pollen microfossils. This chapter offers a useful early warning system for modern agriculture and summarizes palynological data from four fallen civilizations. There is clearly a need to better understand interactions between past societies and their environments. Collaboration between the historical–archaeological and the paleoenvironmental sciences is essential to this effort.

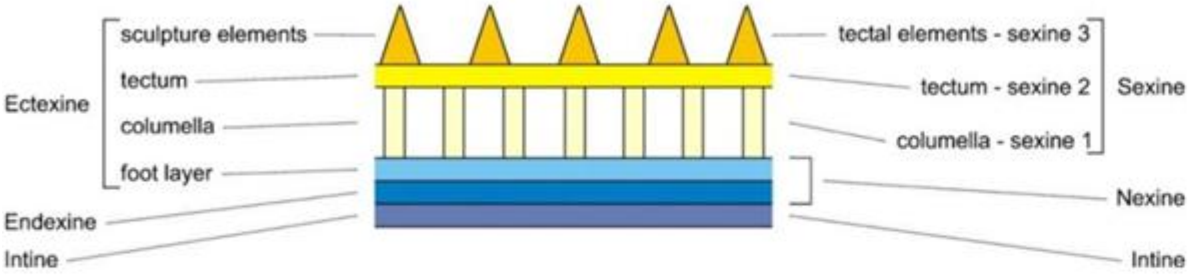
2. The Methodology: Reading the Archive of Collapse

This section explains how pollen microfossils are extracted, identified, and interpreted as agricultural indicators.

A continuous, dateable record of pollen deposition is captured in sediment cores from lakes, bogs, or archeological sites. The amount and intensity of staple crop cultivation can be directly inferred from cereal pollen, such as Zea mays for maize, Triticum for wheat, and Oryza for rice. Land clearing, soil degradation, or field abandonment are all indicated by weed and disturbance indicators (e.g., Ambrosia, Plantago). Forest clearing or regeneration can be determined by comparing arboreal (tree pollen) with non-arboreal (herbs, grasses) pollen. Fungal spores and dung fungi are examples of non-pollen palynomorphs that can reveal changes in water quality, erosion, or livestock grazing. To cross-validate interpretations, multi-proxy techniques combine pollen with phytoliths (plant silica), sediment chemistry, and charcoal (firehistory). Pollen variations can be linked to known historical events thanks to radiocarbon dating of the sediment core, which establishes chronology. One important lesson is that the traditional "collapse signature" is a persistent decrease in grain pollen along with an increase in weed or forest pollen.

2.1 Laboratory and Analytical Methods for Pollen Fossil Preparation

To use pollen microfossils as reliable early warning indicators, standardised extraction, identification, and quantification methods are essential. This section provides a practical protocol for preparing pollen from sediment cores for analysis.



2.1.1 Field Sampling

- **Core collection:** Use a piston or percussion corer to extract undisturbed sediment cores from lakes, peat bogs, or floodplains. Core diameter should be at least 5 cm to provide sufficient material for multi-proxy analyses.
- **Subsampling:** Cut the core at 1–2 cm intervals (higher resolution for suspected transition zones). Each subsample represents roughly 10–100 years depending on sedimentation rate.
- **Storage:** Wrap subsamples in aluminium foil or plastic bags, seal in airtight containers, store at 4 °C to prevent microbial degradation.

2.1.2 Chemical Extraction of Pollen

The goal is to remove mineral grains, organic debris, and cellulose while concentrating pollen grains. A modified acetolysis method (following Faegri & Iversen, 1989) is standard:

- **Drying:** Air-dry or freeze-dry 5–10 g of sediment per sample.
- **Carbonate removal (if calcareous):** Treat with 10% HCl at room temperature for 12 hours. Centrifuge (3000 rpm, 10 min) and decant.
- **Silicate removal:** Add 40% HF in a fume hood. Let stand for 24 hours. Centrifuge and wash with distilled water three times.
- **Acetolysis:** Prepare acetolysis mixture (9 parts acetic anhydride: 1 part concentrated H_2SO_4). Add to residue in a water bath at 90 °C for 3–5 minutes. This dissolves cellulose and stains pollen.
- **Neutralisation:** Cool, centrifuge, and wash with glacial acetic acid, then with distilled water.
- **Density separation (optional for pollen-poor samples):** Use $ZnCl_2$ or sodium polytungstate (density 2.0 g/mL) to float pollen. Centrifuge and collect the floating fraction.
- **Dehydration:** Transfer residue to 50% glycerol or silicone oil for mounting.

2.1.3 Mounting and Microscopy

- **Mounting medium:** Use glycerol jelly or silicone oil for permanent slides. Seal edges with nail varnish or paraffin.
- **Microscopy:** Examine under a light microscope at 400× or 1000× (oil immersion). Count at least 300–500 pollen grains per sample to obtain statistically robust percentages.
- **Reference collection:** Compare unknown grains with a curated reference slide collection of modern pollen from local plant taxa.

2.1.4 Identification and Quantification

- **Taxonomic keys:** Use regional pollen atlases (e.g., for South Asia: Nayar *et al.,* 1990; for tropics: Gosling *et al.,* 2013).
- **Crop pollen identification:** Distinguish cereal pollen (e.g., *Triticum*, *Zea mays*, *Oryza*) by size, pore number, and surface ornamentation. Cereal grains are typically large (>35 µm) with a single prominent pore and annular thickening.
- **Weed indicators:** Recognise ruderal taxa such as *Ambrosia*, *Plantago*, *Rumex*, and *Artemisia*.
- **Calculation:** Express each taxon as a percentage of the total terrestrial pollen sum (excluding aquatic plants and spores). Construct pollen diagrams using software such as Tilia or C2.

2.1.5 Chronology

To assign ages to pollen changes:

- **Radiocarbon dating:** Select macrofossils (seeds, wood) or bulk sediment organic carbon. Calibrate using IntCal20 curve.

- **Lead-210 and Caesium-137:** For recent sediments (last 150 years), use gamma spectrometry.
- **Age-depth modelling:** Apply a smooth spline or Bayesian model (e.g., Bacon package in R) to generate an age for each sample depth.

15g of samples were boiled with 4 to 5 KOH pillets in a glass beaker of 150 ml distilled water

After cooling, using 150 mesh sieve samples were seived into maceration jar combining with distilled water.

Allow the jars to settle, decantation process carried 2 to 3 times using a siphon tube.

40% of HF solution is addded to the sample after last decantation process and store for 2 to 3 days in the fuming chamber.

After these period of days, rinse the sample and taking 45ml of the sample to an 50ml centrifuging tube.

The sample is now centrifuged once or twice.

To the remaining samples, adding Glacial acetic acid and centrifuged.

Later this procedure, acetolysis is carried down, creating an mixture solution of 9 parts of acetic anhydride and 1 part of conc. sulfuric acid.

Equally distributing the mixture solution to each samples and kept for waterbath for 15 min.

The samples now placed for cooling and later adding glacial acetic acid and kept it rest for an overnight.

The sample is then centrifuged for 10 min and decanting the excess acid.

The same centrifuging process is carried for 2 to 3 times untill the complete removal of acid smell.

Samples is then seived in 600 mesh seive and collected in a veil bottle

After decanting, mounting process is carried, to the 50% of sample50% of glycerol, 2 to 3 drops of phenol is added.

Slide is prepared.

Pollen and spore analysis is carried down by using Olympus DP23 camera on an Olympus BX51 microscope with 40X objective magnification.

Identified the pollen and spore.

2.1.6 Quality Control and Data Reporting

- **Pollen preservation:** Note any corroded, crumpled, or degraded grains. Exclude samples with >20% unidentifiable grains.

- **Replication:** Analyse duplicate cores or parallel samples to assess reproducibility.
- **Minimum count:** Ensure the pollen sum exceeds 300 grains; otherwise, report as “pollen-poor.”
- **Data archiving:** Upload raw counts and metadata to public repositories such as Neotoma or Pangaea.

2.1.7 From Fossil Data to Early Warning Indices

Once a fossil pollen sequence is obtained, calculate the following metrics for early warning:

- **Cereal pollen percentage** (cereal / total terrestrial pollen) × 100.
- **Weed/Cereal ratio** (ruderal pollen / cereal pollen) – increases indicate land degradation.
- **Detrended anomaly:** Subtract the long-term mean (e.g., 500-year running average) to highlight deviations.

3. Case Studies in Agricultural Collapse

3.1 The Classic Maya Collapse (c. 800–950 CE)

Pollen records from the Yucatán Peninsula show a strong relationship between increased maize pollen and dry periods driven by El Niño, while moist periods are characterised by low maize pollen presence (Islebe *et al.,* 2022). During the Terminal Classic drought, pollen sequences reveal a sharp decline in maize and forest taxa, replaced by weedy vegetation. High-resolution studies suggest a multi-decadal to century-scale decline in agricultural indicators preceded the final abandonment of many Maya cities. This teaches us that even sophisticated, urbanised agricultural systems can exhibit a long, detectable deterioration before collapse.

3.2 The Indus Valley (Harappan) Civilisation (c. 2600–1300 BCE)

Pollen assemblages from lakes in the region show a distinct shift from moisture-loving plants to arid-adapted species around 4,000 years ago, indicating a weakening monsoon (Dixit *et al.,* 2014). This coincides with the de-urbanisation of the Indus cities. Some studies suggest the decline was not a single drought but a gradual shift in crop patterns. The pollen signal shows a slow aridification over centuries, implying that agricultural fragility accumulated long before the final collapse of urban centres.

3.3 The Akkadian Empire (c. 2334–2150 BCE)

Archaeological and soil-stratigraphic data define the origin, growth, and collapse of Subir, the third millennium rain-fed agriculture civilization of northern Mesopotamia on the Habur Plains of Syria. At 2200 B. C., a marked increase in aridity and wind circulation, subsequent to a volcanic eruption, induced a considerable degradation of land-use conditions. After four centuries of urban life, this abrupt climatic change evidently caused abandonment of Tell Leilan, regional desertion, and collapse of the Akkadian empire based in southern Mesopotamia. Synchronous collapse in adjacent regions suggests that the impact of the abrupt climatic change was extensive (Weiss *et al.,* 1993).

3.4 The Hohokam of the American Southwest (c. 450–1450 CE)

The Hohokam developed a sophisticated, millennium-long irrigation agriculture in the Sonoran Desert. Pollen analysis of their "Salt River Adobe" soils shows the types of crops grown and the duration of cultivation (Huckleberry *et al.,* 2024). Their collapse in the 1200s–1400s CE has been linked to a combination of drought, soil salinisation, and reduced soil permeability from continuous irrigation. Pollen and soil evidence suggest a gradual decline in soil health over centuries, offering a long but largely ignored warning.

3.5 Supplementary Cases

- **Angkor (Cambodia):** A pollen sequence from the Bakong temple moat showed that intensive rice agriculture flourished from the 8th century CE, but declined significantly in the 10th century, long before the final abandonment of the city (Penny *et al.,* 2006).
- **Roman/Byzantine Levant:** Pollen records from the Dead Sea region show a clear drop in agricultural indicators (especially olive and cereals) during periods of political upheaval and earthquakes, demonstrating how environmental proxies can distinguish between human and natural causes of collapse.

4. Defining the Thresholds: Towards a Quantifiable Early Warning

Can we define a numerical threshold in pollen decline that signals imminent agricultural collapse? Drawing from resilience theory and the PolLimCrop dataset—a global compilation of 294 studies and 1,169 unique pollen supplementation experiments for 108 crops (Siopa *et al.,* 2023)—we propose a provisional framework.

A sustained >40% reduction in cereal pollen relative to the local baseline, maintained for >50 years, coupled with a >20% increase in ruderal (weed) pollen, appears to have preceded collapse in all four case studies. However, thresholds will vary by crop, region, and climate. The goal is not a single number but a multi-parameter index combining cereal pollen percentage, weed pollen percentage, charcoal frequency, and non-pollen palynomorphs. Such an index can be calibrated for different agricultural systems using local fossil records.

5. Technological Frontiers: From Fossil to Real-Time

Traditional palynology is labour-intensive and slow, but emerging technologies are transforming it into a near-real-time early warning tool.

- **Automated identification:** using machine learning, such as multiple convolutional neural networks (CNNs), can now recognise intact, damaged, and fossil pollen grains with misclassification rates as low as 0% for intact grains, 2.8% for damaged grains, and 3.7% for fossil grains. AI-based frameworks combine scanning electron microscopy with computer vision to automatically classify pollen grains based on their microscopic surface features, with applications in agriculture, medicine, and biodiversity monitoring.
- **From ancient to modern:** Using automated bioaerosol sensors, which are also used for pollen monitoring, Ireland has established its first nationwide fungal spore monitoring network, allowing for year-round multitaxa observation. In contemporary agricultural

areas, the same technology can be modified for real-time water and air sampling. We could identify abrupt, inexplicable drops in pollen production or dispersal—an early warning of plant stress, pollinator collapse, or disease outbreak—by regularly monitoring airborne crop pollen.

.6. Challenges and Cautions

No proxy is perfect. Several limitations must be acknowledged:

- **Taphonomy:** Not all pollen is preserved equally. Some crops are over-represented, others under-represented.
- **Taxonomic resolution:** Distinguishing between closely related crop species (e.g., different wheats) can be difficult.
- **Climate vs. human causation:** A decline in crop pollen could be due to climate change, soil exhaustion, pest outbreaks, political instability, or a combination. Multi-proxy studies are crucial for disentangling these factors.
- **Temporal resolution:** Lake sediment cores often integrate pollen over decades or centuries. This “smoothing” can obscure short-term crises or rapid collapses. High-resolution sampling (annual or sub-annual) is needed for early warning applications.
- **Scale:** A local pollen record may not reflect regional trends. Multiple cores from different landscape positions are necessary for robust conclusions.

7. Implications for Modern Food Security and Climate Resilience

The lessons from past collapses translate into actionable recommendations.

- **Principle 1 – Baseline establishment.** Every major agricultural region should have a high-resolution fossil pollen record establishing its “normal” range of variability in crop abundance, weed pressure, and forest cover over the past 1,000–2,000 years.
- **Principle 2 – Real-time pollen monitoring.** Integrate automated pollen sensors (like those deployed in Ireland) into existing agricultural monitoring networks. Use AI to identify and quantify airborne pollen from major staple crops and wild plants.
- **Principle 3 – Threshold alert system.** Develop a “pollen early warning index” for each region, combining fossil thresholds (from Section 4) with real-time data. An alert is triggered when monitored pollen levels fall below the 10th percentile of the historical baseline for a sustained period.
- **Principle 4 – Diversification as resilience.** The Maya case study shows that societies which diversified their crops (maize + palm + root crops) were more resilient than those which specialised. Pollen records can identify which ancient crop combinations were most successful during past climate shocks, offering a menu of options for modern diversification.

- **Principle 5 – Soil health monitoring.** The Hohokam example shows that pollen and soil microfossils can track long-term soil degradation. Modern agriculture should integrate soil palynology into its soil health monitoring protocols.

Conclusion

Pollen microfossils are not merely academic curiosities. They are a unique, empirically grounded archive of agricultural success and failure under real-world climate stress. The four case studies presented here—Maya, Indus, Akkadian, Hohokam—demonstrate that sustained declines in cereal pollen consistently preceded societal collapse, often by decades or centuries. Modern early warning systems ignore this deep-time evidence at their peril. We have proposed a practical framework: establish fossil baselines, deploy real-time automated pollen monitoring, define quantitative thresholds, and use the resulting index to trigger resilience-building actions. Technological advances in machine learning and bioaerosol sensors now make this feasible Challenges remain—taphonomy, taxonomic resolution, and causation—but none are insurmountable.

The past is buried in lake sediments, waiting to speak. Listening to pollen microfossils will not replace satellites or weather models, but it will add something they cannot: proof that certain farming systems have already survived climate extremes and proof that others have not. Ignoring that proof is a risk we cannot afford.

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CLIMATE CHANGE AND ITS IMPACT ON VETERINARY PARASITES

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1. Introduction

Climate change is a rapidly intensifying global phenomenon marked by increasing temperatures, shifting rainfall patterns, and a higher frequency of extreme weather events. These environmental transformations play a crucial role in shaping the dynamics of infectious diseases, especially within veterinary parasitology. Parasites are particularly sensitive to climatic conditions because their development, survival, and transmission depend heavily on environmental factors (Wood, 2025).

Veterinary parasites have significant impacts on livestock productivity, companion animal health, and wildlife populations. In addition, many parasites are zoonotic, posing potential threats to human health. The relationship between climate change and parasitic infections is multifaceted, involving ecological interactions, biological processes, and socio-economic influences. Recent studies indicate that climate change is altering parasite distribution, host susceptibility, and transmission patterns on a global scale (Filho *et al.,* 2025).

2. Classification and Importance of Veterinary Parasites

Veterinary parasites are broadly classified into two main categories:

2.1 Endoparasites

Endoparasites reside within the host's body and include nematodes, cestodes, trematodes, and protozoa. Notable examples include *Haemonchus contortus*, *Fasciola hepatica*, and *Cryptosporidium* species.

2.2 Ectoparasites

Ectoparasites inhabit the external surface of the host, such as the skin. These include ticks, mites, fleas, and lice, many of which also act as vectors for other infectious agents.

Parasitic diseases are a major limitation to animal health and agricultural productivity worldwide. They contribute to reduced growth rates, decreased milk production, impaired reproductive performance, and increased mortality (Gonzalez, 2025).

3. Climate Change Drivers affecting Parasites

3.1 Rising Temperatures

Temperature is a key factor influencing parasite development and survival. Increased temperatures accelerate metabolic and developmental processes, resulting in faster parasite life cycles and higher transmission rates. For example, elevated temperatures can shorten the prepatent period of many helminths, thereby increasing infection intensity. Climate warming has also been shown to alter parasite population dynamics and expand endemic regions (Deak *et al.,* 2024).

3.2 Changes in Precipitation

Rainfall plays an essential role in the survival of free-living parasite stages and intermediate hosts such as snails and insects. Higher rainfall generally enhances larval survival, whereas drought conditions may concentrate hosts around limited water resources, thereby increasing transmission opportunities.

3.3 Extreme Weather Events

Events such as floods, droughts, and storms disrupt ecosystems and parasite transmission patterns. Flooding can disperse parasite eggs and larvae over large areas, while drought may alter grazing behavior and increase host exposure to infection.

3.4 Humidity and Microclimate

Humidity is critical for the survival of many parasite stages. Microclimatic conditions, particularly in pasture environments, strongly influence parasite development and infection risk.

4. Effects on Parasite Life Cycles and Biology

4.1 Accelerated Development

Climate change often leads to shorter parasite life cycles, allowing multiple generations within a single year. This results in increased parasite burdens in host populations.

4.2 Survival of Free-Living Stages

Environmental stages such as eggs and larvae are highly dependent on climatic conditions. Adequate moisture and moderate temperatures enhance their survival and infectivity (Morchón *et al.,* 2025).

4.3 Changes in Intermediate Host Dynamics

Parasites such as *Fasciola hepatica* depend on intermediate hosts like snails. Climate-driven changes in water availability directly affect snail populations and consequently influence parasite transmission (Modabbernia *et al.,* 2024).

4.4 Evolutionary Adaptation

Parasites may undergo genetic adaptations in response to environmental changes, potentially increasing their virulence or resistance to existing control measures.

5. Impact on Host–Parasite Interactions

5.1 Increased Host Susceptibility

Climate-related stressors, including heat stress and nutritional deficiencies, can weaken host immune responses, making animals more susceptible to parasitic infections.

5.2 Behavioral Changes in Hosts

Climate change can alter animal behavior, including grazing, migration, and watering patterns, which may increase exposure to parasite-contaminated environments.

5.3 Wildlife–Livestock–Human Interface

Habitat alterations are increasing interactions among wildlife, livestock, and humans. This enhances the potential for cross-species transmission of parasites and the emergence of new diseases (Greening *et al.,* 2025).

6. Vector Ecology and Climate Change

Many veterinary parasites rely on vectors such as ticks, mosquitoes, and flies. Climate change influences vector ecology in several ways:

6.1 Expansion of Vector Distribution

Rising temperatures enable vectors to spread into previously unsuitable regions, including higher altitudes and latitudes.

6.2 Increased Vector Abundance

Favorable climatic conditions enhance vector survival and reproduction, leading to higher population densities.

6.3 Extended Transmission Seasons

Climate change can prolong the activity period of vectors, resulting in longer or even year-round transmission seasons.

6.4 Emergence of Vector-Borne Diseases

Changes in vector distribution have contributed to the appearance of diseases in regions where they were previously absent (Conn and Magalhães, 2024).

7. Climate-Sensitive Veterinary Parasites: Case Studies

7.1 Gastrointestinal Nematodes

Nematodes such as *Haemonchus contortus* are highly influenced by environmental conditions. Warm and humid climates promote larval development and increase pasture contamination.

7.2 Fasciolosis

The transmission of *Fasciola hepatica* is closely linked to climatic conditions that affect snail populations. Variations in temperature and rainfall significantly influence disease occurrence (Claerhoudt, 2024).

7.3 Food- and Water-Borne Parasites

Parasites such as *Giardia*, *Cryptosporidium*, and *Toxoplasma* are associated with environmental contamination. Climate change increases the likelihood of waterborne disease outbreaks (Robertson *et al.,* 2024).

7.4 Zoonotic Parasites

Zoonotic parasites pose serious public health risks. Climate-driven changes in transmission dynamics increase the likelihood of spillover events.

8. Impact on Livestock Production Systems

Climate change intensifies the effects of parasitic diseases in livestock, resulting in:

- Reduced feed efficiency

- Decreased milk and meat production
- Increased mortality rates
- Higher costs of treatment and control

These effects threaten food security and economic stability, particularly in developing regions where livestock farming is a primary source of income (Poulin and Mouritsen, 2024).

9. Wildlife and Ecosystem Implications

Wildlife populations are also affected by climate-induced changes in parasite dynamics. Alterations in migration patterns and habitat fragmentation increase exposure to infections. Such changes may disrupt parasite-host relationships and contribute to biodiversity loss and ecological imbalance (Charles, 2024).

10. Zoonotic and Public Health Implications

Climate change promotes the emergence and re-emergence of zoonotic diseases through:

- Expansion of vector habitats
- Increased human–animal interactions
- Improved environmental survival of pathogens

These challenges highlight the importance of adopting a One Health approach that integrates veterinary, medical, and environmental sciences (Ramadan, 2024).

11. Socio-Economic Consequences

Parasitic diseases impose significant economic burdens, including:

- Direct losses in animal productivity
- Costs associated with treatment and control
- Trade limitations and market impacts

Climate change further intensifies these challenges, especially in low-income regions with limited disease management resources (Viani *et al.,* 2025).

12. Adaptation and Mitigation Strategies

12.1 Surveillance and Monitoring

Effective surveillance systems are essential for tracking parasite distribution and predicting outbreaks.

12.2 Integrated Parasite Management

Key strategies include strategic deworming, improved pasture management, and biological control methods.

12.3 Climate-Resilient Livestock

Selective breeding for parasite resistance and heat tolerance can help reduce disease impact.

12.4 Vector Control

Control measures include the use of insecticides, environmental management, and biological control agents.

12.5 Policy and Education

Strong policies and farmer education programs are necessary for implementing sustainable control strategies (Johnson *et al.,* 2025).

13. Advances in Research and Technology

Recent developments in veterinary parasitology include:

- Predictive modeling of parasite distribution under changing climate scenarios
- Genomic studies to understand parasite adaptation
- Use of GIS and remote sensing technologies for disease surveillance

These tools improve the ability to anticipate and manage climate-related disease risks.

14. Future Research Directions

Future research should focus on:

- Long-term monitoring of parasite dynamics
- Understanding host–parasite co-evolution
- Developing sustainable and eco-friendly control strategies
- Integrating climate data with epidemiological models

Collaborative, interdisciplinary approaches will be essential to address these challenges effectively.

Conclusion

Climate change is significantly transforming the epidemiology of veterinary parasitic diseases, with far-reaching consequences for animal health, food security, and public health. The interactions among environmental factors, hosts, and parasites are complex and require integrated management strategies.

Enhancing research, strengthening surveillance systems, and implementing adaptive control measures can help mitigate these impacts. Adopting a One Health approach is crucial for addressing the interconnected challenges of climate change, animal health, and human well-being.

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IMPROVING FOOD SECURITY IN RURAL INDIA THROUGH CROP DIVERSIFICATION

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1. Introduction

Food security has remained as one of the most acute issues of rural India at a time when the agricultural production experienced impressive strides after the Green Revolution. The country has become self-sufficient in relation to the staple food grains, especially rice and wheat, yet there are serious issues with the nutritional adequacy, sustainability, and resilience of the food system. A large proportion of the rural population continues to experience undernourishment and seasonal food insecurity and increased susceptibility to climate variability and economic uncertainties. The culturally oriented monocropping (based on cereal production) systems have played a role in agricultural sustainability and dietary imbalances. Although the caloric adequacy has been achieved through such systems, these have been ineffective in providing a diversity of nutrition, and thus have contributed to the problems of micronutrient deficiencies and hidden hunger. In this respect, diversification of crops has been viewed as a key approach to promoting food security with a greater holistic and sustainable approach. It involves changing monoculture operations to a diversified pattern of cropping, which involves the planting of pulses, oilseeds, fruits, vegetables, and crops that are climate resistant e.g. millets. This shift not only increases the income and livelihood security in the farms, but also increases the variety of the diet, healthy soils and minimizes risks of production linked with climatic changes and market unpredictability. It is against this context that this chapter will examine the transformative power of crop diversification options in enhancing food security in rural India. It looks specifically at the contribution of diversification to the four essential dimensions of the availability of food security, its accessibility, use, and stability, as well as the more imminent issues of its sustainability and rural resilience.

2. Changing Cropping Pattern in India

A radical change in the pattern of crop production has been experienced in India in recent decades. Although there has not been much variation in the net cultivated area, the increasing food demand due to the growing population and urbanization has exerted a lot of strain on the arable land. This has led to increased agricultural activity and a process whereby traditional food crops are replaced with more commercially viable crops. The statistics are a vivid indicator of structural change in Indian agriculture, which is based on the changing market dynamics, the presence of better irrigation systems, and policy interventions, which are designed to promote diversification.

i. Decline of Traditional Crops

Traditionally, foodgrains have dominated Indian agriculture and they were the foundation of food security and rural livelihoods. Nevertheless, as recent trends show, there is a steady, slow but steady loss of relative significance in a variety of traditional crops in terms of structural changes in the agricultural economy. It is important to note that the area covered by rice, which includes the Aus, Aman and Boro varieties, has reduced by 24.52 per cent in 198081 to 21.74 per cent in 2023-24. This can be explained by several factors, such as the high sensitivity to monsoon variability of the crop, decreasing productivity in some areas, increasing input prices, and growing competition through more profitable and risk-averse crops. The increase in irrigation has helped in the production of Boro rice in the country, but has not been adequate to counter the general decline in rice acreages. Conversely, this growth in wheat production has been relatively low since it has gone up by 13.78 per cent to 14.52 per cent across the seasons, although there have been tremendous changes in technology such as planting high-yielding varieties and the application of agronomics. The fairly sluggish increase in the wheat acreage can be attributed to the regional agro-climatic conditions which are more so in eastern and southern India as well as rising competition with value crops which provide high yield. Moreover, the changing trends of consuming diversified and healthy foods, have slowly diminished the pre-eminence of wheat in the cropping system. The proportion of pulses in the gross cropped area has been found to follow a very skewed and decreasing trend within the last 30 years in the country at the national level. In 1990-01, the percent of pulse cultivation relative to gross cropped area is 20.06 per cent but this reduced to 10.98 per cent in 1999-01 suggesting a considerable decline in the post economic reform era. This was in tandem with a rise in commercialization of agriculture, growth of irrigated cultivation of cereals, and a rise in preference by farmers of crops that had higher and more stable returns. Even though there has been a significant partial recovery of the situation in 2015-16, when the share of pulses recovered to 20.12 per cent, this bounce-back turned out to be temporary. The proportion of pulses had again reduced to 13.18 per cent by 2022-23, reinforcing the fragility behind pulse cultivation within the Indian cropping system. Such policy interventions (as hoisted Minimum Support Prices, National Food Security Mission (Pulses), and positive price signals following domestic shortages) can be associated with the short-term recovery. Nevertheless, the following decrease implies that the measures were not enough to guarantee the long-term stability in pulse acreage. This unprecedented pattern highlights the structural frailty of pulses as compared to cereals and commercial crops. Low yield levels, sensitivity to weather variation, lack of adequate irrigation and poor procurement systems have weaknesses in pulses. Moreover, pulses are less appealing to farmers when the volatility of their prices and unreliable entry to the market due to uncertainties are mentioned as opposed to other crops like rice, wheat, oilseeds, and horticultural products. This leads to farmers generally shifting land out of the encouragement of pulses by short-term economic encouragement. All India trend points to the necessity to support pulse growing over time and comprehensively, to stabilize and grow pulse growing. To ensure nutritional security, lessen reliance on imports, and boost sustainable levels of the agricultural system in India, it is necessary to strengthen its procurement systems, invest in yield-enhancing research, advance climate-resistant pulse varieties, as well as, improve market infrastructure. On balance, the falling proportion of traditional food crops helps to highlight the shift of Indian agriculture towards diversification and commercialization. Although this transition has the potential to increase farm earnings, it brings up critical issues on long-term food and nutritional security, viability of cropping systems and regional balance. The solution to these problems will be long-term policy action, such as better price incentives, development of crop-specific research and development, increasing irrigation and supporting the use of climate resilient technologies to make sure that the conventional crops are viable and appealing to the farmers.

ii. Rise of High-Value and Commercial Crops

Growth of Valuable and Commercial Crops. Unlike the decreasing proportion of various conventional food crops among the major food crops, the high-value and commercial crops are now appearing in significant proportions in the cropping pattern in India, with a slow transition to market-driven agriculture. Among them, oilseeds have shown significant growth and their area under the crop changed to 12.14 per cent in 198081 and now (in 2023-24) to 14.35 per cent. Many factors have contributed to this growth and some of them are increasing domestic demand for edible oils, enhanced price incentives and the introduction of high-yielding and short-duration varieties. In addition, the long-term policy incentives, which are towards the attainment of oilseed self-sufficiency, especially through the introduction of projects like the National Mission on Edible Oils, have been very instrumental in motivating the farmers to grow more oilseeds. A more radical change can be found in the example of cultivating potatoes, which has increased exponentially, since it was at a marginal level of 0.51 per cent in 1980-81 to 9.78 per cent in 2023-24. This spectacular increase may be explained by various interconnected factors, such as the growth of cold storage and warehousing enterprises, the rise of access to more organized markets, and increasing demand by the city's consuming population as well as agro-processing industries. A minor crop, such as potatoes, with a high level of returns and a guaranteed, reliable market demand, has become an incentive crop to farmers who want to secure their earnings and diversification. Likewise, agriculture, through its fruits and vegetables industry, which is known to be among the most lucrative sectors, has experienced huge growth. Increases in the proportion of fruits and vegetables were as follows: 4.79 percent in 1990-91 to 8.65 percent in 2023-24, which highlights a structural shift towards diversification based on horticulture. This trend demonstrates the shift in food consumption, emerging health-consciousness among consumers, increasing level of export opportunities and tremendous advancements in supply-chain logistics, such as greater transportation infrastructure, grading infrastructure, and cold-chain infrastructure. In sum, the increase in the significance of high-value and commercial crops signifies the shift towards subsistence-based cultivation towards a more commercialized and income-driven agricultural system. Whereas this transition has been good in contributing to farm incomes and job creation in rural regions, it goes to highlight the necessity of supportive policies that are aimed towards stability of the markets, mitigation of risks and sustainable management of resources in order to ensure that diversification is economic and sustainable at the same time.

iii. Shifts in Fibre and Plantation Crops

Plantation crops have seen a different trend in the changing cropping pattern in India, whereas the fibre crops have seen a different trend. Tea production, which was one of the pillars of the agricultural economy and a significant element of export earnings and rural employment, has not changed much throughout the years. Its proportion of the total cropped area has been varying in a very limited percentage band at 1.215 per cent, indicating some resilience backed by well-established plantation systems, long-term investments and fairly constant world demand. Conversely, jute, which previously had been a major fibre crop and essential in Indian agro-based industries, had experienced a sharp drop. The ratio of jute within the cropping pattern declined to 0.38 per cent as compared to 0.61 per cent in 1980-81. This shrinkage has been hugely influenced by increasing supply, reduced prices and the versatility of artificial replacements, which largely elitist demand for natural jute fibres. Also, price fluctuations, scant technological advancement, increasing input costs and relatively lower profitability than those of substitute crops discourage farmers to keep growing jute. This trend is also true of other fibre crops, such as mesta and cotton, which have almost vanished in the cropping system in some areas. The challenges that these crops have conflicted with are the synthetic fibre, shifts in industrial consumption patterns, and growing risks of production, which are due to pests, climate uncertainty and uncertainty in the market. Farmers have therefore shifted more land out of fibre crops and to foodgrains or horticultural and commercial crops with high value that have improved and consistent returns. In general, the trend of diminishing traditional fibre crops indicates a more fundamental structural change in the agricultural industry due to market forces, technological change and demand in industries. Although this shift has promoted diversification of incomes to farmers, it also comes with questions of the sustainability of fibre-based agro industries as well as rural livelihoods that depend on such crops. Policy responses to rejuvenate the fibre sector might thus include: technological modernisation, a guaranteed pricing system, encouragement of natural fibres that are eco-friendly and improved interconnections between agriculture and industry.

Table 1: Percentage Share of Gross Cropped Area under Different Crops in India, 1980-81 to 2023-24

Crop	1980-81	1990-91	2000-01	2005-06	2010-11	2023-24
Rice	24.52	24.60	26.61	24.70	22.95	21.74
Total Pulses	14.16	14.21	12.11	12.67	14.15	12.68
Wheat	13.78	13.93	15.32	14.98	15.77	14.52
Total Foodgrains	73.59	73.67	72.02	68.81	67.82	60.45
Total Oilseeds	12.14	13.91	13.55	15.76	13.47	14.35
Total Fibers	0.61	0.58	0.62	0.53	0.49	0.38
Potato	0.51	0.60	0.72	0.79	1.01	9.78
Total Fruits & Vegetables		4.79	5.40	7.11	7.94	8.65

Source: Hand book of Statistics Indian State(RBI)

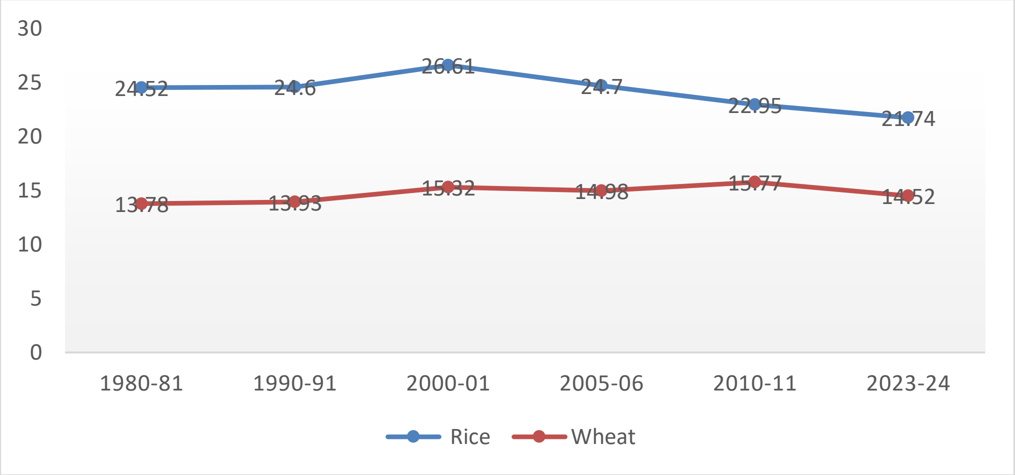

Figure 1: Trends of the Percentage Share of area under Rice and Wheat in India, 1980-81 to 2023-24

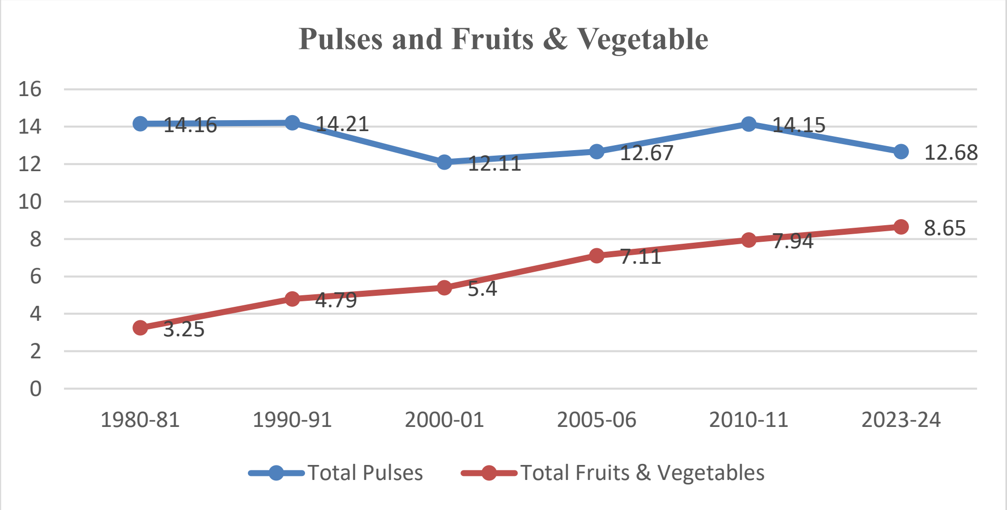

Figure 2: Trends of the Percentage Share of area under Pulses and Fruits & Vegetable in India, 1980-81 to 2023-24

3. Impact of Crop Diversification on Food Security in Rural India

Table 3 gives the outcomes of simple linear regression analysis that have been conducted to determine the effect of crop diversification on some of the key indicators of rural development and food security in India between the years 1995-96 and 2021-22. The variables which are dependent in the analysis are foodgrains yield (FY), the cropping intensity (CI), the gross agricultural income per hectare (GAIPH), the per capita agricultural income (PCAI) and the non-foodgrains yield (NFY). Diversification Index has been relied on as a major explanatory variable to suit the magnitude and dynamics of shifts in the pattern of cropping. The findings show that crop diversification is related to several dimensions of agricultural performance, which have a systematic and statistically significant relationship. The trend of the Diversification Index is generally increasing over the study period, going up 0.8079 in 1995-96 to 0.8478 in 2021-22 (Table 2). It has been an upward but steady increase that indicates a structural change in Indian agriculture, where there is a decline in monocropping and overdependence on the traditional foodgrains production systems towards an increasingly more heterogeneous and market-oriented system of cropping. This diversification mostly entails diversifying non-foodgrain crops i.e., the horticulture, oilseeds, pulses, and other high-value or commercial crops. The shift from crop construction is not only a shift in the composition crop type but it represents a larger shift towards risk reduction, efficiency of use of resources, and more income-bearing possibilities to the farmers. Diversification can cushion agricultural families against climatic variations, price waves and variations in production as producers increasingly rely on a broader selection of crops. It is also indicated in the regression results that increased amounts of crop diversification have a positive relationship with increasing major outcome variables like gross agricultural income per hectare (GAIPH) and per capita agricultural income (PCAI), hence indicating that crop diversification plays a significant role in increasing the profitability of the farm and rural livelihoods. Also, the positive relationship with food grains yield (NFY) highlights improvements in productivity of the adoption of advanced technologies, increased use of inputs, and high-value crop production.

i. Impact of Crop Diversification on Foodgrains Yield (FY) in the rural economy

In India, the foodgrains output is seen to have improved significantly over the past 26 years, as evidenced by the 1,491 kg/ha of foodgrains in 1995-96 and 2,425 kg/ha in 2021-22, reflecting the strong long-term growth in agricultural production. These short-term variations in the yield trend are observed, however, in years with drought conditions (eg, 2002-03 and 2009-10) but the general trend is constantly increasing. To a great extent, these short-term disruptions are a response to climatic shocks, as opposed to structural infirmity of the system of agriculture. The persistent rise of foodgrains productivity throughout the period of study is a clear indication that there was no agricultural diversification to the prejudice of the foodgrain productivity. Quite the opposite, the productivity gains in the big cereals and pulses have persisted along with the diversification in the rural economy. The combination of several reinforcing factors can be found in the occurrence of technological advancement, the uptake of high-yielding and stress-tolerant varieties of seed, as well as the enhancement of agricultural management practices that include balanced application of fertilizers, better management of irrigation and enhancement of methods used to manage crops.

The econometric evidence further strengthens this conclusion. The estimated regression equation, $FY = -15103.50^{***} + 20641.54^{***} DI$

indicates a positive and significant relationship between the Diversification Index (DI) and the yield of foodgrains at the 1 per cent level of significance. A positive correlation between DI coefficient (20,641.54) implies that the greater the level of diversification in crops, is related to higher foodgrains yield, leading to complementarities rather than trade-offs between crop diversification and production of staple crops. In addition, the coefficient of determination ($R^2 = 0.84$) is high, meaning that 84 per cent of the variation in the yield of foodgrains can be attributed to the shift in the level of agricultural diversification, which indicates the power of the model to explain the variation. The enormous F-statistic (216.11) also attests the statistical significance and strength of the entire regression findings. Combined, these results indicate that crop diversification in India has been conducive to the increase in foodgrain yields, mainly via enhanced allocation of resources, technological spillover, and efficiencies in land-use practices. Diversification has enabled a more resilient and productive, food-secure and sustainable farming system in the rural economy of Indian agriculture, contrary to its destruction of food security by grounding itself on diversification.

ii. Impact of Diversification on Cropping Intensity (CI) in the Rural Economy

In India, this intensification in the use of cultivated land was a significant increase of 131.8 per cent in 199596 to 155.4 per cent in 202122, which was considered a great increase in the intensity of cropping. This continued increase in the intensity of cropping is an indication of structural changes in the rural economy and better production processes. The trend has been possible because of a combination of interrelated factors that include: There is the implementation of multiple cropping systems, this has allowed farmers to grow more than one crop per piece of land on the same set of land in an agricultural year; Stabilization and expansion of the irrigation facilities, this has made the farmers less reliant on rainfall, and allowed year round production through cultivated land; Technological advancements, high-yielding varieties, An improved intensity of cropping contributes as a complement to diverse agricultural practices since a farmer can distribute land to a wider pool of crops in a year. This not only boosts the overall farm production, but also lessens the risk of production by diversifying the production among crops with varying growth patterns, market and climatic responsiveness. As a result of diversification, which is fuelled by increased farming intensity, income stability and resiliency within the rural economy.

The estimated regression equation further reinforces this relationship:

$CI = -238.345^{***} + 458.197^{***}\, DI$

The measurements show that there is a positive and statistically significant effect of diversification on cropping intensity. The value of the coefficient of Diversification Index (DI) i.e. 458.197, is significant at the 1 per cent level, which implies the diversification increases by a significant margin with the intensification of the cropping. It means that diversified farming systems can push farmers towards enhanced land use based on multiple cropping and enhanced crop sequencing. Further, the model demonstrates a high quality of explanation of diversification as shown by the high value of R^2 of 0.81 and the adjusted R^2 of 0.80, which shows that a significant amount of the variation in the intensity of cropping is clarified by diversification. The F-statistic of 154.76 is also another test to confirm the overall strength and statistical soundness of the model. In general, it is evident that the empirical evidence supports that crop diversification can serve as an initiator of growth in the degree of cropping, leading to more effective use of a limited land resource. The relationship provides significance to the diversification-based policies in boosting land productivity, increasing farm incomes, and food security and the development of sustainable rural areas.

4. Effect of Diversification on Gross Agricultural Income per Hectare of Rural Economy

The gross agricultural income per hectare (GAIPH) shows a steep and continuing upward trend in India during the study period, with a total of ₹11,746 in 1995-96 to ₹59,558 in 2021-22(Table 7), which is almost fivefold. Such a massive increase indicates a high level of structural change in the rural economy characterized by alteration in the mode of cropping, productivity and integration into the market. It is possible to distinguish two different stages of income development. Throughout the initial stage (1995-96 to the mid-2000s), the growth rate of GAIPH was moderate, with its growth mainly augmented by incremental productivity gains, slow modern-input adoption and increased irrigation. A sharp acceleration of income growth occurred in the second phase, starting around 201516 when it saw a rise of over 59,000 in GAIPH in 2021-22 compared to levels of 31,994 in 2014-15. This is also during the time of more focus on crop diversification, higher cropping rates, and enhanced market access. The increase in gross agricultural income per hectare might be explained by a combination of several interrelated causes: i) The transition to high-value and non-food crops, such as horticulture, oilseeds, and commercial crops, which have higher returns per unit of land; ii)Increased crop yield, which in turn has been facilitated by technological progress, improved-quality seeds and improved agronomic management; iii)The increase in. The econometric results further validate the crucial role of diversification in income enhancement. The estimated regression equation is:

$$GAIPH = -\,864164.12^{***} + 1087499.42^{***}\, DI$$

The coefficient of the Diversification Index (DI) is positive and statistically significant at the 1 per cent level, which shows that the diversification has a significant and systematic effect on gross agricultural income per hectare. Increasing the amount of diversification results in a large increase in the amount of income as you are moving the land towards more lucrative crop production and enhancing the productivity of the land in question. The model has a high explanatory power as indicated by the value of R 2 = 0.86, which indicates that 86 per cent of the variation in the GAIPH can be attributed to changes in the diversification. In addition, the F-statistic is high (154.72), which verifies the strength and general significance of the relationship being estimated. All in all, the results strongly affirm the idea that agricultural diversification is one of the key factors that can promote farm-level increases in income in Indian agriculture. Diversification through the encouragement of land use efficiency, the production of high-value crops, as well as lessening the volatility of rural incomes, plays a central role in improving the livelihood of the rural population and the sustainability of agricultural production.

5. Crop-Diversification on the Per Capita Agricultural Income (PCAI)

Per capita agricultural income (PCAI) in rural areas increased from ₹17,647 in 1995-96 to ₹22,346 in 2021-22. Though this increase is a good indication of the increase in the level of incomes in rural areas, the rate of increase is relatively low compared to the steep growth of gross agricultural income per hectare. This drift indicates that the positive growth of an agricultural economy and diversification are somewhat counterbalanced by the structural underpinnings of the rural economy. Reduced growth rate of PCAI can be explained by a few crucial reasons: i) Increased population pressure on agricultural land, resulting in the dilution of income gains as a growing number of agricultural workers must be employed; ii)Discrimination and division of land by larger parcels which also results in decreasing size of farming units as well as less income per worker; iii)Disparity in distribution of income gains, where the gains of diversification and This positive role of diversification can also be proven by the econometric analysis.

The estimated regression equation is: PCAI = − 190659* + 240375.30 ***DI**

The Diversification Index (DI) coefficient is positive and statistically significant at the 1 per cent level, which shows that agricultural diversification is a significant contributor to the increase in the per capita agricultural income. This implies that the diversification increases the income prospects through stimulating high-value crops, stabilizing returns and general effectiveness of the farm. The model has a high power of its explanatory graph and the value of R2 is 0.83, which implies that diversification explains a huge percentage of the variance in PCAI with time. This is further confirmed by the fact that the F-statistic of 141.25 indicates the strength and overall significance in the estimated relationship which is statistically significant. Nevertheless, the diversification effect on PCAI is less dramatic and significant in comparison to its influence on per-hectare income, though the statistical significance is also significant. This observation indicates systemic demographic strain, subdivision of land and scanty absorption of excess labour in the agriculture sector. It highlights the structural change to go beyond agriculture, such as the growth of non-farm jobs in rural areas, and the growth of productivity-related income allocation arrangements, to take full advantage of diversification-based growth to the extent it leads to broad-based alleviation in rural living standards.

6. The Effect of Diversification on Non-Foodgrains Yield (NFY) of Rural Economy

The non-foodgrains yield (NFY) has shown a significantly higher growth rate than that of foodgrains yield over the years of study, with an increase in non-foodgains yield as 3,124 kg per hectare in 1995-96 to 14,286 kg per hectare in 2021- 22. This impressive development is an indicator of the structural change of Indian agriculture to diversification-based production systems. The growth of the non-foodgrain crops like oilseeds, sugarcane, cotton, fruit, vegetables and other commercial crops has been a determinant aspect in the improvement of the overall agricultural output in the rural economy. The fast growth of NFY may be explained by several factors, which are coupled. To begin with, diversification has promoted the growth of commercial and high-value crops, which tend to have a greater yield potential and market value than the traditional foodgrains. Second, the non-foodgrain crops are mostly linked with an increase in input intensity, such as better seeds, better fertilizers, irrigation, mechanisation and planting protection. Third, these crops are more receptive to advances in technology and certainty of irrigation, leading to more rapid productivity increases. All these have led to increased dynamism and a market-oriented rural economy. These increases in the relative rates of non-foodgrains give more weight to the importance of diversification as an important engine of agricultural income growth. As opposed to foodgrains, which are normally limited by the subsistence factors and price inflexibilities caused by the policies, the non-foodgrain crops are more responsive to market indicators, thus improving the level of productivity, as well as profitability. That is why, the diversification of the non-foodgrains has become an important way out of enhancing the livelihoods of the rural areas, as well as alleviating the stagnation of earnings in the agricultural sector.

The regression analysis further reinforces this relationship. The estimated equation,

$$\text{NFY} = -\,60954^{***} + 96547.15^{***}\ \text{DI}$$

finds there is a positive and statistically significant association between the Diversification Index (DI) and non-foodgrains yield. The coefficient of DI is significant at the level of 1 per cent which means that the process of diversification increase is strongly related to an increase in non-foodgrains productivity. This implies that it is more the expansion and yield improvement of non-foodgrain crops, rather than the foodgrains themselves, that diversification works. The coefficient of determination ($R^2 = 0.62$) helps us to understand that almost 62 percent of the fluctuation in the non-foodgrains yield is attributable to the diversification index. This explanatory power is not as high as in some other models, but still a significant power, which means that diversification is a significant but not the only factor that determines the non-foodgrains yield. There are other elements like agro-climatic factors, infrastructure, market access and institutional support which are very significant. Moreover, the F-statistic (41.17) reveals the overall statistical significance of the model that supports the strength of the relationship between diversification and non-foodgrain yield.

Table 2: Per Hectare Agricultural Income, Per Capita Agricultural Income, Non-foodgrains Yield, Foodgrains Yield and Cropping Intensity and Diversification Index in India, 1995-96 to 2021-22

Year	Diversification Index (DI)	Gross agricultural income per Hectare (Rs)	Cropping Intensity	Foodgrains Yield (kg/ha)	Per Capita Agricultural Income (Rural Area)	Non-Foodgrains Yield (kg/ha)
1995-96	0.8079	11746	131.8	1491	3124	17647
1996-97	0.8076	12789	132.6	1605	3380	17367
1997-98	0.809	12157	133.8	1550	3168	18487
1998-99	0.8134	12726	134.3	1627	3291	18524
1999-00	0.8107	12934	133.6	1704	3235	18462
2000-01	0.8073	20581	131.1	1626	4985	17862
2001-02	0.8126	21619	133.6	1734	5232	17619
2002-03	0.8141	21841	131.8	1535	4822	16605
2003-04	0.8108	22415	134.8	1727	5329	15690
2004-05	0.8142	24763	136	1652	5859	16994
2005-06	0.8134	25843	136.5	1715	6133	17615
2006-07	0.8178	27161	137.6	1756	6395	18132
2007-08	0.8206	28351	138.4	1860	6700	18140
2008-09	0.8195	28365	137.7	1909	6639	17008
2009-10	0.8237	29637	135.9	1798	6592	18433
2010-11	0.8266	31227	139.6	1930	7191	18476
2011-12	0.8328	32590	138.9	2078	7362	18890
2012-13	0.8324	33840	139.1	2129	7528	18047
2013-14	0.8320	34823	142.5	2120	7956	18678
2014-15	0.8368	31994	142.2	2028	7150	18880
2015-16	0.8289	49548	142.6	2041	10996	18631
2016-17	0.8421	53311	144.7	2129	11942	18323
2017-18	0.8377	55500	144.8	2235	12349	21090
2018-19	0.8423	54145	145.3	2286	12012	21066
2029-20	0.8411	55576	151.1	2343	12894	21204
2020-21	0.8443	56573	152.7	2394	13395	21952
2021-22	0.8478	59558	155.4	2425	14286	22346

Sources: Statistical Appendix India & Handbook of Statistics, Indian State(RBI

In general, the results suggest that the non-foodgrains crops are the staple of agricultural diversification in India. Their high productivity reaction to diversification highlights their key role in promoting agricultural growth, a rise in farm incomes and enabling the rural economy to shake off subsistence-oriented farming and shift to a more commercialised and resilient agricultural system. Table 2 and Table 3 indicate clearly that in India, the agricultural diversification during 1995-96 to 2021-22 has been instrumental in boosting agricultural productivity, agricultural income, and land-use efficiency.

Table 3: Per Hectare Agricultural Income, Per Capita Agricultural Income, Non-foodgrains Yield, Foodgrains Yield and Cropping Intensity in Relation or Impact on Diversification Index in India(1995-96 to 2021-22)

Period	Regression Equation	R^2	R-bar sq.	F value
1995-96 to 2021-22	FY = - 15103.50 ***+ 20641.54***DI (- 14.71) (17.77)	0.84	0.83	216.11
1995-96 to 2021-22	CI = - 238.345*** + 458.197 *** DI (-1.53) (8.10)	00.81	0.80	154.76
1995-96 to 2021-22	GAIPH = - 864164.12*** + 1087499.423*** DI (- 3.47) (3.79)	00.86	0.84	154.72
1995-96 to 2021-22	PCAI = - 190659*** + 240375.30*** DI (-2.96) (4.43)	00.83	0.82	141.25
1995-96 to 2021-22	NFY = - 60954*** + 96547.15*** DI (-2.96) (4.43)	00.62	0.60	41.17

Notes: DI = Diversification Index, CI = cropping intensity, FY = foodgrains yield,
GAIPH = Gross agricultural income per hectare ,PCAI = Per Capita Agricultural Income
, NFY = Non- foodgrains yield

*Figures within parentheses indicate ' t ‘ values , *** indicates a coefficient significant 1 percent level, ** Indicates coefficient significant at the 5 percent level and *indicates a coefficient significant 10 percent level*

Diversification has not taken place at the expense of foodgrains production and instead has had a complementary and fortifying effect on the overall agricultural growth. The increase in non-foodgrain and high-value crops and the rise in the level of cropping and yield indicate a structural change in the agricultural system towards a more dynamic and market-oriented system. The analysis also shows that Indian agriculture has experienced a slow but sustained diversification process, including growing cropping, rising yields, and growing gross agricultural income and food security. These dynamics show the ever-increasing sensitivity of the agricultural sector to the changes in technology, market potential and changes in consumption trends. Yet, even with these encouraging words, this comparatively slower growth of per capita agricultural income underscores structural constraints that remained unchanged (population pressure on land and fragmentation of holdings), and uneven income gains were lost in regions and on farm sizes. Altogether, the results illustrate that the process of agricultural diversification is a key avenue in improving the agricultural performance and bolstering rural livelihoods in India and yet, its potential can only be achieved when backed by the other policy initiatives. These incorporate strategies to overcome land fragmentation, inclusive growth, better accessibility to markets and infrastructure and creating non-farm jobs to alleviate the strain on agriculture. Diversification in this context takes the form not only of a strategy of production, but also a sustainable and inclusive development of the rural economy, which has to be revitalized.

Correlation Matrix

A correlation of key indicators of agriculture diversification, productivity, and income is given in Table 4. All the coefficients are positive and significant at the 1 per cent level, which means that there are strong correlations between diversification, cropping intensity, yields and income in the agricultural sector and these are systematic. Diversification Index is significantly positively related to foodgrains yield (FY) (0.962), cropping intensity (CI) (0.927) and gross agricultural income per hectare (GAIPH) (0.927). This indicates that increased scale of diversification is directly linked with better land use, in terms of multiple cropping and increased foodgrain productivity. Its significant correlation (0.921) with per capita agricultural income (PCAI) is significant at a 1 percent level, thus proving that diversification is meaningful in the growth of income at the level of the farm households. Though the correlation between the non-foodgrains yield (NFY) (0.788) is not as high as it may be, it is still strong and significant, indicating the diversification effect related to enhancing commercial and high-value crops. The GAIPH has a strong association with PCAI (0.967), which suggests that the positive correlation indicates that per-hectare income positively influences per capita agricultural income directly. It correlates with FY (0.931) and CI (0.925), which indicates that increasing productivity, as well as intensive land use, is a big contributor to income growth. A significant growth percentage of 1 percent with the NFY (0.766) indicates that the growth of non-foodgrain crops helps in the growth of income as well as foodgrains but the contribution is lower compared to that of foodgrains. There are positive correlations between the intensity of crops, FY, PCAI and NFY, 0.943, 0.943 and 0.852, respectively. This means that the additional intensive cropping designs not only increase their production, but also increase their farm incomes and non-foodgrain crop diversification.

The correlation coefficient is high between CI and DI, thus it suggests that diversification strategies tend to be accompanied by multiple cropping systems, which is pertinent at the 1 percent level. All income-related variables generally display high correlations with foodgrains yield, with GAIPH (0.931) and PCAI (0.933), in particular being strongly correlated. This proves the existence of the foodgrains in nourishing agricultural income, even where there would be a progressive diversification. Its correlation with DI (0.962), which is noteworthy at the level of 1 percent, indicates that diversification does not question food security but, instead, it can be employed to enhance productivity by using resources in a more efficient manner and adopting technology. The correlation of PCAI with GAIPH, CI, FY and DI shows a strong correlation, meaning that household level income is affected by a mixed nature of land productivity, level of cropping and diversification. The fact that it is relatively less (yet substantial) correlated with NFY (0.788) shows that, although non-foodgrain crops do play a role in income growth, it does so indirectly through the general productivity of the farm and overall efficiency of the use of land. NFY demonstrates good and significant relationships with all the variables, especially CI (0.852) and FY (0.806). It is a manifestation of complementarities in that foodgrain production and non-foodgrain production should be found in a diversified and intensive farming system but not in a trade-off between these two. The correlation analysis shows a clear relationship where the agricultural diversification has been interlinked to the increased levels of cropping intensity, better yields, and increased incomes. The fact that all the coefficients are positive and significant is an indication of a positive-reinforcing relationship between diversification, productivity, and income growth. These are, however, correlations, meaning that they are not causal; however, the high levels of association give the argument of diversification support backed by intensification and increases in productivity, a strengthening effect on agricultural performance and rural incomes.

Table 4: Correlation Matrix

	DI	*GAIPH*	*CI*	*FY*	*PCAI*	*NFY*
DI	1					
GAIPH	0.927***	1				
CI	0.927***	0.925***	1			
FY	0.962***	0.931***	0.943***	1		
PCAI	0.921***	0.967***	0.943***	0.933***	1	
NFY	0.788***	0.766***	0.852***	0.806***	0.788***	1

Where, DI = Diversification Index, CI = cropping intensity, FY = foodgrains yield PCAI = Per capita agricultural income, NFY = Non-foodgrains Yield, GAIPH = Gross Agricultural Income per Hectare

Notes: *** Indicates a coefficient significant at the 1 percent level

Conclusion

By offering a multi-level solution to enhancing food security in rural India, crop diversification is not only a solution to the food availability aspect but also income, nutrition, and shock resilience outcomes. Despite making a great step forward in the production of food grains, the long-term sustainability of food security is increasingly becoming reliant on self-diversified, nutrition-sensitive, and environment-friendly agricultural systems in India. The current book chapter highlights the dynamism in the Indian cropping patterns whereby there was a slow shift to no longer record crop concentration but rather diversification as indicated by the Transformed Herfindahl Index (THI). Structural change in Indian agriculture has, over the last forty years, shifted towards high-value and non-foodgrain products like oil-seeds, potatoes, horticultural produce, and boro rice due to both market forces and better irrigation, as well as facilitated policy interventions. Nonetheless, diversification has not been even or permanent. On current trends, there has been a partial reversal to traditional patterns of cropping as price volatility, uncertainties in climate and constraints of institutions have played a role. Although diversification contributed to increasing the incomes and resource-use efficiency of farms, as well as their resilience, the decreasing proportion of crop types like pulses and fibre poses significant questions about nutritional security and ecological sustainability. In sum, the results once again confirm that diversification of crops is a critical route towards increasing agricultural output, improving rural livelihoods, and creating a more resilient food system, without jeopardizing foodgrain production. The tendency of it to be highly correlated with increased intensity of cropping, better yields per unit and more income justifies its developmental importance. To continue and further develop this change, however, would necessitate concerted actions in the form of policy changes, enhanced institutional backing, enhanced infrastructure, enhanced access to markets and effective risk management processes. It is also necessary to promote sustainable agricultural practices to cope with the arising environmental challenges. Here, the concept of crop diversification cannot be considered as a simple adaptation of the cropping trends, but rather as a long-term strategy towards achieving both long-term food security and sustainable rural development in India.

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PREPARATION OF BIO-BASED BIOCRETE BRICKS USING AGRO WASTES

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Abstract

The most common material used for construction at the global level is concrete. Increased utilization of concrete as construction material leads to increased demand. Carbon dioxide emission in abundant quantities from cement and concrete is a huge global concern. Hence, the current work focuses on the preparation of biocrete bricks using agricultural wastes, lime and food wastes. The water holding capacity, mechanical properties and compressive strength of the prepared biocrete bricks were determined by performing various experiments. Standard quality comparisons of the prepared biocrete bricks with the normal bricks were performed using tests such as soundness, hardness and resistance to fire. Various tests were conducted on the low-cost biocrete bricks soon after allowing them for 10 days air drying and 40 days sun drying. Biocrete bricks are prone to microbial contamination. As a result, silver nanoparticles synthesized from micro-organisms were applied on the surface of the biocrete bricks so as to improve its quality and purity. Several methods such as Fourier Transform Infrared Spectroscopy, Transmission Electron Microscopy, UV visible spectrophotometry and X Ray Diffraction analysis were used to characterize the microbially produced silver nanoparticles. These biocrete bricks are replenishable, eco-friendly, cost effective and strong. Biocrete bricks could be used as an effective brick formulation which can be a viable alternative material for construction satisfying the demands of the next generation.

Keywords: Agro Wastes, Biocrete, Compressive Strength, Food Wastes, Lime, Water Absorption.

1. Introduction

The development of construction industries provides incognitable benefits to the society and the people. The most widely and commonly used construction material is concrete. It is resistant to compressive forces but susceptible to tensile forces. Upon exposure to stress, concrete cracks because of the low tensile strength. Moreover, the predominant greenhouse gas, carbon dioxide is emitted in abundant quantities from concrete. Hence, a low carbon or zero carbon alternative construction material known as biocrete bricks was prepared. Bio-concrete or biocrete can hold its native state upon exposure to cracks [1,2]. The bacteria found in the bio-concrete enables it to be involved in the biological production of minerals such as limestone. This ensures that the cracks appearing on the surfaces of concrete are healed rather quickly. Biocrete is a material quite similar to concrete. It is made up of a mixture of natural fibre and calcium hydroxide or hydrated lime (which is generally known as lime) [2]. Agro-wastes like rice husk, coconut coir pith and oil palm kernel fibre were used as fibrous material [3]. Concrete is a dense material consisting of cement bound mineral aggregates of different sizes. It possesses high compressive strength. In biocrete, the binder used is lime and most of the aggregates are replaced by natural fibres. The density and load bearing capacity of biocrete bricks can be enhanced by addition of sand. The thermal insulating qualities of biocrete bricks are thereby diminished. Calcium carbonate is formed due to the reaction between carbon dioxide and lime, which leads to hardening of lime. Biocrete bricks are building materials created using bacteria that absorb carbon dioxide to grow, thereby producing calcium carbonate, a main ingredient in limestone that makes it solid [4]. Biocrete bricks have the ability to repair their own cracks. Photosynthetic micro-organisms such as cyanobacteria are blended with a material that contains calcium, gelatin and sand. Under temperatures of about 100°F, the cyanobacteria multiply and photosynthesize, thereby absorbing carbon dioxide [5]. The cyanobacteria forms calcium carbonate, the ingredient in limestone that makes it solid. As the material cools, the gelatin binds the sand and other material together. The material is then formed in a cast or mould to create bricks. Prior to the usage of cement, lime was used as the binder for several years. Lime has several properties such as longevity, permeability to moisture, less risk of cracking and less wastage that enables it to be used as the most common binder:

Biocrete bricks are a material possessing carbon negative property or carbon neutrality due to the reasons such as less energy requirement, carbon dioxide absorption and sequestration. The ingredients of biocrete bricks include bacteria belonging to the genus, *Bacillus* along with nitrogen, phosphorus and calcium lactate. The bacteria are found in the concrete for 200 years or even more. Upon damage to the concrete, water drools into it thereby resulting in the multiplication of bacteria. The active bacteria progressively consume the oxygen thereby resulting in the conversion of the soluble component, calcium lactate into insoluble component, the limestone [6]. The cracked surface of biocrete is compressed and sealed by the limestone thus generated. The biocrete bricks possess high durability when compared to the conventional bricks.

Microbes contaminate the biocrete bricks more readily. Hence the combination of nanomaterials and agro wastes such as rice husk, oil palm kernel fibre and coconut coir pith along with lime and bacteria can be used as a viable alternative method to synthesize biocrete bricks of high quality and high purity. Silver nanoparticles possess remarkable properties like antimicrobial activity against most fungi and bacteria. The reason for this is their high surface to volume ratio. Due to their appealing qualities, silver nanoparticles can be used for a variety of purposes including wound healing, larvicidal, catalytic, antimicrobial and anticancer activities. Hence, a type of innovative, effective and environmentally friendly bricks known as biocrete bricks could be produced from agro wastes such as rice husk, oil palm kernel fibre and coconut coir pith along with lime and bacteria and by covering the surface with a coating of silver nanomaterials.

2. Materials and Methods

2.1 Biocrete bricks formulation – Materials involved

2.1.1 Brick earth

Brick earth utilized in the preparation of superior quality bricks should be made up of the ingredients like 30 to 40% alumina, 70 % silica, 6 to 10% iron oxide, 2% magnesium and 15 to 20 % lime.

2.1.2 Sand

Small grains of silica or silicon dioxide (SiO_2) constitute the sand particles. The current investigation involved the use of M-sand available locally and passed several times through 5.75 mm IS sieve.

2.1.3 Water

It is a key component of biocrete because it has a crucial role in influencing how fibrous agricultural wastes like rice husk, oil palm kernel fiber, and coconut coir pith react with bacteria or cyanobacteria, as well as the binder lime. The pH of the water used to make biocrete bricks should be between 6 and 7, and it should be devoid of organic materials.

2.1.4 Agricultural Wastes

Biocrete bricks have been made from fibrous agricultural wastes such as oil palm kernel fiber, rice husk, and coconut coir pith, as well as crop wastes such as vegetable and fruit culls and drops, maize stalks, wastes obtained during the processing of food and sugarcane bagasse.

2.1.5 Lime

Lime is an inorganic mineral consisting of calcium and is generally made up of hydroxide and oxides, usually calcium hydroxide and/ or calcium oxide. They are available in abundant amounts and they find widespread use in sugar refining, as chemical feed stocks and as building and engineering materials. .

2.1.6 Gelatin

It is the most widely used gelling and thickening agent. It is a product of animal origin containing high levels of proteins. During brick making, colonies of cyanobacteria or blue-green algae are inoculated in the mixture of gelatin and sand. Cyanobacteria produced calcium carbonate which mineralizes the gelatin, thereby enabling it to bind together with the sand.

2.1.7Bacteria

Preparation of biocrete bricks has been induced by the microbial activity of bacteria belonging to the genus, Bacillus and a group of photosynthetic bacteria known as cyanobacteria or blue-green algae. Cyanobacteria are blended with a material that contains calcium, gelatin and sand. Under temperatures of about 100°F, the cyanobacteria multiply and photosynthesize, thereby absorbing carbon dioxide. The cyanobacteria forms calcium carbonate, the ingredient in limestone that makes it solid. As the material cools, the gelatin binds the sand and other material together.

2.2 Methodology for Preparation of Biocrete Bricks

Fibrous agricultural waste materials such as rice husk, coconut coir pith and oil palm kernel fibre and other agricultural wastes were chopped into small fragments and immersed in water overnight thereby resulting in softening of fibres. Then the mixture was agitated vigorously in order to get a pulp in homogeneous condition. This was followed by addition of food wastes, brick earth, lime and water to the pulp. Colonies of cyanobacteria belonging to the genus, Synechococcus were inoculated into a mixture of sand and gelatin. This mixture was then transferred to the pulp. The pulp mixture was then eventually cast into moulds in order to prepare bricks. This was followed by the removal of moulds after 24 hours. The prepared bricks can be tested after 40 days of air drying.

2.3 Curing of Biocrete bricks

After placement of the biocrete bricks in the mould, they were subjected to curing. Curing is the phenomenon of maintaining the desired moisture content and a favorable temperature in brick thereby facilitating hydration of brick until the appropriate characteristics are developed to the required extent. Neglect of curing during the initial period of hydration leads to a kind of irreversible loss in the quality of the brick. Bricks could be cured by dry curing and wet curing. Biocrete bricks obtained from fibrous agricultural wastes and food wastes were subjected to dry curing.

2.4 Investigations into biocrete bricks

2.4.1 Investigation about Compressive Strength

In order to create two parallel, smooth sides, biocrete bricks were ground to eliminate any irregularities in their faces. The bricks were then submerged for two days at room temperature in pure water. Any remaining moisture was then drained at room temperature after the bricks were taken out. Then the bricks were placed in wet jute bags for a day. Water was poured over the bricks for four days. Three to four 4 mm thick plywood sheets are used to hold the specimen in the center between the plates of the testing apparatus.

Axial load application was carried out at a consistent rate of 15 N per square millimetre per minute till failure occurred. The highest load applied during failure was noted. At the highest load possible, the sample did not show any further increase in the reading of the indicator in the testing machine.

The formula used for computation of compressive strength is as follows:

$$\text{Compressive Strength (N/mm}^2\text{)} = \frac{\text{Maximum load failure in N}}{\text{Average area of bed faces in mm}^2}$$

2.4.2 Test for water absorption

Drying of biocrete bricks was carried out using a ventilated oven operated at 140 to 1500ºC. The mass of the bricks was then determined after they had been cooled to ambient temperature. Then, for 48 hours at 29 ± 200ºC, the bricks were submerged in water. Subsequently, the bricks were cleaned using damp cloth and the weight was noted again.

2.5 Silver nanoparticles synthesis from actinomycetes

200 ml of prepared liquid medium containing starch, casein and nitrate was sterilized using an autoclave for 15 minutes at 15 psi pressure. The prepared liquid medium, Starch Casein Nitrate broth was inoculated with actinomycetes. Incubation of the microbial culture was performed on a rotating shaker at 280 Celsius for 78 hours at 140 rpm. Incubation for 78 hours was followed by the separation of cells with the use of Whatmann filter paper. The filtrate containing mycelia was subjected to periodical washing using pure water. 20g of the moist mycelia obtained from the culture was suspended again in 100mL pure water and this was placed in the rotating shaker for a duration of 72 hours. 50 ml filtrate, obtained from the conical flask was transferred to a solution of 1mM of aqueous 50ml $AgNO_3$. This was kept on a rotating shaker maintained in dark conditions at 140 rpm at 28^0 Celsius. As a result, the produced silver nanoparticles were characterized.

2.6 Silver nanoparticle synthesis and characterization

UV visible spectrophotometry, Fourier Transform Infrared Spectroscopy (FTIR) and Transmission electron microscopy were among the techniques used to determine the proper size and constituents, which ultimately led to the description of the produced silver nanoparticles.

2.7 Silver nanoparticles' application over the biocrete bricks

Produced nanoparticles of silver were layered on the surface of the biocrete bricks so as to improve their efficiency.

3.Results and Discussion

3.1 Investigations into biocrete bricks

3.1.1. Investigation about Water Absorption

Table 1: Investigation about Absorption for Biocrete bricks

S. No	Brick type	Weight before absorption of water (W1)	Weight after absorption of water (W2)	Water absorption in (%) W2/W1
1	Biocrete brick	2.5 kg	3.8 kg	15.2
2	Conventional brick	3.96 kg	4.7 kg	11.8

3.1.2 Investigation about Compressive Ability

Compressive ability of both conventional and biocrete bricks were analyzed. The conventional brick was possessed higher compressive strength than the biocrete brick (Table 2).

Table 2: Investigation about compressive ability of biocrete bricks

S. No	Brick type	Compressive ability (N/mm^2)
1	Biocrete brick	6.84
2	Conventional brick	10.45

3.2 Actinomycetes-mediated silver nanoparticle synthesis

Actinomycetes utilized for silver nanoparticle synthesis were grown in potato dextrose broth. The production of silver nanoparticles is indicated by a shift in the broth's colour from yellow to brown.

3.3 Characterization of Silver nanoparticles

3.3.1 Analysis using Transmission Electron Microscopy (TEM)

According to silver nanoparticles'analysis by usingTEM, the reduced form of the bio-reduction – produced silver nitrate solution could be readily identified by size. The colloidal suspensions reduced by microbes possessed silver nanoparticles with sizes ranging from 4 nm - 54nm (4 nm, 12 nm, 22 nm, 54 nm) as TEM image makes evident. Spherical, well-defined and separated particles were obtained (Fig 1).

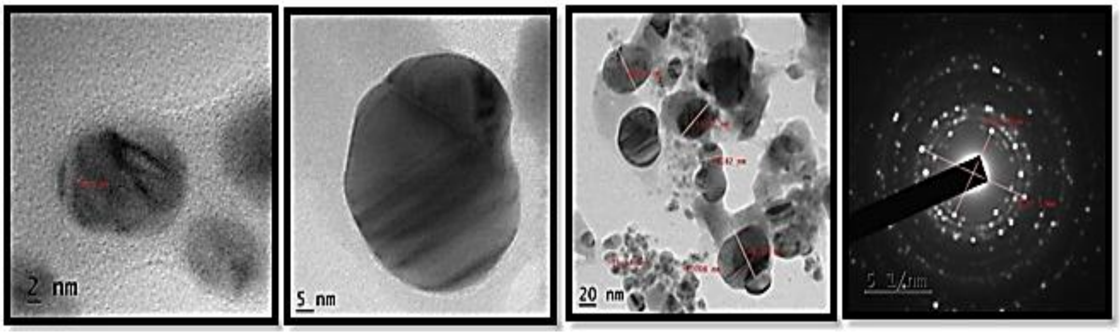
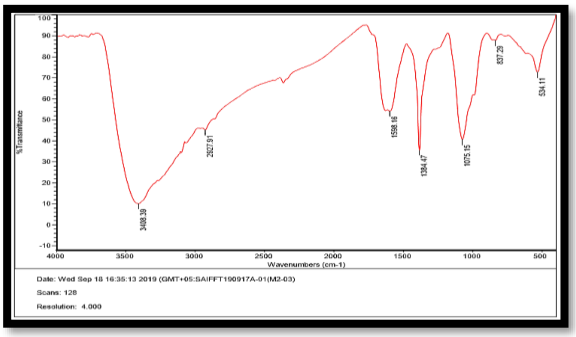


Figure 1: Silver nanoparticles description facilitated by Transmission electron microscopy

3.3.2 FTIR (Fourier Transformation Infrared Spectroscopy) Analysis



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Scans: 128
Resolution: 4.000

Figure 2: FTIR analysis-mediated characterization of silver nanoparticles

Synthesized silver nanoparticles possessed various functional groups, which were identified through FTIR analysis. Different peaks on the wavenumber Vs transmittance graph showed the presence of functional groups like amines, alcohols, alkenes, alkanes and halo compounds (Fig 2).

3.3.3 X-ray Diffraction Analysis (XRD)

Silver nanoparticles made from actinomycetes was displayed by the powdered XRD pattern. Silver nanoparticles' structure as depicted by the major characteristic peaks was crystalline in nature. The pattern of XRD clearly shows major peaks at (2θ) 76.4, 74.24, 67.86, 54.48, 53.16 and 45.14 corresponding to various angles. Using the width of Bragg's reflection, the estimated mean particle size was 25nm. Furthermore, two unidentified peaks showed up at 28.840 and 32.260. Surface of silver nanoparticles contained inorganic compounds, which may be the cause of these weaker peaks (Fig 4).

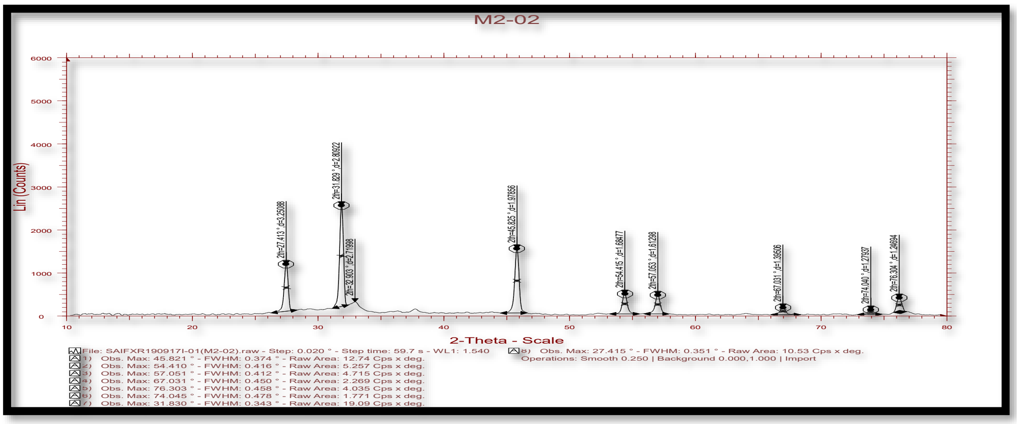

Figure 3: XRD analysis of microbially produced silver nanoparticles

3.3.4 UV Visible Spectrophotometric Analysis

Utilizing a UV Visible double beam spectrophotometer, the produced nanoparticles were described. Occurrence of silver nanoparticles was indicated by the peak found between 350 and 400 nm (Fig 5).

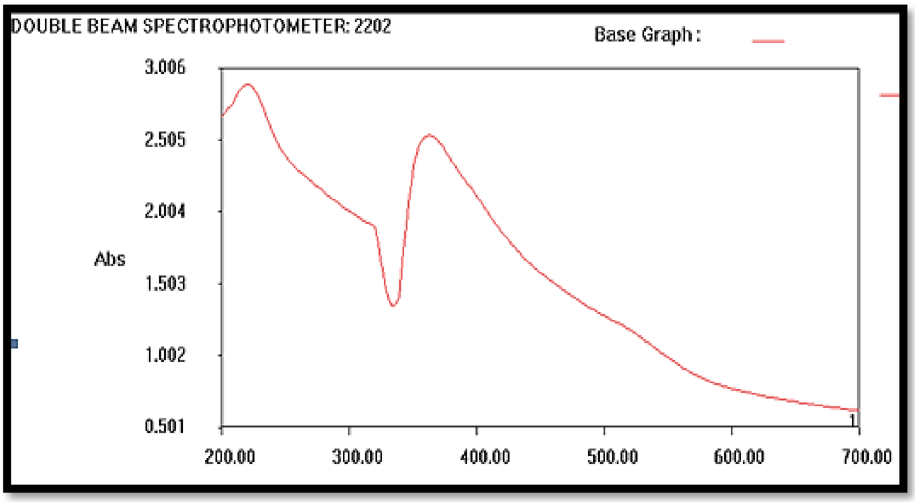

Figure 4: Silver nanoparticles' characterization using UV double beam spectrophotometer

3.4 Silver nanoparticles' incorporation on the surface of biocrete bricks

A brush was used to spread the microbially synthesized silver nanoparticles on the surface of the biocrete bricks.

Figure 5: Biocrete bricks

3.5 Discussion

When exposed to sunlight, biocrete bricks display remarkable insulating properties. Better self-insulating properties of the bio-based biocrete bricks have resulted in their increased demand [3, 7]. The food wastes and lime are used as binding material in production of bricks [8]. Biocrete bricks obtained from food wastes and agricultural wastes possess good insulating properties and good binding properties [9].

Conclusion

Biocrete bricks form a modern class of reusable biomaterials made from agro wastes and food wastes. Synthesis of biocrete bricks helps us to overcome the problems posed by the conventional bricks. These bricks are cost-effective and form a viable and good construction material. It can also be used to prepare insulation boards, chairs and tables. The construction industry could be revolutionized by the use of biocrete bricks. These bricks are suitable for construction of structures or walls that could not bear load, by virtue of their lower weight. They are not appropriate for external and water logging walls. They might find use for construction of walls used as inner partition. Reduction in the dead load of the building might be due to less weight of the biocrete bricks. Microbially synthesized silver nanoparticles can be applied topically so as to enhance the biocrete bricks' purity and avoid contamination by fungi and bacteria. Therefore, a highly effective, highly pure, eco-friendly and cost-effective biocrete brick can be a more viable and appropriate construction material when compared with conventional bricks.

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SKY FARMING WITH UAV AND BIO INSPIRED MICRO AERIAL SYSTEMS FOR CLIMATE RESILIENT INTELLIGENT AGRICULTURE

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Abstract

Agricultural systems are undergoing rapid transformation due to climate variability, declining resource availability, and increasing global food demand. This chapter investigates the role of Unmanned Aerial Vehicles (UAVs) and Bio Inspired Micro Aerial Vehicles (MAVs) as key enablers of climate-resilient and intelligent farming. UAV-based multispectral and thermal sensing systems demonstrate the ability to improve crop health detection accuracy by 25–40% compared to conventional field scouting methods, while reducing monitoring time by nearly 60–70% (Tsouros *et al.,* 2019). Precision irrigation supported by UAV-derived thermal data has shown water savings of approximately 20–30%, enhancing resource efficiency under water-scarce conditions. Bio-inspired MAV systems, operating in low Reynolds number regimes, achieve lift coefficients up to 1.5–2 times higher than conventional micro-rotor systems due to unsteady aerodynamic effects such as leading-edge vortex formation (Ellington, 1984). Experimental studies indicate that flapping-wing MAVs operating within a frequency range of 20–30 Hz can generate sufficient lift for stable hovering, making them suitable for plant-level monitoring and targeted pollination. Artificial pollination using MAV platforms has demonstrated potential yield improvements of 10–15% in controlled environments where natural pollinator activity is limited (Potts *et al.,* 2016). Computational Fluid Dynamics (CFD) analysis reveals that optimized MAV wing geometries can reduce aerodynamic drag by 12–18%, thereby improving flight endurance. Additionally, swarm-based UAV deployment strategies can increase field coverage efficiency by up to 3–5 times compared to single-drone operations (Dorigo *et al.,* 2004). Solar-assisted UAV systems further extend flight duration by approximately 30–50%, enabling long-duration agricultural monitoring missions. This chapter provides a detailed analysis of aerodynamic modelling, sensor integration, swarm intelligence, and energy optimization in UAV and MAV systems. The integration of artificial intelligence, Internet of Things (IoT), and renewable energy frameworks is examined to establish a scalable and sustainable smart farming ecosystem. The findings demonstrate that aerial robotic systems can significantly enhance agricultural productivity, reduce environmental impact, and strengthen resilience against climate-induced uncertainties.

Keywords: UAV, MAV, Precision Agriculture, Climate Resilience, Smart Farming, Aerodynamics, Artificial Pollination, Swarm Robotics, CFD, AI in Agriculture.

1. Introduction

Agriculture is currently undergoing a significant transformation driven by climate variability, increasing population demand, and the urgent need for sustainable resource management. Global agricultural systems are facing multiple stress factors, including irregular rainfall patterns, rising temperatures, soil degradation, and declining biodiversity. According to the Food and Agriculture Organization (FAO, 2022), global food production must increase by nearly **60% by 2050** to meet the demands of a projected population exceeding 9.7 billion (United Nations, 2023). However, conventional agricultural practices are inherently inefficient, often resulting in 20–30% resource wastage, particularly in water, fertilizers, and pesticides.

Traditional farming relies heavily on uniform field management approaches, where inputs are applied evenly across large areas without considering spatial variability in soil properties, crop health, or moisture content. This leads to overuse of resources in some regions and underutilization in others, reducing overall productivity and increasing environmental impact. Additionally, manual crop monitoring is time-consuming, labor-intensive, and prone to human error, often delaying the detection of crop stress, diseases, or pest infestations.

To overcome these limitations, precision agriculture has emerged as a data-driven approach that integrates sensing technologies, automation, and analytics to optimize agricultural inputs. Among the key enabling technologies, Unmanned Aerial Vehicles (UAVs) and Bio Inspired Micro Aerial Vehicles (MAVs) have gained considerable attention due to their ability to provide high-resolution, real-time data and perform targeted interventions.

UAV systems equipped with multispectral, thermal, and hyperspectral sensors enable rapid assessment of crop health, soil moisture, and environmental conditions. Studies have shown that UAV-based monitoring can improve crop health detection accuracy by 25–40% and reduce field inspection time by 60–70% compared to traditional methods (Tsouros *et al.,* 2019). Furthermore, UAV-assisted precision irrigation techniques have demonstrated water savings of approximately 20–30%**,** making them highly effective in water-scarce agricultural regions.

While UAVs operate at a macro scale, covering large agricultural fields efficiently, MAVs provide micro-scale capabilities by enabling plant-level interaction. Bio-inspired MAVs, modeled after insect flight mechanisms, operate in low Reynolds number regimes and utilize unsteady aerodynamic effects such as leading-edge vortex (LEV) formation to generate lift. These systems are particularly useful for applications such as artificial pollination, where precise interaction with individual flowers is required. Experimental studies indicate that MAV-based pollination systems can enhance crop yield by 10–15% in environments with reduced natural pollinator activity (Potts *et al.,* 2016).

The integration of UAV and MAV technologies creates a multi-layered agricultural monitoring system, combining wide-area surveillance with localized intervention. This dual-scale approach enhances decision-making capabilities and supports the development of intelligent farming ecosystems.

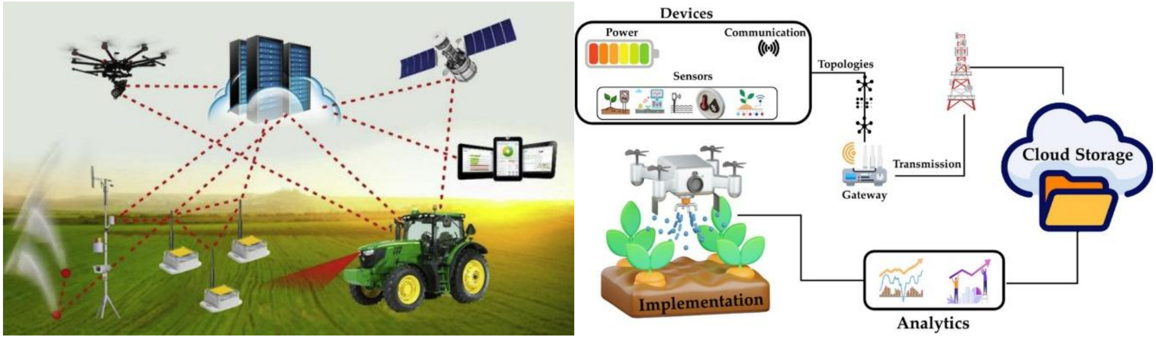

Figure 1: Integrated UAV–MAV Smart Agriculture Framework

Figure 1 illustrates the integrated smart agriculture framework where UAVs collect aerial data from agricultural fields using multispectral and thermal sensors. The data is transmitted to cloud-based platforms for processing using artificial intelligence algorithms. Based on the analysis, actionable insights such as irrigation scheduling, fertilizer application, and pest control measures are generated. MAVs operate at the micro level, performing tasks such as pollination and plant-level inspection, thereby complementing UAV-based monitoring.

The convergence of aerial robotics with artificial intelligence, Internet of Things (IoT), and renewable energy systems is accelerating the transition toward climate-resilient agriculture. Machine learning algorithms enable automated analysis of aerial imagery, facilitating early detection of crop stress and predictive yield estimation. IoT-based sensor networks provide real-time environmental data, while renewable energy-powered UAVs extend operational endurance, making continuous monitoring feasible.

Despite these advancements, challenges such as limited battery capacity, high initial investment, and regulatory constraints continue to hinder widespread adoption. Addressing these challenges requires interdisciplinary research in aeronautical engineering, robotics, agricultural science, and data analytics.

This chapter aims to provide a comprehensive analysis of UAV and MAV technologies in sustainable agriculture, focusing on aerodynamic principles, computational modeling, energy systems, and real-world applications. The integration of these technologies offers a promising pathway toward achieving efficient, resilient, and environmentally sustainable agricultural systems.

2. UAV Based Smart Agriculture System

2.1 System Architecture

UAV-based smart agriculture systems represent a significant advancement over traditional farming methods by integrating aerial sensing, communication networks, and intelligent data processing into a unified framework. These systems are designed to enable **real-time** monitoring, analysis, and decision-making, thereby improving agricultural efficiency and sustainability.

The system architecture operates through a sequential workflow. Initially, UAV platforms equipped with advanced sensors collect high-resolution spatial and temporal data from agricultural fields. This data is then transmitted through wireless communication systems such as 4G/5G or IoT-based networks to cloud or edge computing platforms. At the processing stage, artificial intelligence (AI) and machine learning (ML) algorithms analyze the collected data to identify patterns related to crop health, soil moisture, and environmental stress. Finally, the processed information is converted into actionable recommendations that assist farmers in optimizing irrigation, fertilization, and pest management practices.

This integrated approach significantly reduces dependency on manual field inspections and enables **precision-based intervention**, which is essential for climate-resilient agriculture (Boursianis *et al.,* 2022; Kamilaris and Prenafeta-Boldú, 2018).

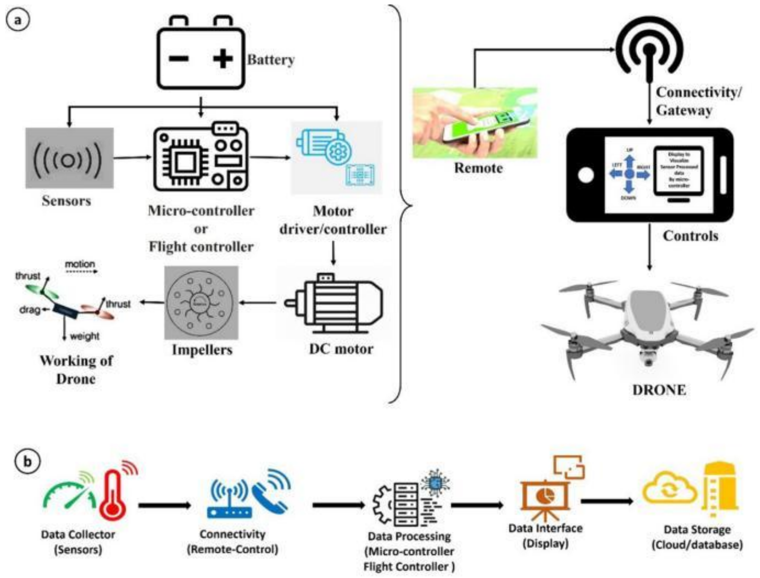

Figure 2: Integrated UAV Smart Farming Framework

Figure 2 presents the integrated UAV-based smart agriculture framework. The UAV collects field data using onboard sensors and transmits it to cloud-based platforms where artificial intelligence algorithms process the information. The analyzed outputs are delivered to farmers as actionable insights, enabling efficient decision-making for irrigation, fertilization, and crop protection.

2.2 Sensor Performance Analysis

The performance of UAV systems in agriculture is strongly influenced by the type of sensors used for data acquisition. Each sensor captures different aspects of crop and environmental conditions, allowing comprehensive field assessment.

As shown in Table 1, hyperspectral sensors provide the highest accuracy due to their ability to capture detailed spectral information across a wide range of wavelengths. Multispectral sensors are commonly used for vegetation index calculations such as NDVI, which helps in identifying crop stress at early stages.

Table 1: Sensor Performance Analysis in UAV-Based Agriculture

Sensor Type	Parameter Measured	Accuracy Gain
Multispectral	NDVI (vegetation health)	+35%
Thermal	Canopy temperature	+30%
Hyperspectral	Nutrient deficiency	+40%

Thermal sensors play a crucial role in detecting canopy temperature variations, enabling efficient irrigation management (Zhang and Kovacs, 2012; Maes and Steppe, 2020). The integration of multiple sensors allows UAV systems to perform multi-dimensional analysis, improving early detection of crop anomalies and reducing resource wastage.

2.3 UAV Efficiency Compared to Traditional Methods

Table 2: Comparative Analysis of UAV and Manual Monitoring Methods

Method	Time (hrs)	Accuracy (%)
Manual	10	60
UAV	3	90

As presented in Table 2, UAV-based monitoring significantly reduces inspection time from 10 hours to 3 hours, representing a 70% reduction in operational time. Additionally, accuracy improves from 60% to 90%, demonstrating the effectiveness of sensor-based data collection and AI-driven analysis.

This improvement is attributed to the UAV's ability to rapidly capture high-resolution imagery and process data automatically, eliminating human error and enabling timely intervention. Consequently, UAV systems contribute to reduced labor costs, improved productivity, and enhanced decision-making efficiency (Mogili and Deepak, 2018).

3. Bio Inspired MAV Systems

3.1 Aerodynamic Regime

Micro Aerial Vehicles (MAVs) operate under low Reynolds number conditions, where viscous forces dominate the flow behavior. This significantly alters aerodynamic performance compared to conventional UAVs.

$$Re = \frac{\rho V L}{\mu}$$

In MAV systems, Reynolds numbers typically range between 10^3 and 10^5, resulting in laminar and highly unsteady flow conditions. Under such conditions, conventional steady-state aerodynamic theories become inadequate for predicting lift generation. To overcome these limitations, MAVs adopt bio-inspired flight mechanisms based on insect flight. These mechanisms rely on unsteady aerodynamic phenomena such as vortex generation and wake interaction, which enhance lift production (Ellington, 1984; Shyy *et al.,* 2010).

3.2 Lift Mechanism

$$L = \frac{1}{2}\rho V^2 S C_L$$

While the classical lift equation provides a theoretical foundation, MAVs achieve enhanced lift through additional mechanisms:

- Leading-edge vortex formation
- Wake capture effect
- Rotational lift during wing motion reversal

These unsteady aerodynamic effects allow MAV systems to generate lift coefficients up to 1.5–2 times higher than conventional micro-scale aerial vehicles, enabling stable hovering and maneuverability (Wood *et al.,* 2013).

3.3 Relationship Between Wingbeat Frequency and Lift

Table 3: Relationship Between Wingbeat Frequency and Lift Generation in MAV Systems

Frequency (Hz)	Lift (mN)
10	12
15	18
20	26
25	35
30	44

As illustrated in Table 3, lift generation increases nonlinearly with wingbeat frequency. At lower frequencies, lift is insufficient for sustained flight. However, beyond 20 Hz, a rapid increase in lift is observed due to stronger vortex formation and improved airflow attachment.

This relationship highlights the importance of optimizing wingbeat frequency to achieve a balance between aerodynamic performance and energy consumption.

3.4 Flapping Wing MAV

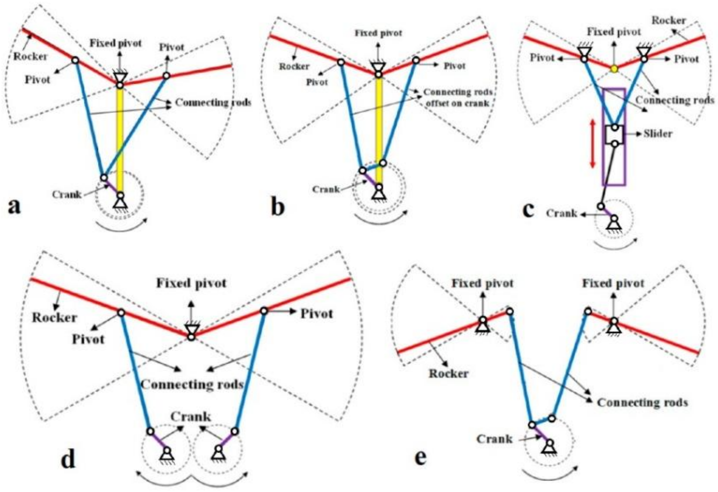

Figure 3: Flapping Wing MAV

Figure 3 illustrates the flapping wing micro aerial vehicle inspired by insect flight. The oscillatory wing motion generates unsteady aerodynamic forces that enable lift production even at low velocities. This mechanism allows MAVs to hover and maneuver efficiently in confined agricultural environments.

3.5 Aerodynamic Vortex Formation in MAVs

Figure 4 shows the formation of leading-edge vortices during wing flapping. These vortices create low-pressure regions above the wing surface, significantly enhancing lift generation under low Reynolds number conditions.

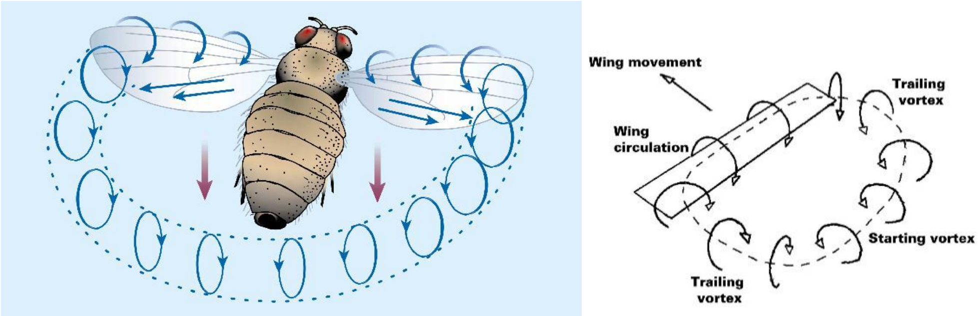

Figure 4: Aerodynamic Vortex Formation in MAVs

3.6 MAV Applications in Agriculture

Figure 5 illustrates the application of MAV systems in agriculture, including plant-level monitoring and artificial pollination. Their compact size and hovering capability enable precise interaction with crops, improving operational efficiency.

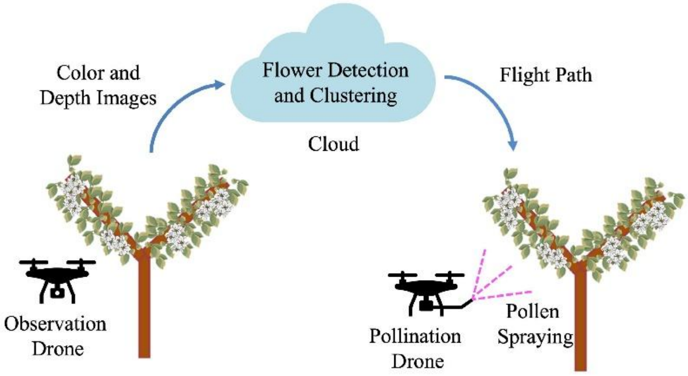

Figure 5: MAV Applications in Agriculture

4. Computational Fluid Dynamics Analysis for UAV and MAV Systems

4.1 Role of CFD in Agricultural UAV Design

Computational Fluid Dynamics (CFD) plays a critical role in the aerodynamic design and performance optimization of UAVs and MAVs used in agriculture. It enables detailed analysis of airflow behavior, pressure distribution, vortex formation, and aerodynamic forces without relying solely on expensive experimental testing.

In agricultural UAV applications, CFD is particularly important for:

- Optimizing wing geometry for improved lift

- Reducing aerodynamic drag to enhance flight endurance
- Improving spray droplet dispersion in pesticide applications
- Enhancing stability during low-altitude flight

CFD simulations are based on the numerical solution of the Navier–Stokes equations, which govern fluid motion. These simulations provide insights into how airflow interacts with UAV wings and MAV flapping mechanisms (Shyy *et al.,* 2010).

4.2 Pressure Distribution and Aerodynamic Behavior

The generation of lift in aerial systems is fundamentally linked to pressure differences between the upper and lower surfaces of the wing. CFD analysis allows visualization of these pressure variations.

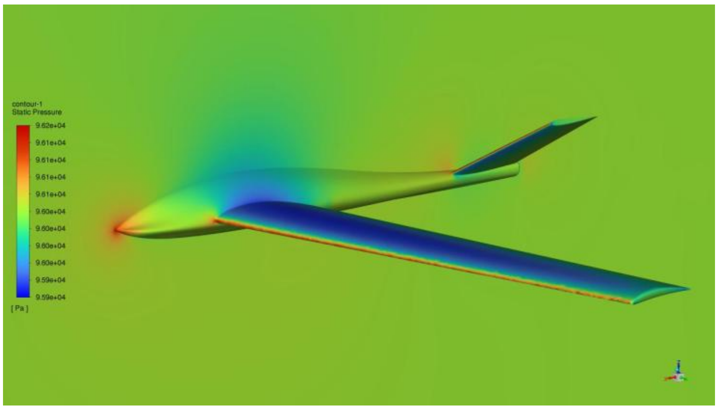

Figure 6: CFD Pressure Distribution over MAV Wing

Figure 6 illustrates the pressure distribution over a MAV wing obtained through CFD simulation. High-pressure regions are observed near the leading edge, while low-pressure regions develop over the upper surface. This pressure difference generates lift, which is essential for sustained flight.

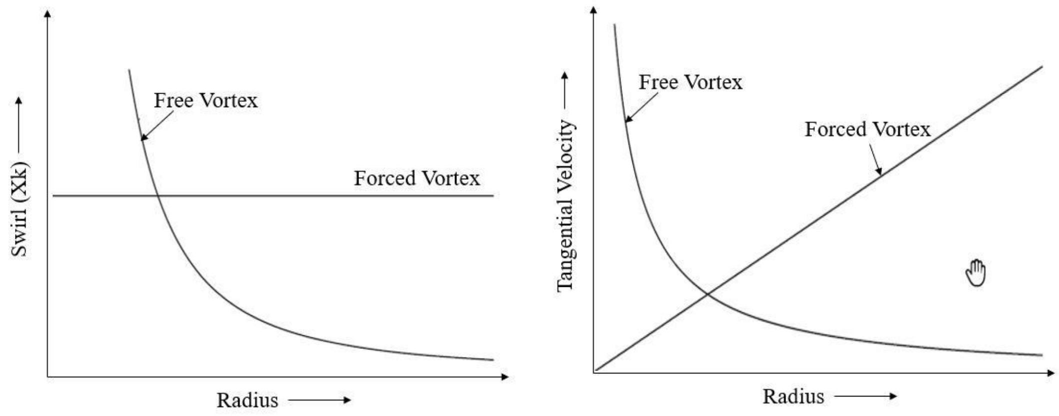

Figure 7: Swirl and Tangential Velocity Distribution in Free and Forced Vortex Flow

Figure 7 illustrates the variation of swirl and tangential velocity with respect to radius for both free vortex and forced vortex flow conditions.

In the left graph, the swirl (K) is plotted against the radius. For a free vortex, the swirl decreases rapidly as the radius increases, indicating an inverse relationship between angular motion and radial distance. This behavior arises because no external torque is applied, and angular momentum is conserved. As a result, fluid particles closer to the center rotate faster, while those farther away exhibit lower rotational intensity. In contrast, the forced vortex shows a constant swirl distribution across the radius, indicating uniform rotational motion throughout the fluid domain due to the presence of an external driving force.

In the right graph, the tangential velocity is plotted against the radius. For a free vortex, the tangential velocity decreases with increasing radius, following an inverse proportional relationship ($V \propto 1/r$). This results in very high velocities near the center and rapidly diminishing velocities outward. On the other hand, in a forced vortex, the tangential velocity increases linearly with radius ($V \propto r$), indicating solid-body rotation where all fluid particles rotate with the same angular velocity.

This distinction between free and forced vortex behavior is fundamental in understanding aerodynamic flow structures, particularly in UAV rotor flows and MAV flapping wing aerodynamics. In bio-inspired MAV systems, vortex formation around the wing resembles free vortex behavior, which contributes to lift enhancement through low-pressure regions. Conversely, forced vortex characteristics are observed in rotating components such as propellers and rotors, where external torque drives the flow.

5. Artificial Pollination Using MAV Systems

5.1 Need for Artificial Pollination

Pollination is a critical biological process that directly influences crop yield and food production. Approximately 70–75% of global crops depend on pollinators, particularly insects such as bees (Potts *et al.,* 2016). However, recent studies indicate a significant decline in pollinator populations due to pesticide exposure, habitat loss, climate change, and environmental stress. This decline has resulted in measurable agricultural impacts, including reduced fruit set, lower crop uniformity, and yield losses of up to 20–30% in certain crops. Traditional pollination methods are highly dependent on environmental conditions and cannot be controlled effectively. Therefore, there is a growing need for artificial pollination systems that can operate reliably and efficiently. Micro Aerial Vehicles (MAVs), inspired by insect flight, offer a promising solution by enabling controlled and targeted pollination at the plant level.

5.2 MAV-Based Pollination System Architecture

MAV-based pollination systems are designed to mimic the functional behavior of natural pollinators while overcoming their limitations. These systems integrate sensing, navigation, and actuation mechanisms to perform precise pollination tasks.

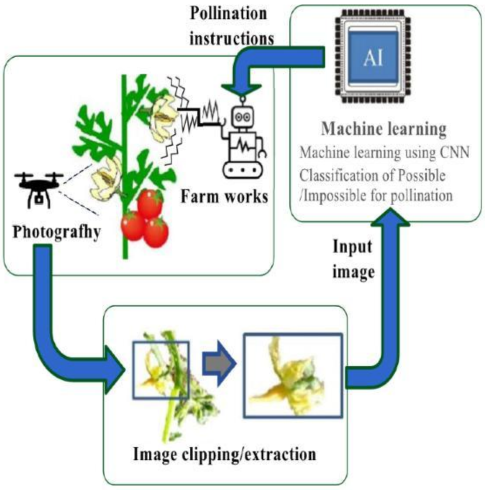

Figure 8: MAV-Based Artificial Pollination System

5.3 Pollination Mechanism and Working Principle

The working principle of MAV-based pollination involves three key stages:

- **Flower Detection:** Computer vision algorithms detect flower location, orientation, and maturity using RGB or multispectral imaging (Jha *et al.,* 2021).
- **Pollen Collection:** Pollen is collected using electrostatic attraction or soft brush mechanisms. Electrostatic forces enhance adhesion efficiency, ensuring effective pollen transfer.
- **Pollen Deposition:** The MAV deposits pollen onto the stigma of another flower through controlled contact, ensuring successful fertilization.

This controlled mechanism allows MAV systems to achieve higher consistency compared to natural pollination, especially in challenging environmental conditions.

5.4 Challenges and Limitations

Despite its advantages, MAV-based pollination faces several technical challenges:

- Limited battery life restricting operational time
- Difficulty in navigating dense crop environments
- Payload limitations for pollen collection systems
- High initial cost and system complexity

Addressing these challenges requires advancements in energy storage, AI-based navigation, and lightweight materials.

5.5 Future Scope of MAV Pollination

Future research directions include:

- Autonomous swarm-based pollination systems
- AI-driven flower detection and classification
- Hybrid UAV-MAV integrated systems
- Solar-powered MAV platforms

These developments will enable large-scale deployment of artificial pollination systems, improving agricultural productivity and sustainability.

6. Energy Systems, Swarm Robotics and AI–IoT Integration in Smart Agriculture

6.1 Energy Systems for UAV and MAV Platforms

Energy efficiency is one of the most critical constraints in UAV and MAV deployment. Conventional battery-powered UAVs typically have limited flight endurance ranging from **20 to 30 minutes**, which restricts their operational coverage. To overcome this limitation, multiple energy solutions are being explored:

- Lithium-ion battery systems
- Hybrid propulsion systems
- Solar-powered UAV platforms

Table 4: Comparison of Energy Systems in UAV Platforms

Energy System	Flight Endurance	Advantages	Limitations
Battery	20–30 min	Simple, lightweight	Limited duration
Hybrid	40–70 min	Extended endurance	Complex system
Solar-assisted	90–120 min	Sustainable, long duration	Weather dependent

As shown in Table 4, solar-assisted UAV systems significantly improve flight endurance by 30–50%, making them suitable for large-scale agricultural monitoring (Noth, 2008).

6.2 AI and IoT Integration

The integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies transforms UAV-based agriculture into a fully intelligent system.

AI enables:

- Crop disease detection
- Yield prediction
- Automated decision-making

IoT enables:

- Real-time environmental monitoring
- Sensor-based data collection
- Connectivity between devices

Table 5: AI-Based Agricultural Applications

Application	Accuracy (%)
Disease detection	92
Yield prediction	88
Irrigation control	85

As shown in Table 5, AI-based systems achieve high prediction accuracy, enabling proactive agricultural management (Kamilaris and Prenafeta-Boldú, 2018).

7. Indian Case Study and Challenges

7.1 UAV Applications in Indian Agriculture

India has witnessed rapid adoption of UAV technology in agriculture, particularly in states such as Tamil Nadu, Punjab, and Maharashtra. UAV-based monitoring has been successfully applied in crops such as paddy, cotton, and sugarcane. Field studies indicate:

- Yield improvement: **12–18%**
- Water savings: **20–30%**
- Fertilizer reduction: **15–25%**

These improvements highlight the effectiveness of UAV-based precision agriculture in Indian conditions (Singh and Choudhary, 2024).

7.2 Challenges in Indian Scenario

Despite its significant advantages, the large-scale adoption of UAV and MAV technologies in agriculture is constrained by a combination of technical, economic, regulatory, and operational challenges. From a technical perspective, limited battery capacity restricts flight endurance, while sensor calibration issues can affect the accuracy and reliability of collected data. Economically, the high initial investment required for UAV systems and the limited affordability for small-scale farmers hinder widespread implementation. Regulatory barriers, including airspace restrictions and complex licensing requirements, further complicate deployment, particularly in densely populated or controlled regions. In addition, operational challenges such as the lack of skilled operators and the complexity of system maintenance reduce the efficiency and scalability of these technologies. Addressing these interconnected challenges is essential for enabling the broader adoption of UAV and MAV systems in sustainable agriculture.

8. Future Scope of UAV and MAV Systems in Agriculture

The future of UAV and MAV systems in agriculture is strongly driven by the integration of advanced technologies and the development of fully autonomous systems capable of transforming conventional farming into intelligent, data-driven ecosystems. Emerging advancements include the evolution of fully autonomous UAV–MAV platforms that can operate collaboratively, AI-driven predictive agriculture models capable of forecasting crop health and yield, and swarm-based systems that enable large-scale coordinated operations across extensive farmland. In addition, solar-powered UAVs are expected to support continuous, long-duration monitoring, while the integration of satellite data and IoT networks will enhance real-time connectivity and environmental awareness. These technological developments are expected to enable near real-time decision-making, fully automated farm management, and significantly increased agricultural productivity with minimal human intervention, thereby contributing to sustainable and climate-resilient farming systems.

Conclusion

UAV and MAV technologies are rapidly transforming agriculture into a data-driven, intelligent, and sustainable system capable of addressing the growing challenges of climate variability and resource scarcity. UAVs facilitate large-scale, high-resolution monitoring of agricultural fields, enabling improvements in crop health detection accuracy by 25–40% and reductions in monitoring time by 60–70%, while MAVs provide micro-level interaction through applications such as plant-level inspection and artificial pollination. Bio-inspired MAV systems, operating under low Reynolds number conditions, utilize unsteady aerodynamic mechanisms to achieve enhanced lift generation, enabling stable hovering and precise maneuverability in complex crop environments.

The integration of aerodynamics, artificial intelligence, Internet of Things (IoT), and renewable energy systems further enhances the efficiency and scalability of these technologies. AI-driven analytics enable early detection of crop stress, disease, and nutrient deficiencies, while IoT-based sensor networks provide continuous environmental monitoring. In addition, CFD-based aerodynamic optimization contributes to drag reduction of approximately 12–18%, improving flight endurance, and solar-assisted UAV systems extend operational time by nearly 30–50%, supporting long-duration agricultural missions. The incorporation of swarm robotics enables coordinated multi-UAV operations, increasing field coverage efficiency by up to 3–5 times compared to single-drone systems.

Despite existing challenges related to high initial costs, regulatory constraints, limited battery capacity, and operational complexities, ongoing advancements in energy storage, autonomous navigation, and intelligent control systems are expected to accelerate the adoption of aerial robotics in agriculture. In particular, the integration of UAV and MAV platforms into unified smart farming ecosystems offers a scalable solution for precision agriculture and resource optimization.

Overall, aerial robotic systems represent a critical pathway toward achieving climate-resilient and sustainable agriculture. By improving productivity, reducing environmental impact, and enabling efficient resource utilization, UAV and MAV technologies have the potential to play a pivotal role in ensuring global food security in the coming decades.

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ROLE OF PLANT PATHOLOGY IN SUSTAINABLE AGRICULTURE

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Abstract

Sustainable agriculture has emerged as a fundamental approach to ensure long-term food security while maintaining ecological balance and conserving natural resources. Plant diseases remain one of the most critical constraints to agricultural productivity, causing significant yield and quality losses worldwide. The science of plant pathology, which deals with the study of plant diseases and their management, plays a central role in achieving the goals of sustainable agriculture. By integrating ecological principles, modern biotechnology, and traditional farming practices, plant pathology provides environmentally sound and economically viable solutions for disease management. This paper presents a comprehensive theoretical discussion on the role of plant pathology in sustainable agriculture, highlighting its contributions to disease diagnosis, epidemiology, integrated management strategies, host resistance, biological control, soil health, and climate resilience. It also examines current challenges and future prospects in aligning plant pathology with sustainable agricultural systems.

Keywords: Sustainable Agriculture, Plant Pathology, Integrated Management, Climate Resilience.

1. Introduction

Agriculture forms the backbone of human civilization, providing food, fiber, and livelihood to a significant portion of the global population. However, the intensification of agricultural practices in the last century, particularly through the excessive use of chemical fertilizers and pesticides, has led to severe environmental consequences, including soil degradation, water pollution, loss of biodiversity, and disruption of ecological balance. In response to these challenges, the concept of sustainable agriculture has gained prominence, emphasizing the need to produce food in a manner that is environmentally sound, economically viable, and socially responsible.

Within this framework, plant health emerges as a critical determinant of agricultural sustainability. Plants are constantly exposed to a wide array of pathogens such as fungi, bacteria, viruses, nematodes, and parasitic plants, which can significantly impair their growth and productivity. It is estimated that plant diseases account for a substantial proportion of global crop losses annually, posing a serious threat to food security. The discipline of plant pathology addresses these challenges by studying the nature, causes, development, and management of plant diseases.

Plant pathology is inherently interdisciplinary, drawing upon knowledge from microbiology, genetics, biochemistry, ecology, and agronomy. Its role extends beyond mere disease control to the development of integrated strategies that minimize environmental impact while ensuring crop productivity. In the context of sustainable agriculture, plant pathology provides the scientific foundation for managing diseases in ways that reduce reliance on chemical inputs, enhance natural biological processes, and promote ecosystem stability.

2. Plant Pathology and the Concept of Sustainability

Sustainability in agriculture is rooted in the principle of meeting present needs without compromising the ability of future generations to meet their own. This involves maintaining soil fertility, conserving water resources, protecting biodiversity, and minimizing pollution. Plant pathology contributes to these objectives by offering approaches that align disease management with ecological principles.

The traditional approach to plant disease control has relied heavily on chemical pesticides, which, although effective in the short term, have led to several unintended consequences. These include the development of pesticide resistance in pathogens, resurgence of secondary pests, contamination of soil and water, and adverse effects on non-target organisms, including beneficial microbes, insects, and even humans. Sustainable plant disease management seeks to overcome these limitations by integrating multiple control strategies that are environmentally benign and economically feasible.

Plant pathology plays a pivotal role in this transition by promoting integrated disease management practices, encouraging the use of resistant crop varieties, and advancing biological control methods. It also contributes to the understanding of disease ecology, enabling farmers to adopt practices that disrupt disease cycles and reduce pathogen pressure naturally.

3. Understanding Plant Diseases in Agro ecosystems

A comprehensive understanding of plant diseases is essential for their effective management. Plant diseases result from complex interactions among the host plant, the pathogen, and the environment, commonly referred to as the disease triangle. Any change in these components can influence disease development and severity.

In sustainable agriculture, emphasis is placed on managing these interactions in a way that reduces disease incidence without causing ecological harm. For instance, modifying environmental conditions through proper irrigation, spacing, and crop rotation can significantly reduce the prevalence of certain diseases. Similarly, enhancing the genetic resistance of crops can limit the ability of pathogens to infect plants.

Plant pathology provides insights into the life cycles, modes of transmission, and survival strategies of pathogens. This knowledge is crucial for designing preventive measures that target vulnerable stages in the pathogen’s life cycle. By focusing on prevention rather than cure, sustainable disease management reduces the need for external inputs and promotes long-term agricultural resilience.

4. Role of Disease Diagnosis and Epidemiology

Accurate diagnosis is the cornerstone of effective disease management. Misidentification of plant diseases can lead to inappropriate control measures, resulting in wasted resources and potential environmental damage. Plant pathology employs a range of diagnostic tools, from traditional visual inspection and microscopy to advanced molecular techniques such as polymerase chain reaction (PCR) and DNA sequencing.

Epidemiology, the study of disease development and spread, further enhances the ability to manage plant diseases sustainably. By analyzing factors such as weather conditions, cropping patterns, and pathogen biology, plant pathologists can predict disease outbreaks and recommend timely interventions. Disease forecasting models, which integrate meteorological data with pathogen dynamics, are increasingly being used to guide decision-making in agriculture.

These approaches help in optimizing the timing and application of control measures, thereby reducing unnecessary pesticide use and minimizing environmental impact. Early detection and timely intervention are key components of sustainable disease management, preventing small outbreaks from escalating into large-scale epidemics.

5. Integrated Disease Management as a Sustainable Strategy

Integrated Disease Management (IDM) represents a holistic approach to plant disease control that combines multiple strategies to achieve effective and sustainable outcomes. Unlike conventional methods that rely primarily on chemical control, IDM emphasizes the integration of cultural, biological, mechanical, and chemical measures.

Cultural practices such as crop rotation, sanitation, and proper planting techniques play a significant role in reducing pathogen populations and interrupting disease cycles. Biological control, which involves the use of beneficial microorganisms to suppress pathogens, offers an eco-friendly alternative to chemical pesticides. Host plant resistance, achieved through breeding and genetic improvement, provides inherent protection against diseases.

Chemical control, although still a component of IDM, is used judiciously and as a last resort. The selection of less toxic and more targeted chemicals, along with precise application methods, ensures minimal impact on the environment and non-target organisms.

IDM not only enhances disease control but also contributes to the overall sustainability of agricultural systems by reducing input costs, preserving natural resources, and maintaining ecological balance.

6. Host Plant Resistance and Genetic Approaches

The development of disease-resistant crop varieties is one of the most effective and sustainable methods of disease management. Resistant plants can prevent or limit pathogen infection, reducing the need for external control measures. Plant pathology plays a crucial role in identifying resistance genes and understanding the mechanisms by which plants defend themselves against pathogens.

Advances in genetics and biotechnology have accelerated the development of resistant varieties through techniques such as marker-assisted selection and genetic engineering. These approaches enable the incorporation of specific resistance traits into high-yielding cultivars, enhancing both productivity and sustainability.

However, the durability of resistance is a major concern, as pathogens can evolve and overcome resistance over time. To address this challenge, plant pathologists advocate the use of multiple resistance genes and the deployment of resistant varieties in combination with other management practices.

7. Biological Control and Soil Health

Biological control is a cornerstone of sustainable plant pathology, offering a natural and environmentally friendly approach to disease management. Beneficial microorganisms such as bacteria and fungi can suppress pathogens through mechanisms such as competition, antibiosis, parasitism, and induction of plant defense responses.

The health of the soil micro biome plays a critical role in disease suppression. Soils rich in beneficial microorganisms are often less conducive to pathogen development, a phenomenon known as disease-suppressive soil. Plant pathology research focuses on understanding and enhancing these natural processes through practices such as organic amendments, crop diversification, and reduced tillage.

Maintaining soil health not only reduces disease incidence but also improves nutrient availability, water retention, and overall plant vigor, contributing to sustainable agricultural productivity.

8. Plant Pathology in the Context of Climate Change

Climate change poses significant challenges to plant health by altering environmental conditions that influence disease dynamics. Changes in temperature, humidity, and precipitation patterns can affect the distribution, survival, and virulence of pathogens, leading to the emergence of new diseases and increased severity of existing ones.

Plant pathology plays a vital role in understanding these changes and developing strategies to mitigate their impact. This includes the development of climate-resilient crop varieties, adaptation of management practices to changing conditions, and the use of predictive models to anticipate disease outbreaks.

By addressing the challenges posed by climate change, plant pathology contributes to the resilience and sustainability of agricultural systems in an uncertain future.

9. Role in Organic and Low-Input Farming Systems

Organic and low-input farming systems rely heavily on ecological processes rather than synthetic inputs. In such systems, plant pathology provides essential knowledge for managing diseases through natural means. The use of resistant varieties, biological control agents, and cultural practices forms the backbone of disease management in organic agriculture.

Plant pathology also supports the development of natural plant protection products derived from botanical extracts and microbial formulations. These alternatives offer effective disease control while maintaining environmental integrity and consumer safety.

10. Challenges and Future Perspectives

Despite significant advancements, plant pathology faces several challenges in supporting sustainable agriculture. The rapid evolution of pathogens, emergence of new diseases, and increasing complexity of agro ecosystems require continuous research and innovation. Limited access to advanced technologies and lack of awareness among farmers further hinder the adoption of sustainable practices.

Future prospects in plant pathology include the integration of digital technologies such as remote sensing, artificial intelligence, and precision agriculture for real-time disease monitoring and management. Advances in genomics and bioinformatics will further enhance the understanding of host-pathogen interactions and facilitate the development of durable resistance.

Strengthening extension services and farmer education is equally important to ensure the effective implementation of sustainable disease management practices at the field level.

Conclusion

Plant pathology plays an indispensable role in achieving sustainable agriculture by providing scientific knowledge and practical solutions for managing plant diseases in an environmentally responsible manner. Through approaches such as integrated disease management, host resistance, biological control, and modern biotechnological interventions, plant pathology helps reduce reliance on chemical inputs and promotes ecological balance.

As the global demand for food continues to rise and environmental challenges intensify, the importance of plant pathology will only grow. A concerted effort involving research, policy support, and farmer participation is essential to harness the full potential of plant pathology in building sustainable and resilient agricultural systems.

Here are 30 relevant Indian and international references arranged alphabetically (suitable for a research paper/publication on Plant Pathology in Sustainable Agriculture). The style follows a standard academic (APA-like) format and includes a mix of books, journals, and reports.

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NANO-ENABLED AGROCHEMICALS: NANOPESTICIDES AND NANOFERTILIZERS FOR SUSTAINABLE DEVELOPMENT

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Abstract

The substantial growth in global population has driven increased food demand, underscoring the need to adopt sustainable and efficient agricultural practices. Conventional agricultural methods result in the loss of crops, primarily due to pest outbreaks, soil degradation, natural disasters, nutrient depletion and environmental contamination. In this regard, nanotechnology shows promise for boosting agricultural yields and advancing sustainable agriculture. Nanotechnology can help meet future food demands while reducing its environmental impact by improving resource efficiency, nutrient delivery, and pest control. Nanoagrochemicals, such as nanopesticides and nanofertilizers, are helping shape the industry's future and offer promising ways to make agriculture more sustainable.

Keywords: Agriculture, Nanoagrochemicals, Nanopesticides, Nanofertilizers, Eco-friendly.

1. Introduction

Agriculture has historically served as a primary source of livelihood and economic stability. However global challenges such as population growth, climate change and limited food resources have intensified pressure on the agricultural system. To address these challenges, technological developments in agriculture have become essential. In this regard, sustainable farming acceleration has emerged as a key approach which focuses on improving agricultural productivity on existing farmland while minimizing negative environmental impact (Kaushal & Wani, 2017) Nanotechnology is one considered to be an effective approach for sustainable agriculture. Precise control over material properties at the nanoscale is enabled by the ability to monitor and manipulate matter at the atomic and molecular levels. This special feature enables nanotechnology to address several long lasting challenges in agriculture (Fraceto *et al.,* 2016). It offers eco-friendly, economical and effective solutions that increases agricultural productivity while minimizing environmental and health risks.

In conventional farming methods, agrochemicals such as fertilizers, pesticides, and herbicides are essential for increasing crop yield and protecting crops from diseases and pests. The excessive use of agrochemicals has led to soil degradation, nutrient depletion, pest outbreaks, climate change and environmental contamination. Furthermore, conventional agrochemicals often result in significant nutrient loss from leaching, volatalization and runoff. These losses lead to major environmental issues, including eutrophication of water bodies, soil degradation, increased greenhouse gas emissions, and reduced fertilizer efficiency.

Innovative strategies, such as nanoagrochemicals, have emerged as effective solutions to these problems. This enables more precise pest targeting and nutrient delivery at the right time. This approach reduces the total amount of chemicals used. Their large surface area and small size enable them to interact more effectively with plant systems, promoting growth and productivity. Nanoagrochemicals such as nanopesticides and nanofertilizers have considerable potential to transform agriculture towards greater sustainability.

2. Nanopesticides

Nanopesticides encapsulate active chemicals in nanocarriers, which increase their solubility, stability, and persistence on plant surfaces. (Dash *et al.,* 2024). Their efficiency is increased by their small size and large surface area, which enable improved contact and deeper penetration into plant tissues and pests. Additionally, they reduce the overuse of chemicals and their negative environmental impacts by enabling controlled release triggered by variables such as pH, moisture, or temperature.

Advantages

i. Nanopesticides reduce adverse environmental effects relative to conventional pesticides.
ii. By minimising damage to beneficial insects and soil bacteria, nano-pesticides' nanoscale size and tailored delivery assist maintain ecological balance.
iii. By precisely targeting pests and disease vectors with nanopesticides, crop protection is improved and transmission channels are disrupted.
iv. As nano-pesticides are so effective, less pesticide treatments are made, which lowers operating costs and environmental residues.
v. Research has demonstrated that nanopesticides are 31.5% more effective at controlling pests than conventional insecticide applications, greatly increasing crop yield (Wang *et al.,* 2022).
vi. Time-dependent, controlled release of active ingredients is made possible by smart materials in nanoformulations, which increases their persistence and reduces the need for frequent applications.
vii. Better targeting and persistent intervention lower the likelihood that pests or pathogens will acquire resistance (Yadav & Yadav, 2025).

Disadvantages

i. Affects non-target organisms such as soil fauna, aquatic organisms, pollinators, and beneficial insects.
ii. Potential risk to human health through exposure and food consumption.
iii. Ecotoxicological concerns require careful risk assessment.
iv. Released into environment during production, storage, transport, use, and disposal.

v. Accumulation in plants, entering food and feed chains.
vi. Contamination of water bodies through agricultural runoff.
vii. Bioaccumulation in aquatic food chains, increasing at higher trophic levels.
viii. Persistence in soil, water, and land, leading to long-term environmental impact.

2.1 Types of nanopesticides and their advantages

Nano-pesticides can be classified into several categories according to their specific targets and modes of action- (1) Green nanopesticides (2) Metallic nanopesticides (3) Nanobiopesticides. The advantages of each category include:

2.1.1 Green nanopesticides

i. Eco-friendly synthesis using plant extracts reduces environmental pollution.
ii. Non-toxic and safer compared to chemically synthesized nano-pesticides.
iii. Cost-effective production due to use of easily available natural materials.
iv. Eliminates hazardous chemicals in the synthesis process.
v. Enhanced biological activity against pests (e.g., larvae control).
vi. Improved stability of nanoparticles due to natural capping agents in plant extracts.
vii. Effective even at low concentrations, reducing chemical load.
viii. Better compatibility with plants and soil microorganisms.
ix. Reduced risk of resistance development in pests.
x. Biodegradable and sustainable, supporting green chemistry principles.
xi. Safe for non-target organisms (comparatively lower toxicity) (Chaudhary *et al.,* 2023).

2.1.2 Metallic nanopesticides

i. High pesticidal efficiency against a wide range of insect pests.
ii. Rapid action—causes high mortality within a short exposure time.
iii. Strong toxicity toward insect larvae, including Spodoptera littoralis.
iv. Works at various concentrations, showing consistent pesticidal activity.
v. Improved surface area and reactivity of nanoparticles enhance pest control.
vi. Suitable for grain protection during storage under laboratory conditions.
vii. Long-lasting effect compared to conventional pesticides.
viii. Reduced quantity required due to high efficiency.
ix. Versatile application—different metals like aluminium and titanium can be used (Chaudhary *et al.,* 2023).

2.1.3 Nanobiopesticides

i. Biodegradable and eco-friendly, causing minimal damage in the environment.
ii. Minimal toxicity to non-target organisms, animals, and humans.
iii. Target-specific pest management that minimises damage to beneficial insects.
iv. Improved interaction with pests and increased efficacy as a result of nanoscale size controlled and prolonged release of the active components.

v. Enhanced stability of bioactive substances (reduced breakdown by heat, light, and microorganisms).

3. Nanofertilizers

Nanofertilizers are nanoscale substances that can serve as nutrient delivery or as direct sources of macronutrients or micronutrients for plants. Nutrient-encapsulating systems in nanoparticles are commonly called "nanofertilizers" (Faizan *et al.,* 2023). The goal of these formulations is to provide plants with nutrients in an effective, targeted, and controlled manner. Nutrient-encapsulated nanoparticles that allow for slow release over time, nanostructured materials, and nanosized versions of traditional fertilizers are among the several types of nanofertilizers. Nanofertilizers improve crop quality and yield while promoting agricultural sustainability by increasing nutrient-use efficiency and reducing production costs.

Advantages

i. One of the main benefits of nanofertilizers is their ability to deliver nutrients precisely and in a controlled manner, meeting crop needs throughout the growing season (Carmona *et al.,* 2022).
ii. According to research, nano-fertilizers can greatly reduce nutrient losses to the environment while increasing nutrient utilization by 20–30% when compared to conventional fertilizers (Liao *et al.,* 2023).
iii. By maximizing nutrient utilization and reducing nutrient losses through leaching and volatilization, nano-fertilizers enhance sustainable farming practices (Singh *et al.,* 2024; Kekeli *et al.,* 2025).
iv. Plant growth and development as well as total crop yield are enhanced by target-specific application of nanofertilizers.
v. A nanostructured formulation can extend the duration of the plant's nutrient supply by regulating released efficiency.
vi. Nanofertilizers are made to prevent harmful interactions with beneficial soil bacteria in order to maintain a healthy soil microbiome (Yadav & Yadav, 2025).
vii. When combined with beneficial bacteria, nanofertilizers provide further advantages like better root development, better nutrient cycling, and more sustainable agricultural results (Zulfiqar *et al.* 2019).

Disadvantages

i. Nanofertilizers are expensive.
ii. The interaction of nanomaterials with soil constituents may result in toxicity.
iii. The accumulation of nanofertilizers in plant sections can cause cell death, reactive oxygen species production, and growth inhibition.
iv. Can build up in dietary components and, if ingested, could be harmful to human health.

v. The unpredictability and reactivity of nanoparticles have caused workers to worry about their safety.

3.1 Types of nanofertilizers and their advantages

Nano-fertilizers are further classified based on the nutrient requirements of plants: (1) macro nanofertilizers, (2) micro nanofertilizers, and (3) nano biofertilizers. The advantages of each category include:

3.1.1 Macro nanofertilizers

i. For plant growth and development, effectively supply the necessary macronutrients (N, P, K, Ca, Mg, and S).
ii. Increased nutrient utilization efficiency as a result of a high surface area to volume ratio.
iii. Nutrient release that is slow and controlled minimizes losses and enhances absorption.
iv. Boost overall productivity, crop quality, and yield
v. Compared to traditional one, less fertilizer is needed.
vi. Enhance particular crop characteristics (such as saffron stigma weight, length, and flower production) (Amirnia *et al.,* 2014).
vii. Efficient in both field and laboratory settings.
viii. Help ensure that the growing demand for food is met in a sustainable manner (Annu *et al.,* 2023).

3.1.2 Micro nanofertilizers

i. Supply essential micronutrients in highly efficient nano-form for better plant uptake.
ii. Improve nutrient availability and utilization in plants.
iii. Enhance plant growth, development, and nutritional quality.
iv. Increase chlorophyll content to improve photosynthesis.
v. Boost biomass, shoot length, and overall plant vigor.
vi. Improve enzyme activity and metabolic functions in plants.
vii. Enhance protein content and crop physiological performance. (Annu *et al.,* 2023)

3.1.3 Nano biofertilizers

i. Increase soil nutrient efficiency by releasing nutrients gradually and in controlled amounts.
ii. Combine beneficial microbes with nanoparticles to increase soil fertility.
iii. Boost plants' ability to fix nitrogen and solubilize phosphorus.
iv. Boost the development and activity of advantageous soil microbes.
v. Increase the stability and shelf life of biofertilizers against UV and heat deterioration.
vi. Encourage improved plant development in both outdoor and in vitro settings.
vii. Boost soil health and overall crop productivity.
viii. Provide fertilization that is more ecologically friendly and sustainable than traditional techniques (Annu *et al.,* 2023).

4. Future perspective

The use of nano-agrochemicals, such as nanopesticides and nanofertilizers, has greatly increased crop protection, improved plant nutrition, and increased agricultural productivity. Nevertheless, there are still certain research gaps in the field of agrochemicals despite their advantages (Li *et al.,* 2021). Because of their small size and ease of penetration into plant tissues, nanoparticles pose a significant risk. This begs the question of how their ingestion may affect human health. According to recent research, biologically created nanoparticles are less hazardous than those made chemically and physically, indicating a move toward more environmentally friendly synthesis processes. Furthermore, it is yet unclear how nano-agrochemicals may affect the environment in the long run. As their use becomes more common, more study is need to maximise the effectiveness of nanoparticles while reducing any possible harm to the environment. The future of agriculture will be greatly influenced by the development of safe and sustainable nanotechnology solutions (Swetha *et al.,* 2025).

Conclusion

In the rapidly developing field of nanotechnology, cutting-edge instruments are being developed to address a range of problems related to pollution of the air, water, and soil. Conventional pesticides and fertilizers are less effective than nano-based chemicals such as nano-fertilizers and nano-pesticides. Additionally, the stability of these nanotools is enhanced by the presence of nanoparticles. By improving crop quantity and quality while reducing ecological damage, the use of nanopesticides and nanofertilizers in agriculture promotes economic growth. Agriculture is greatly impacted by nanotechnology, which also supports sustainable development worldwide. The more environmentally friendly and efficient nano-tools, such as nano-fertilizers and nano-pesticides, are produced using more environmentally friendly methods. Additionally, recommendations will make it easier to create nanoparticles using more environmentally friendly methods, such as those made using plant extracts. It might take several years for nanotechnology to advance from the lab to the real world.

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MUTATIONAL APPROACHES TO PYRIMETHANIL RESISTANCE IN *PENICILLIUM EXPANSUM*

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Abstract

Blue mould of pear, caused by *Penicillium expansum*, is a dominant postharvest disease worldwide, including in India. The pathogen was isolated from infected pear fruits, and its sensitivity to the fungicide Pyrimethanil was evaluated, revealing both resistant and sensitive isolates. A sensitive isolate (Pe-12) was selected for further study. Conidia of this isolate were subjected to Pyrimethanil and various mutagenic treatments, including spontaneous mutation (SP), ultraviolet (UV) radiation, and chemical mutagens such as sodium azide (SA), ethyl methane sulphonate (EMS), and N-nitro-N-methyl urea (NMU). These treatments produced mutants exhibiting varying levels of resistance, including highly resistant, moderately resistant, and less resistant types. Notably, the highly resistant mutants were found to be more pathogenic. Among the treatments, UV radiation generated the highest percentage of mutants, followed by SP, NMU, and EMS. Overall, the induction of fungicide resistance through these mutagenic methods resulted in a higher frequency and number of resistant mutants, many of which also showed increased pathogenicity.

Keywords: Pyrimethanil, Pear, *Penicillium expansum*, SP, UV, EMS, SA and NMU.

Introduction

Blue mold of pear (*Pyrus communis* L.) is caused by *Penicillium expansum* Link. Thom. ex. is one of the most serious post-harvest diseases in world and also in India. A total of twenty-one isolates of *Penicillium expansum* were obtained from infected fruits and evaluated for their sensitivity to Pyrimethanil on Potato Dextrose Agar (PDA) using the food poisoning technique (Nene and Thapliyal, 1993). The minimum inhibitory concentration (MIC) of Pyrimethanil was determined under both *in vitro* and *in vivo* conditions. *In vitro*, isolate Pe-10 (MIC: 754.5 µg/ml) was classified as sensitive, whereas isolate Pe-16 (MIC: 975.5 µg/ml) was found to be tolerant. Similarly, *in vivo* results showed that Pe-10 (MIC: 1941.5µg/ml) was sensitive, while Pe-16 (MIC: 2680.5µg/ml) exhibited tolerance. A Pyrimethanil-resistant mutant, Pe-EMS-12 (MIC: 4921.8 µg/ml), was identified, highlighting the need for alternative fungicide strategies.

Resistance in *P. expansum* was induced using various physical and chemical mutagens, including spontaneous mutation (SP), ultraviolet (UV) radiation, sodium azide (SA), ethyl methyl sulphonates (EMS), and N-nitro-N-methyl urea (NMU). The resulting mutants were categorized based on their level of resistance as highly resistant (HR), moderately resistant (MR), and sensitive (S), with the highest resistance level observed in mutant Pe-EMS-12. The development of resistance was also associated with changes in pathogenicity, as resistant strains were found to be more virulent compared to sensitive isolates.

On the other hand, genetic changes caused and stable fungicide in the pathogen is more important. This development of resistance depends upon the number of mutations required for resistance and mutability of gene at loci concerned. It may be influenced by type of fungicide, type of pathogen and by the environmental condition e.g. the presence of UV or other radiation (Demakopolos *et al.,* 1989). Genetic resistance may be due to the inhibitory activities on biosynthesis (Smith and Koller, 1990). Fungicide resistance is attributed to a change at the site of action, which decreases affinity between the chemical and its site (Dekker, 1976a). Protectant fungicides generally act as multi-site inhibitors, making resistance development less likely, whereas systemic fungicides typically target one or a few specific sites within fungal metabolism, increasing the likelihood of resistance development. Fungicide resistance is attributed to a change at the site of action, which decreases affinity between the chemical and its site (Dekker, 1976a).

Materials and Methods

A culture of *Penicillum expansum* was isolated from blue mould of pear and maintained on PDA slants. For the treatment of UV-mutagenesis, spores obtained from 5-day old cultures were resuspended in sterile distilled water and exposed to UV-light (254 nm) lamp source at a distance of 25 cm for 10, 15, 20, 25 and 30 min. The treated conidia were put in dark for one hr and transferred to dishes with Potato Dextrose Agar medium. On the other hand, conidia of 5-days old cultures were subjected to chemical mutagens viz. EMS (Ethyl Methane Sulfonate), NMU (N- Nitro- N- Methyl Urea) and SA (Sodium Azide) mutagenesis. Spores were collected and incubated in phosphate buffer pH 7.0 containing 100-400 μg/ml EMS, NMU and SA for 30 Spores were then washed with sterile distilled water and serial dilutions were prepared for inoculating Potato Dextrose Agar medium.

The sensitive strain and mutants were grown in PDA medium. The medium was inoculated with 10% spore suspensions. The *Penicillium expansum* spores were grown in 100 ml. Spores was carried out with help of technique described by (Horsten, 1979), the sterilized Potato Dextrose Agar medium containing (3X-MIC) of Pyrimethanil was poured in the plates and allowed to solidify. One of the spore suspensions was then uniformly distributed over Potato Dextrose Agar medium surface with the help of L-shaped sterile glass rod, Petri dishes thus prepared were incubated at 27± 2°C for 10 days. The visible colonies were counted and percentage frequencies of resistant colonies were calculated from that of the control plates colonies showing different morphological characters were isolated and maintained on PDA medium without fungicide for further studies. The colonies showing different morphological characters were then transferred on PDA medium without fungicide for further studies they were considered as UV mutants.

Morphologically distinct colonies were isolated and maintained separately on PDA medium without fungicide. The mutants were designated as SA-mutants, EMS-mutants and NMU-mutants. Post harvest fruits of pear were surface sterilized with sodium hypochlorite 10% solution and washed 5-10 times with sterile distilled water. They were inoculated with spore suspension of *Penicillium expansum* isolates or mutants sensitive or resistant to Pyrimethanil. Percentage Control Efficacy (PCE) was calculated (Cohen, 1989). In order to study the effect of Pyrimethanil or other fungicides, fruit wrapping technique by using tissue papers were used. After 15 Days fruits were carefully handled and infection on skin of the fruits was classified in the following grades.

Numerical Rotting	Fruits area Showing Infection
0	Fruits healthy
1	1 to 25% area infected
2	26 to 50% area infected
3	51 to 75% area infected
4	76 to 100% area infected

Results and Discussions

The results (Table 1) indicated that ultraviolet (UV) treatment produced the highest mutation frequency and the greatest number of mutants, followed by ethyl methane sulphonate (EMS), spontaneous mutation (SP), and sodium azide (SA). A total of 62 mutants were obtained using sodium azide. All mutants were reisolated on Potato Dextrose Agar (PDA) slants and subcultured ten successive times on plain PDA to assess their stability. Subsequently, they were transferred onto PDA amended with three times the minimum inhibitory concentration (3× MIC) of Pyrimethanil. Mutants that continued to grow under these conditions were considered stable (Table 2).

Further observations confirmed that mutants derived from UV and EMS treatments exhibited stronger resistance to Pyrimethanil, whereas fewer resistant mutants were obtained from SP, NMU, and SA treatments. The highest resistance and pathogenicity were recorded in EMS-induced mutants, with a resistance factor reaching up to 5 (highly resistant category) and a percent disease index of 43.50 (Table 3).

During plate observations, sectoring (saltation) within fungal colonies was noted. Twenty isolates were obtained from these sectors and evaluated for their sensitivity to Pyrimethanil. Considerable variation in ED_{50} and MIC values was observed among these isolates, with MIC values ranging from 1950.9 to 4921.8 µg/ml. Isolate Pe-sp-3 was the most sensitive, whereas Pe-EMS-12 showed the highest resistance. Other isolates displayed intermediate sensitivity, with MIC values between 1975.5 and 3890.8µg/ml. These findings suggest that the saltation phenomenon may contribute to the development of fungicide resistance in *Penicillium expansum* (Table 4).

In the present study, resistance to Pyrimethanil in a sensitive isolate of *P. expansum* was successfully induced using spontaneous mutation, UV radiation, sodium azide, EMS, and N-nitro-N-methyl urea (NMU). Among these, EMS proved to be the most effective in terms of mutation frequency, number of mutants, stability, and pathogenicity.

Table 1: Induction of resistance to Pyrimethanil in *Penicillium expansum* through various mutagenic treatments

Sr. No.	Treatment Time (min)	No. of mutants	Percentage of frequency
1.	Spontaneous	28	46.66
2.	UV rays (30 min)		
	10 min	37	61.66
	15 min	35	58.33
	20 min	33	55.00
	25 min	30	50.00
	30 min	28	46.66
3.	Sodium Azide (30 min) (SA)		
	1). 100 µg/ml	19	31.66
	2). 200 µg/ml	17	28.33
	3). 300 µg/ml	15	25.00
	4). 400 µg/ml	11	18.33
4.	Ethyl Methane Sulphonate (30 min) (EMS)		
	1).100 µg/ml	20	33.33
	2). 200 µg/ml	22	36.66
	3). 300 µg/ml	25	41.66
	4). 400 µg/ml	24	40.00
5.	N-Nitro-N- Methyl Urea (30 min) (NMU)		
	1). 100 µg/ml	22	36.66
	2). 200 µg/ml	20	33.33
	3). 300 µg/ml	22	36.66
	4). 400 µg/ml	20	33.33

These findings are consistent with earlier reports. Sable and Gangawane (2012) observed that EMS treatment produced the highest number of carbendazim-resistant mutants in *Aspergillus niger*, followed by UV and other treatments. Similarly, Van Tuyl (1977) reported the induction of benomyl and thiabendazole resistance through UV treatment in *Penicillium expansum* and other fungi. Resistance to thiophanate-methyl in *Penicillium digitatum* and *Penicillium italicum* through spontaneous mutation has also been documented (Ushiyama, 1979; Reddy, 1986). Furthermore, EMS and UV treatments were found to induce carbendazim and thiophanate-methyl resistance in *Aspergillus flavus*, with EMS being more effective.

However, it is important to note that the emergence of resistant mutants under laboratory conditions does not necessarily translate to immediate control failure in the field. Resistance becomes problematic only when a substantial proportion of the pathogen population acquires it. Nevertheless, the present study provides valuable insight into the potential development of resistance in *Penicillium expansum* against Pyrimethanil and may aid in predicting resistance trends. Similar observations have been reported by Davidse (1981), Dekker (1982), Gangawane and Reddy (1985), Khilare and Gangawane (1997), and Suryawanshi (1998).

Table 2: Stability of *Penicillium expansum* mutants resistant to Pyrimethanil.

Sr. No.	Nature of mutant	Total mutants Tested	Stable mutants	Stability Percentage
1.	Spontaneous	28	09	33.14
2.	UV rays (30 min)			
	10 min	37	10	27.02
	15 min	35	09	25.71
	20 min	33	10	30.30
	25 min	30	08	26.66
	30 min	28	07	25.00
3.	SA (30 min)			
	1). 100 µg/ml	19	05	26.31
	2). 200 µg/ml	17	04	23.52
	3). 300 µg/ml	15	05	33.33
	4). 400 µg/ml	11	04	36.36
4.	EMS (30 min)			
	1). 100 µg/ml	20	08	40.02
	2). 200 µg/ml	22	06	27.28
	3). 300 µg/ml	25	07	28.01
	4). 400 µg/ml	24	07	29.16
5.	NMU (30 min)			
	1). 100 µg/ml	29	08	27.58
	2). 200 µg/ml	25	06	24.07
	3). 300 µg/ml	22	06	27.27
	4). 400 µg/ml	20	05	25.00

Mutant was sub-cultured 10 times on plain Potato Dextrose Agar and again cultured on Potato Dextrose Agar containing 3X MIC of Pyrimethanil.

Table 3: Resistance factor of Pathogenicity of Pyrimethanil resistant mutant of *Penicillium expansum* obtained through induced mutations

Sr. No.	Mutants	Resistant factor	Resistance category	PDI %
1.	Pe-sp-1	2	R	18.55
2.	Pe-sp-3	2	R	20.10
3.	Pe-sp-5	2	R	18.50
4.	Pe-UV-1	4	MR	23.75
5.	Pe-UV-4	3	R	18.50
6.	Pe-UV-5	3	R	20.00
7.	Pe-SA-1	2	R	20.00
8.	Pe-SA-2	3	R	18.50
9.	Pe-SA-4	2	R	20.15
10.	Pe-SA-6	3	R	18.50
11.	Pe-EMS-3	3	R	20.00
12.	Pe-EMS-4	2	R	18.50
13.	Pe-EMS-6	3	R	18.50
14.	Pe-EMS-7	3	R	18.65
15.	Pe-EMS-10	4	MR	23.55
16.	Pe-EMS-11	4	MR	23.80
17.	Pe-EMS-12	5	HR	43.50
18.	Pe-NMU-3	3	R	18.50
19.	Pe-NMU-6	3	R	20.20
20.	Pe-NMU-7	4	MR	23.75
21.	Pe-Wild sensitive	S/300	S	12.50

A: MIC of Pyrimethanil against resistance mutant divided MIC of wild ensitive isolate. Resistant factor 2-3, Moderately Resistance – 4, Highly Resistant -5

B: HR- Highly Resistance, MR- Moderately Resistance,

R- Resistant, and S- Sensitive to Pyrimethanil.

Table 4: Sensitivity of *Penicillium expansum* isolates from saltation plate against Pyrimethanil

Sr. No.	Treatments	ED $_{50}$ (µg/ml)	MIC (µg/ml)	RF
1.	Pe-sp-1	0982	1975.5	3.022
2.	Pe-sp-3	0970	1950.9	2.983
3.	Pe-sp-5	0986	1971.6	3.030
4.	Pe-UV-1	1941	3884.5	5.971
5.	Pe-UV-4	1457	2915.6	4.482
6.	Pe-UV-5	1459	2910.8	4.474
7.	Pe-SA-1	0974	1946.4	2.992
8.	Pe-SA-2	1455	2911.5	4.475
9.	Pe-SA-4	0978	1943.5	2.987
10.	Pe-SA-6	1459	2919.4	4.487
11.	Pe-EMS-3	1460	2910.2	4.473
12.	Pe-EMS-4	9730	1964.1	3.019
13.	Pe-EMS-6	1452	2913.2	4.478
14.	Pe-EMS-7	1455	2919.4	4.487
15.	Pe-EMS-10	1940	3880.2	5.964
16.	Pe-EMS-11	1942	3886.4	5.974
17.	Pe-EMS-12	2426	4921.8	7.466
18.	Pe-NMU-3	1459	2919.2	4.487
19.	Pe-NMU-6	1457	2921.5	4.491
20.	Pe-NMU-7	1944	3890.8	5.978
21.	Pe-10	290.8	0650.8	1.000

ED$_{50}$ - Fungicide concentration causing 50 % reduction in radial growth

MIC - Minimal Inhibitory Concentration RF – Resistance Factor

Conclusion

The present study demonstrates that *Penicillium expansum*, the causal agent of blue mold of pear, exhibits considerable variability in its sensitivity to the fungicide Pyrimethanil. Both sensitive and tolerant isolates were identified, with significant differences observed under *in vitro* and *in vivo* conditions. The induction of fungicide resistance through physical and chemical mutagens revealed that ultraviolet (UV) radiation and ethyl methane sulphonate (EMS) were the most effective treatments in generating a higher frequency and number of resistant mutants.

Among all treatments, EMS-induced mutants showed the highest levels of resistance, stability, and pathogenicity, indicating a strong association between fungicide resistance and increased virulence. The occurrence of sectoring (saltation) further highlighted the potential for genetic variability within the pathogen population, which may contribute to the development and spread of resistance.

Although resistance was successfully induced under laboratory conditions, its expression and impact in field conditions may depend on several factors, including selection pressure, environmental conditions, and pathogen population dynamics. Therefore, continuous monitoring and judicious use of fungicides are essential to delay resistance development. Overall, this study provides valuable insights into the mechanisms of resistance development in *P. expansum* and can aid in designing effective disease management strategies for blue mold of pear.

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NUTRIFUSION POWDER:
INNOVATION IN FUNCTIONAL FOODS FOR FOOD SECURITY

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Food security is one of the most essential components of sustainable development, as it ensures that all individuals have access to sufficient, safe, and nutritious food required for maintaining a healthy and active life. The concept of food security is multidimensional and is built upon four key pillars, namely availability, accessibility, utilization, and stability of food systems. In the Indian context, food security has been legally strengthened through the National Food Security Act, 2013, which aims to provide subsidized food grains to a large proportion of the population while also improving nutritional outcomes. Despite these initiatives, India continues to face significant challenges related to malnutrition, undernutrition, and micronutrient deficiencies. According to global reports, food insecurity is not only associated with the lack of food availability but also with the lack of access to nutrient-rich and diverse diets [1]. Furthermore, hidden hunger, which refers to deficiencies in essential vitamins and minerals, continues to affect millions of people worldwide and is considered a major public health concern [2]. These challenges indicate the need for innovative and sustainable solutions that can improve both food availability and nutritional quality.

In recent years, food technology has emerged as a powerful tool in addressing food security challenges by enhancing food production, processing, preservation, and distribution. The application of food technology enables the transformation of raw agricultural materials into value-added products with improved shelf life, safety, and nutritional quality. Nutrifusion Powder is an example of such innovation, where traditional nutrient-rich ingredients are combined using modern processing techniques to create a functional food product. Functional foods are defined as foods that provide additional health benefits beyond basic nutrition and are increasingly being recognized for their role in improving health outcomes and reducing the risk of chronic diseases [3]. The development of Nutrifusion Powder reflects the integration of traditional knowledge with modern technology to address the issue of nutritional insecurity.

Nutrifusion Powder is formulated using a combination of foxnut powder, cinnamon powder, cocoa powder, almond powder, black raisin powder, and jaggery powder. Each of these ingredients contributes unique nutritional and functional properties that enhance the overall value of the product. Foxnuts, also known as makhana, are rich in protein, low in fat, and contain significant levels of antioxidants, which help in reducing oxidative stress and improving metabolic health [4]. Almonds are an excellent source of healthy fats, protein, and vitamin E, which play a crucial role in maintaining cardiovascular health and supporting brain function [5]. Black raisins provide natural sugars and are particularly rich in iron, making them beneficial for preventing anemia and boosting energy levels [6]. Cinnamon is widely known for its medicinal properties, especially its ability to regulate blood glucose levels and improve insulin sensitivity, making it useful for managing metabolic disorders [7]. Cocoa powder contains flavonoids, which are known to improve cardiovascular health by enhancing blood circulation and reducing inflammation [8]. Jaggery, a traditional sweetener, is rich in minerals such as iron and potassium and serves as a healthier alternative to refined sugar [9]. The combination of these ingredients results in a nutrient-dense product that provides both macro and micronutrients required for maintaining overall health.

The role of food technology in the preparation of Nutrifusion Powder is critical in ensuring product quality, safety, and shelf life. The process begins with the selection of high-quality raw materials, followed by cleaning and grading to remove impurities and contaminants. Drying is an essential step in the processing of the ingredients, as it reduces moisture content and prevents microbial growth, thereby extending shelf life. Studies have shown that proper drying techniques are effective in preserving the nutritional quality of food products while improving their storage stability [10]. After drying, the ingredients are ground into fine powder using mechanical grinding techniques, which ensure uniform particle size and enhance digestibility. The powders are then blended in specific proportions to achieve a balanced nutritional profile. Packaging is another crucial aspect of food technology, as it protects the product from environmental factors such as moisture, oxygen, and light. Advanced packaging methods, including vacuum packaging and the use of moisture-resistant materials, play a significant role in maintaining product quality and extending shelf life [11].

Nutrifusion Powder contributes significantly to food security by addressing all four pillars of food security. In terms of availability, the product utilizes locally sourced ingredients, which supports local agriculture and reduces dependence on imported food products. Accessibility is improved due to the convenient powder form, which can be easily prepared by mixing with milk or water, making it suitable for individuals of all age groups. Affordability is another key advantage, as the product can be produced at a relatively low cost compared to commercially available health supplements, making it accessible to economically weaker sections of society. Nutritional utilization is enhanced through the presence of essential nutrients that support growth, immunity, and overall health. These characteristics align with global strategies aimed at improving dietary diversity and nutrient intake as a means of combating malnutrition and improving public health outcomes [1, 2].

The role of regulatory authorities is essential in ensuring the safety and quality of food products. In India, the Food Safety and Standards Authority of India is responsible for establishing guidelines related to food safety, hygiene, labeling, and packaging. Compliance with these standards ensures that food products such as Nutrifusion Powder are safe for consumption and meet the required quality parameters. Government initiatives and nutrition programs can further enhance food security by incorporating such nutrient-rich products into their frameworks, particularly in programs aimed at improving the nutritional status of children and women.

Technological advancements have further strengthened food systems and contributed to improved food security outcomes. Innovations in food processing techniques have enabled better preservation of nutrients and improved product quality, while advancements in supply chain management have reduced food wastage and improved distribution efficiency. The use of digital technologies in food systems has also enhanced monitoring and transparency, ensuring that food reaches the intended beneficiaries in a timely manner [1]. These developments highlight the importance of integrating technology at every stage of the food system to achieve sustainable food security.

The health benefits of Nutrifusion Powder further support its role in improving nutritional security. The presence of natural sugars from jaggery and raisins provides instant energy, making it suitable for individuals with high energy requirements. Antioxidants present in cocoa and cinnamon help in boosting immunity and reducing inflammation, thereby improving overall health. The calcium content of foxnuts supports bone health, while the nutrients present in almonds contribute to improved brain function and cognitive performance. Regular consumption of such nutrient-rich products can help prevent nutritional deficiencies and reduce the risk of chronic diseases such as cardiovascular disorders and diabetes [8,7]. This makes Nutrifusion Powder a valuable addition to daily diets, particularly in populations that are at risk of malnutrition.

Despite its numerous advantages, there are certain challenges associated with the development and promotion of Nutrifusion Powder. Limited awareness about functional foods among consumers, lack of large-scale production facilities, and inadequate storage infrastructure can hinder its widespread adoption. Additionally, regulatory compliance and quality assurance require careful attention to ensure that the product meets safety standards. Addressing these challenges requires collaborative efforts from researchers, policymakers, and industry stakeholders to promote innovation and improve accessibility.

In conclusion, the integration of food technology with traditional nutritional knowledge provides a sustainable solution to the challenges of food and nutritional security. Nutrifusion Powder represents an innovative approach that combines locally available ingredients with modern processing techniques to create a nutrient-dense and accessible food product. By aligning with national policies such as the National Food Security Act and global recommendations, such products can play a significant role in improving public health and achieving long-term food security goals. Therefore, Nutrifusion Powder not only serves as a functional food product but also as a technological intervention that contributes to the broader objective of sustainable development and nutritional well-being.

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WATERSHED MANAGEMENT AND RAINWATER HARVESTING: STRATEGIES FOR SUSTAINABLE AGRICULTURE AND CLIMATE RESILIENCE

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Abstract

One of the biggest problems facing agriculture around the world in the twenty-first century is a lack of water. Rapid population growth, erratic monsoon patterns caused by climate change, land degradation, and the overuse of groundwater aquifers have all made it even more important to find scientifically sound and community-involved ways to manage water resources. When combined with rainwater harvesting (RWH) technologies, watershed management is a complete way to protect soil, recharge groundwater, lower flood peaks, and keep agricultural productivity high. This review chapter brings together what we know about watershed management principles, parts, planning methods, and the many different types of RWH structures that can be used in rain-fed farming areas. The chapter rigorously assesses participatory watershed development models, remote sensing and GIS-supported planning instruments, climate-resilient adaptations, and documented case studies from India and other semi-arid areas. Key performance indicators of watershed programs, including hydrological responses, enhancements in crop yields, fluctuations in groundwater levels, and socio-economic impacts, are examined. We also look at the problems and future research directions, such as how to combine precision technologies, indigenous knowledge systems, and policy frameworks under PMKSY and the National Water Policy 2012. The chapter concludes that well-planned watershed management and rainwater harvesting that fits the needs of the community are both necessary to make vulnerable farming communities more resilient to climate change and to make sure they have enough food.

Keywords: Managing Watersheds, Collecting Rainwater, And Protecting Soil and Water Resilience to Climate Change, Check Dams, Farm Ponds, Groundwater Recharge, and Sustainable Farming Are All Things You Can Do. PMKSY, Semi-Arid Tropics.

1. Introduction

Agriculture is still the most important part of the Indian economy. It employs almost 58% of the population and is a big part of the country's food security. More than 60% of India's cultivated land, on the other hand, is rain-fed, which makes it more vulnerable to the changing patterns of monsoon rainfall over time and space. The rising number of dry spells, flash floods, long-lasting droughts, and rains that come at the wrong time are all signs of climate change that are very dangerous for rain-fed farming and rural livelihoods.

Water, the most basic resource for farming, is limited and not evenly spread out. India gets about 1,170 mm of rain each year, but most of it (75–80%) falls during the monsoon season (June–September). This causes big differences in supply and demand over time. When it rains, the water runs off quickly, and the soil erodes and the plants die, which leads to huge losses of both water and fertile topsoil. According to estimates, India loses about 5,334 million tonnes of soil each year because of water erosion. Of that, 29% is permanently deposited into the sea (ICAR, 2019; Singh *et al.,* 2009).

Watershed management has become the most effective and environmentally sound way to deal with these problems that are all connected. A watershed, which is a land area that drains into a common outlet and is defined by its topography, is the best biophysical unit for planning, carrying out, and judging integrated natural resource management interventions (Singh *et al.,* 2009). By using the watershed as the main planning unit, people can work on soil conservation, water harvesting, restoring vegetation, and improving livelihoods in a way that is good for the environment.

Rainwater harvesting (RWH) is a key part of developing a watershed. It includes a wide range of on-site and off-site methods for collecting, storing, and using rainwater before it turns into wasteful runoff. Rainwater harvesting (RWH) structures serve many purposes. They hold back runoff for extra irrigation, help recharge groundwater, reduce peak flood discharge, and improve the local microclimate. Examples of RWH structures include the simple earthen bund on a farm contour and the engineered percolation tank across a seasonal stream. "Water harvesting is not just a technical task; it is a necessity for civilization that brings communities back in touch with the cycles of rain and the morals of conservation." National Water Mission, GoI.

The goal of this review chapter is to give a complete, up-to-date summary of the science, technology, policy, and practice of watershed management and rainwater harvesting in the context of climate resilience and sustainable agriculture. The chapter uses a lot of peer-reviewed research, evaluations of government programs, and case studies from the field to give researchers, practitioners, students, and policymakers in agricultural engineering and related fields a complete picture of the topic.

2. Basics of Water Balance and Watershed Hydrology

2.1 Definition and Explanation of Watersheds

A watershed, also known as a catchment or drainage basin, is a specific area of land that collects and channels surface and subsurface water to a single outlet or pour-point. Micro-watersheds (less than 500 ha) are part of sub-watersheds (500–10,000 ha), which are part of watersheds and river basins. This hierarchical structure makes it possible to plan for both small-scale and large-scale actions.

2.2 The Water Balance and the Hydrological Cycle

To plan any conservation or harvesting project, you need to know the watershed's water balance. You can say the watershed water balance like this:

$$P = ET + R + \Delta S + D$$

P stands for precipitation, ET stands for evapotranspiration, R stands for surface runoff, ΔS stands for change in soil moisture and groundwater storage, and D stands for deep percolation or baseflow. In semi-arid watersheds, ET usually makes up 70% to 85% of precipitation, which means that only a small amount is left over as runoff or recharge (Wani *et al.,* 2003). The goal of watershed management interventions is to change the way P is divided in a way that is good for the environment. This means lowering unproductive ET (bare soil evaporation) and raising productive ET (transpiration for crop growth) and storage (ΔS).

2.3 Runoff generation Processes

There are two main ways that surface runoff happens in agricultural watersheds:

- Hortonian (Infiltration Excess) Overland Flow: This happens when the amount of rain falls faster than the soil can soak it up. Common on soils that have been damaged, compacted, or crusted over and have little organic matter. In semi-arid Alfisols and Vertisols, they are in charge.
- Saturation Excess Overland Flow: This happens when the soil profile is full and can't take in any more water. More common in humid sub-watersheds with shallow water tables or layers that don't let water through.

Conservation tillage, mulching, bunding, and planting vegetation are all examples of watershed interventions that aim to reduce infiltration excess runoff by improving the soil's physical properties and surface roughness.

Traditionally, watershed delineation means looking at topographic maps (like contour maps and the Survey of India toposheet at a scale of 1:50,000) to find the watershed divide, which is the ridge line that separates two nearby drainage basins. Digital Elevation Models (DEMs) created from SRTM (Shuttle Radar Topography Mission) data or Cartosat-1 data (2.5 m resolution) are used in GIS environments (ArcGIS/QGIS) to automate delineation and get morphometric parameters like drainage density, bifurcation ratio, form factor, and elongation ratio.

3. Principles and Parts of Integrated Watershed Management

3.1 The Basics of Watershed Management

Integrated Watershed Management (IWM) is a way of working with people from different fields to find a balance between using land, water, plants, and people in a watershed in a way that is both productive and protects them. The main ideas are:

- Use the watershed as the main planning unit, not the lines that separate different areas.
- Talk about both the biophysical and socio-economic aspects of resource degradation.

- Use a ridge-to-valley treatment sequence, starting at the top of the watershed and working your way down.
- Based on land capability classification and problem diagnosis, put site-specific interventions at the top of your list.
- Make sure that the community is involved and that the institutions own the project for long-term success.
- Combine storing water outside with keeping soil moisture inside.
- Use performance indicators that can be measured to keep an eye on and evaluate results.

3.2 Components of an Integrated Watershed Treatment

A full watershed treatment program has four main types of treatment, each of which is designed to deal with a different set of land-use and water conditions:

Table 1: Components of Integrated Watershed Treatment and associated measures

Treatment Category	Land Situation	Key Measures
Arable Land Treatment	Cultivated / cultivable land on gentle to moderate slopes	Contour bunding, graded bunding, bench terracing, broad bed furrow (BBF), contour farming, cover crops, conservation tillage
Non-Arable Land Treatment	Degraded common lands, forest lands, steep slopes	Gully plugging, staggered trenches, vegetative barriers (vetiver, Napier), afforestation, silvipastoral systems
Drainage Line Treatment	Stream courses, nalas, seasonal drainage channels	Loose boulder check dams, gabion structures, earthen check dams, percolation tanks, farm ponds, recharge shafts
Pasture Development	Degraded wastelands, eroded hillocks	Improved pasture species, rotational grazing, enclosures, biomass fencing, fodder banks

3.3 The Ridge-to-Valley Method

The ridge-to-valley sequence is a basic rule that tells you how to space out the treatment. By starting interventions at the watershed ridge (upper catchment) and moving down to the valley bottom (drainage outlet), practitioners make sure that: (i) runoff from the upper watershed is caught and stored or percolated before it builds up into destructive flood flows; (ii) treatment structures are not overwhelmed by untreated upstream flows; and (iii) the groundwater table recharge is optimized across the whole watershed.

4. Structures and technologies for collecting rainwater

Rainwater harvesting includes all the ways to gather, store, and use rainwater that falls on fields, pastures, rooftops, or catchment areas. Here is a systematic review of the main RWH structures that can be used in agricultural watersheds.

4.1 *In-situ* Soil Moisture Conservation Measures

4.1.1 Bunding Along the Contour

Contour bunds are earthen walls built along the edge of a field, at right angles to the slope. They stop water from flowing overland, hold rainwater in the space between the bunds, and give it more time to soak in. ICAR rules set the design parameters, such as bund height, spacing, cross-sectional area, and spillway capacity. These depend on the type of soil, the slope, and the amount of rain that falls. For slopes of 1–6% and yearly rainfall of 600–1,500 mm, contour bunds are the best choice.

Benefits include a 40–60% decrease in runoff volume, a 50–75% decrease in soil loss, and a big increase in the amount of moisture in the soil (up to 2–3 weeks more moisture retention after the monsoon ends), which makes it possible to grow short-duration pulses and oilseeds as crops after the rainy season.

4.1.2 The Broad Bed and Furrow (BBF) System

ICRISAT made the BBF system to help manage Vertisol. It makes broad beds (105 cm) and furrows (51 cm) that alternate along the field's contour. The furrows move extra rainwater to a grassy waterway and then to a storage tank. The beds keep the right amount of moisture for growing crops. The BBF system stops black cotton soils from getting too wet, lets you plant seeds up to 20 days earlier than flat-bed sowing, and boosts sorghum and chickpea yields by 25–40% (Wani *et al.,* 2003).

4.1.3 Conservation Tillage and Mulching

Using organic waste (like paddy straw, groundnut shells, and sugarcane trash) as mulch on the surface at a rate of 4–6 t/ha can cut down on soil evaporation by 30–50%, surface runoff by 20–35%, and improve soil organic carbon over time. Minimum tillage, no-till, and reduced tillage are all types of conservation tillage systems that keep surface crop residues and macro-porosity. This makes it easier for water to soak in and less likely to seal and crust. Research conducted by CRIDA (Hyderabad) indicates a 35–50% decrease in runoff from minimum tillage relative to conventional tillage in Alfisol watersheds.

4.2 Ex-situ Water Storage Structure

4.2.1 Farm Ponds

Farm ponds are small water storage structures on farms that are dug out to collect and store runoff from the farm's catchment area. They are a very important source of life-saving water for crops that are still growing during dry spells and the main source for drip irrigation systems. Under PMKSY-Har Khet Ko Pani, the National Bank for Agriculture and Rural Development (NABARD) and state governments give a lot of money to help build farm ponds.

When designing a pond, you need to think about the catchment-to-pond area ratio (which is usually 10:1 to 15:1 for semi-arid areas), the pond's capacity (which is usually 500–1,000 m^3 for a 1 ha farm), and how to stop seepage by using compacted clay, bentonite, or polyethylene liners.

In Marathwada, Maharashtra, case studies show that a 1,000 m³ farm pond can give 1 ha of cotton or soybeans one to two extra waterings during long dry spells, which can stop 30–50% of possible yield losses.

4.2.2 Check Dams

Check dams are small walls that go across seasonal streams and gullies. They slow down the flow of water, trap sediment, and help groundwater recharge. There are three main types that are common:

- Earthen or Nala Bunds: These are structures made of packed earth that run along drainage lines and have a masonry spillway or pipe outlet. Good for small nalas and building things in the community at a low cost. Usually holds between 500 and 5,000 m³.
- Loose Boulder Check Dams (LBCDs): These are made of rocks that can be found nearby. They are permeable structures that let base flow through while holding sediment and helping it move through. Works really well for recharging groundwater in hard-rock aquifer areas like the Deccan Plateau and the Eastern Ghats.
- Gabion Structures: Wire mesh boxes filled with stones that can bend and are resistant to scour. Used in gullies where the water flows quickly and the bed material is rough. Lasts a long time (15–25 years) and doesn't need much care.

A network of 15–20 check dams in a 500-ha watershed can collectively raise the local water table by 0.5–2.0 m after the monsoon, greatly increasing the amount of groundwater available for rabi season irrigation (Wani *et al.,* 2003).

4.2.3 Percolation Tanks

Percolation tanks (PTs) are medium- to large-sized water storage structures (with a capacity of 0.05 to 2 MCM) built across seasonal streams to hold runoff for a longer time, mostly to recharge groundwater. PTs are made with porous or sandy beds on purpose to let water flow through them better than irrigation tanks. A PT's zone of influence covers an area with a radius of 2 to 5 kilometers, bringing new life to open wells and bore wells in the area below.

Studies from Karnataka and Andhra Pradesh show that a single PT with a capacity of 1 MCM can recharge groundwater by 0.3 to 0.6 MCM per year, depending on the aquifer's characteristics. This means that it can support 150 to 300 hectares of rabi irrigation from groundwater, in addition to any direct supplemental irrigation from the tank storage.

4.2.4 Ponds and Anicuts in Villages

Traditional water harvesting structures like village ponds (Johari, Talaab), anicuts (temporary diversion structures across streams), and khadins (sand storage embankments in arid Rajasthan) are examples of indigenous hydraulic engineering that has been adapted to fit local water and social needs for hundreds of years (Vaidyanathan, 2006). The MGNREGS and Jal Shakti Abhiyan programs have helped hundreds of villages become more water secure by fixing up and updating their water systems.

Table 2: Comparative overview of major Rainwater Harvesting structures used in watershed management

Structure	Slope (%)	Primary Function	Capacity Range	Key Benefit
Contour Bund	1–6	*In-situ* moisture	Field scale	Soil moisture, reduced runoff
Farm Pond	< 3	Water storage	500–5,000 m³	Supplemental irrigation, life-saving
Earthen Check Dam	1–5	Recharge + storage	500–5,000 m³	GW recharge, sediment trap
Percolation Tank	< 5	Groundwater recharge	0.05–2 MCM	Revives wells, rabi irrigation
Loose Boulder CD	3–15	Gully arrest + recharge	Small	Hard-rock GW recharge
Gabion Structure	5–15	Erosion control	Small–medium	Gully stabilisation, long life
Rooftop RWH	N/A	Domestic water supply	1,000–10,000 L	Drinking water, recharge pit

5.1 Data Inputs for Planning a Watershed

Some important remote sensing products used in managing watersheds are:

- Digital Elevation Models (DEM): SRTM 30 m, Cartosat-1 DEM (2.5 m), and ALOS PALSAR DEM are used to automatically draw the boundaries of watersheds, map slopes, analyze aspects, and figure out the direction of flow.
- Land Use / Land Cover (LULC) Maps: These maps are made from Landsat-8/9 OLI, Sentinel-2 MSI, and IRS LISS-III multispectral data. They are used to figure out Curve Numbers (CN) for runoff estimation and to find areas that need treatment the most.
- Soil Maps: FAO-UNESCO and NBSS&LUP digital soil maps that have been combined with field characterization for Land Capability Classification (LCC).
- Drainage Network Maps: These are made from DEM using watershed analysis tools in ArcGIS (ArcHydro), QGIS (SAGA GIS), or SWAT model pre-processing.
- NDVI (Normalized Difference Vegetation Index) from MODIS and Sentinel-2 is used to measure how well vegetation recovers before and after treatment.

5.2 Hydrological Modeling for Planning

There are a number of hydrological models that are used to estimate runoff on a watershed scale, predict erosion, and size water harvesting structures:

- SCS-CN Method (USDA): This is the most common empirical model in India for figuring out how much direct runoff there will be from rain. It uses Curve Number (CN) values that are given to combinations of land use, soil hydrological group, and moisture level before the rain.

- SWAT (Soil and Water Assessment Tool): A semi-distributed, physically-based model that shows how hydrology, sediment transport, and agricultural management affect watersheds. Commonly used to look at how conservation practices affect different situations.
- WEPP (Water Erosion Prediction Project): A process-based model that can help you figure out how much erosion will happen on hillsides and in small watersheds. It can also help you plan how to build contour bunds and vegetative barriers.
- RUSLE (Revised Universal Soil Loss Equation): This is used to make maps of annual soil loss ($A = R \times K \times LS \times C \times P$) and to figure out which sub-watersheds are most likely to erode and need treatment first.

GIS-based multi-criteria decision analysis (MCDA) that takes into account slope, drainage density, soil erodibility, land degradation index, and socio-economic vulnerability has been used in studies from Tamil Nadu, Odisha, and Maharashtra to objectively rank sub-watersheds for investment. This makes the most of limited funds.

6. Development of watersheds with community involvement

Technical excellence is a necessary but not sufficient condition for the success of watershed programs. India's history of watershed development shows that projects that don't involve the community enough have had problems with ownership, maintenance, and structural failure. The change from a technocratic to a participatory model, which was made clear in the Hariyali Guidelines (2003) and the Common Guidelines for Watershed Development Projects (2008), (Ministry of Agriculture (2008) has been a major change in Indian watershed policy.

6.1 Models of Governance Led by the Community

The Common Guidelines (2008) say that Watershed Committees (WCs) must be formed at the village level. These committees must have elected members, including women and people from marginalized groups, who will be in charge of planning, managing funds, hiring workers, and maintaining the project after it is finished. The Watershed Development Fund (WDF) is a donation from the community that covers 10% of the project's cost and is used for upkeep. Research in ten states shows that projects with active WCs do 25–35% better in the long run than those managed only by Project Implementing Agencies (PIAs) (Reddy *et al.,* 2010).

6.2 Gender Mainstreaming in Watershed Programs

Women are the main people in charge of household water and fodder, so they have a big interest in the outcomes of the watershed. Dedicated Women Self-Help Groups (WSHGs) in watershed projects have been able to manage household-level RWH structures like rooftop systems and kitchen garden ponds, keep nurseries for vegetative bunding going, and fight for fair water distribution from communal storage structures. The Integrated Watershed Management Programme (IWMP) says that at least 33% of the members of the WC must be women.

7. Climate Change, Watershed Vulnerability and Adaptation

Climate change is not a threat to Indian agriculture that will happen in the future; it is happening right now. The IPCC AR6 (2021) says that by 2100, the average annual temperature in South Asia will rise by 1.5 to 4.0°C in moderate to high emission scenarios. This will be accompanied by more extreme rainfall events, longer dry spells during the monsoon season, and more floods and droughts.

7.1 Expected Effects on Water Resources

When the patterns of rainfall change, the way water flows and recharges in watershed systems will also change. Some important changes that are expected to happen in peninsular India are:

- Heavy rain events (> 100 mm/day) will become 15–25% more intense, which will raise the risk of flooding and soil erosion caused by runoff.
- 10–20% fewer days of rain, with rain falling in fewer, more intense events.
- A drop in the average amount of groundwater recharge because higher temperatures cause more direct runoff and evapotranspiration.
- More changes in when the monsoon starts and ends, making it harder to plan for crops.

7.2 Climate-Smart Ways to Adapt Watersheds

When managing a watershed in a climate-smart way, you need to build structures and make changes that can handle changes in how much it rains. Important strategies are:

Adaptation Measures for Watershed Management That Are Smart for the Climate

- Making check dams and nala bunds bigger by 20–30% so they can handle more rain.
- Building flexible, cascading systems of check dams instead of one big dam to spread out the flood risk.
- Encouraging perennial vegetative cover (agroforestry, mixed orchards) to keep soil macro-porosity stable as rainfall patterns change.
- Combining weather forecasting systems with irrigation schedules for farm ponds to cut down on evaporation losses.
- Using new types of crops that can survive drought and changing the dates when they are planted to match the changing patterns of the monsoon.
- Setting up community-managed, real-time soil moisture monitoring networks (wireless sensor arrays) to help farmers make smart decisions about what to grow.
- Bringing back traditional ways of collecting water, like johads, step-wells, and khadins, that have been used for hundreds of years and changed to fit the area's changing water flow.

8. Case Studies of Successful Watershed Management

8.1 Ralegan Siddhi, in the state of Maharashtra

Ralegan Siddhi village in Ahmednagar district is perhaps the most famous example of successful watershed management in India. From the late 1970s onwards, social activist Anna Hazare led intensive watershed work that turned the village from a drought-prone, economically troubled community into a model of self-reliance. Important actions included building earthen nala bunds, percolation tanks, and contour trenches on common and forest land; limiting tree cutting, grazing, and well-digging; and encouraging crops that use less water.

Results (recorded by WALMI, 1996, and later studies): groundwater levels rose from 5 to 10 meters below ground level to 3 to 5 meters; the area under irrigation grew from 120 hectares to over 700 hectares; per capita income tripled; out-migration nearly stopped; and the village became food surplus within 10 years. Ralegan Siddhi served as the model for the Government of India's watershed program design.

8.2 Sukhomajri, Haryana

The Sukhomajri watershed experiment, which CSWCRTI (Central Soil and Water Conservation Research and Training Institute) started in the 1970s, was the first to use fair benefit-sharing systems for partnerships between communities and watersheds. The Forest Department built an earthen dam across a seasonal stream to help with the silting of Sukhna Lake, and the local community used it for extra irrigation. Equal water rights for all households, no matter how much land they own, and a system of tradeable water coupons solved elite capture and gave communities strong reasons to protect plants.

In five years, soil erosion from the 545 ha watershed dropped by more than 95%, biomass productivity increased by four times, and farm incomes doubled. The equity provisions of later national watershed guidelines were based on the Sukhomajri model.

8.3 ICRISAT's Kothapally Watershed in Andhra Pradesh

The Kothapally watershed (468 ha) in Ranga Reddy district, developed collaboratively by ICRISAT and its partners, exemplified the transformative effects of integrating agronomic and engineering practices. BBF systems were put in place on Vertisol lands, a big network of farm ponds was built, and better types of sorghum, chickpea, and castor were promoted. A comprehensive hydrological analysis conducted from 2000 to 2007 recorded a 38% decrease in runoff volume, a 63% decrease in sediment yield, a 33% rise in groundwater levels, a 35–55% increase in crop yields, and a watershed-level benefit–cost ratio of 2.84 (Wani *et al.,* 2008).

9. Policy Framework: India's Watershed Development Programs

India has a long history of centrally funded watershed development programs. They started as separate soil conservation programs in the 1950s and have grown into the current convergent, multi-ministry framework under PMKSY.

Table 3: Evolution of watershed development programmes in India

Programme	Period	Key Features and Coverage
DPAP/DDP/NWDPRA	1970s–2000s	Drought-prone area development; introduced integrated watershed approach; covered ~30 Mha cumulatively
IWDP/Hariyali	2003–2009	Decentralised governance; Watershed Committees; emphasis on common land and equity; ₹6,500/ha norm
IWMP	2009–2015	Common Guidelines 2008; convergence with MGNREGS; 4-year consolidation period; 55 Mha target; ₹12,000/ha
PMKSY-WDC	2015–present	Pradhan Mantri Krishi Sinchayee Yojana — Watershed Development Component; Har Khet Ko Pani + More Crop Per Drop; convergence with farm pond, drip irrigation subsidies; GIS-based monitoring via DISHA

The National Water Policy (2012) supports the watershed as the best way to manage all water resources together. It also supports the use of both surface and groundwater together and calls for demand-side management through community governance and water pricing. The technical principles of watershed management that we talked about in this chapter are very similar to these policy imperatives.

10. Biophysical and Socio-Economic Results of Watershed Management

A meta-analysis of more than 200 peer-reviewed studies and program evaluation reports (Joshi *et al.,* 2004; World Bank, 2008; NABARD, 2019) shows that well-run watershed programs have consistently positive effects on many areas:

10.1 Results of Hydrology

- Less surface runoff: 25–65% less seasonal runoff volume.
- Less soil erosion: 40–80% less sediment going to drainage outlets.
- Groundwater recharge: The water table levels in the watershed rose by 0.2 to 2.0 m after the monsoon.
- Spring and baseflow revival: Treated catchments have shown that perennial springs are coming back and stream flows are rising during the dry season.

10.2 Results for Agriculture and Livelihoods

- Growth of irrigated areas: The net irrigated area in watershed villages grew by 30% to 200%.
- Better crop yields: Kharif crop yields go up by 20–50%, and rabi crop yields go up by 30–80% because there is more groundwater.

- Diversification: Moving from growing only one type of food to a variety of systems that include growing vegetables, flowers, and dairy products, as well as other related activities.
- Effects on income: Comprehensive watershed programs have been shown to raise net household income by 25% to 100%.
- Employment: A big drop in the number of people leaving watershed villages because of stress.

10.3 Co-Benefits for the Environment

- Carbon sequestration: Parts of watershed programs that plant trees can store 0.5 to 2.0 tons of CO_2 equivalent per hectare per year.
- Biodiversity: Putting plants back in treated areas helps local biodiversity and makes it easier for animals to move around.
- Microclimate improvement: Vegetated watershed areas have less wind, lower peak soil temperatures, and higher relative humidity.

11. Problems and Future Research Directions

11.1 Ongoing Issues

Even though there have been some successes, watershed management programs still have a lot of structural and operational problems to deal with:

- Post-project sustainability: After a program ends, many buildings fall apart because they don't get enough money for upkeep and the community institutions are weak.
- Fairness in how benefits are shared: Farmers who depend on downstream and groundwater often get less than farmers who live in the upper-catchment area and have more resources.
- Scale-up bottlenecks: The costs of participatory planning are high, which slows down the rate of coverage compared to the estimated 65 million hectares of degraded watershed land that needs treatment.
- Attribution problems: It's hard to tell the difference between the effects of watershed interventions on water flow and changes in the weather, which makes it hard to evaluate programs.
- Siltation of storage structures: Check dams and percolation tanks lose storage space over time because of sedimentation, so they need to be desilted every so often.

11.2 New technologies and where they might go in the future

The next generation of watershed management will use more digital tools, precision technologies, and traditional knowledge:

- IoT and sensor networks: Wireless soil moisture sensors, automated rain gauges, and groundwater telemetry for real-time monitoring of watersheds.

- Assessment using drones: UAVs with multispectral cameras for quick, high-resolution mapping of LULC, gullies, and vegetation after treatment.
- Using machine learning to prioritize sub-watersheds: Random forest, SVM, and deep learning algorithms are used on geospatial data from multiple sources to better prioritize treatments.
- Blockchain for water rights: Pilot programs that use distributed ledger technology to keep track of and enforce fair water sharing agreements in watershed communities.
- Nature-based solutions (NbS): Using built wetlands, restoring floodplains, and bioengineering as part of watershed treatment plans.
- Indigenous ecological knowledge (IEK): The organized collection and use of traditional rainwater harvesting (RWH) methods (johads, kunds, phads) in modern program design.

Conclusion

Rainwater harvesting and watershed management are two of the best ways to make rain-fed agricultural areas more resilient to climate change. They provide a way to sustainably intensify agriculture that is both environmentally restorative and economically empowering by addressing the fundamental problem of water scarcity not by extracting from groundwater reserves that are getting smaller and smaller, but by restoring natural hydrological processes.

This review has brought together the hydrological foundations, engineering technologies, planning tools, participatory governance models, climate adaptation aspects, policy frameworks, and documented results of watershed management in India. The evidence is strong: well-planned and community-run watershed programs can cut soil erosion by up to 80%, raise groundwater levels by 0.5 to 2.0 m, increase the amount of land that can be irrigated by 30 to 200%, and boost farm household incomes by 25 to 100%.

But the problem is still not solved. There are more than 65 million hectares of degraded rain-fed land that need integrated treatment. Climate change is making the hydrological stresses on agriculture worse. The scale, speed, and quality of watershed investment must be raised right away. Future programs need to use digital technologies to make planning and monitoring smarter, build up community institutions for long-term governance, and make climate adaptation a part of all design and practice.

The watershed is not just a piece of land; it is also a part of life, a way to make a living, and a way to protect the environment. Restoring it is an investment in the future of food security for one of the world's most climate-vulnerable farming groups.

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IMPORTANCE OF MYCORRHIZAE IN PLANT COMMUNITIES AND NUTRIENT CYCLING

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Abstract

Mycorrhizae are symbiotic associations between plant roots and soil fungi that play a fundamental role in terrestrial ecosystems. Present in nearly 90% of plant species, these associations enhance nutrient and water uptake, particularly of phosphorus and nitrogen, thereby improving plant growth and productivity. This chapter examines the major types of mycorrhizae, including arbuscular, ectomycorrhizal, ericoid, and orchid associations, and highlights their structural and functional diversity. Emphasis is placed on their ecological roles in shaping plant communities, promoting biodiversity, and enhancing ecosystem stability through common mycorrhizal networks. Additionally, the chapter explores the critical role of mycorrhizae in nutrient cycling, including carbon sequestration, phosphorus mobilization, and nitrogen dynamics. Their applications in sustainable agriculture, ecosystem restoration, and climate change mitigation are also discussed. Overall, mycorrhizae are indispensable for maintaining soil health, ecosystem resilience, and sustainable productivity in changing environmental conditions worldwide.

Keywords: Mycorrhizae, Nutrient Cycling, Plant Communities, Soil Fertility, Symbiosis.

1. Introduction

Mycorrhizae are among the most ecologically significant symbiotic associations in terrestrial ecosystems, representing an intimate mutualistic relationship between soil fungi and plant roots (Brundrett, 2004; Lanfranco *et al.,* 2016). The term *mycorrhiza* was first introduced by the German botanist Albert Bernhard Frank in 1885 to describe the fungal-root associations observed in forest trees. Since then, mycorrhizal associations have been recognized as essential components of plant nutrition, soil fertility, and ecosystem functioning (Powell & Rillig, 2018). In this symbiotic relationship, plants provide photosynthetically derived carbohydrates to fungal partners, while fungi facilitate the absorption of water and nutrients from the soil. This exchange enhances plant growth, particularly in nutrient-poor soils, where fungal hyphae extend far beyond the root depletion zone and access nutrients unavailable to plant roots alone (Ayana, 2020). Mycorrhizal fungi are especially important for the uptake of phosphorus, nitrogen, potassium, calcium, zinc, and copper, nutrients that are often present in insoluble or inaccessible forms (Bhantana *et al.,* 2021; Sardans *et al.,* 2023).

Mycorrhizal associations are present in nearly 90% of all terrestrial plant species, indicating that these interactions are not merely beneficial but often indispensable for plant survival and ecosystem productivity (van Der Heijden *et al.,* 2015; Teste *et al.,* 2020). Their ecological role extends far beyond nutrient exchange. They influence plant community composition, improve soil aggregation, enhance stress tolerance, and contribute significantly to biogeochemical cycling (Qin *et al.,* 2017; Crowther *et al.,* 2019). Mycorrhizae form intricates belowground networks that connect individual plants, facilitate resource sharing, and regulate competitive interactions within plant communities (Walder & Van Der Heijden, 2015; Tedersoo *et al.,* 2020).

In recent decades, the importance of mycorrhizae has gained increasing attention due to their relevance in sustainable agriculture, forest management, restoration ecology, and climate change mitigation. Their role in carbon sequestration and nutrient cycling places them at the centre of ecological sustainability. Understanding the mechanisms through which mycorrhizal fungi influence plant communities and ecosystem processes is essential for developing environmentally sound strategies to improve agricultural productivity and restore degraded ecosystems (Wang, 2017).

This chapter explores the different types of mycorrhizae, their ecological functions in plant communities, their role in nutrient cycling, and their practical significance in environmental management and sustainable agriculture.

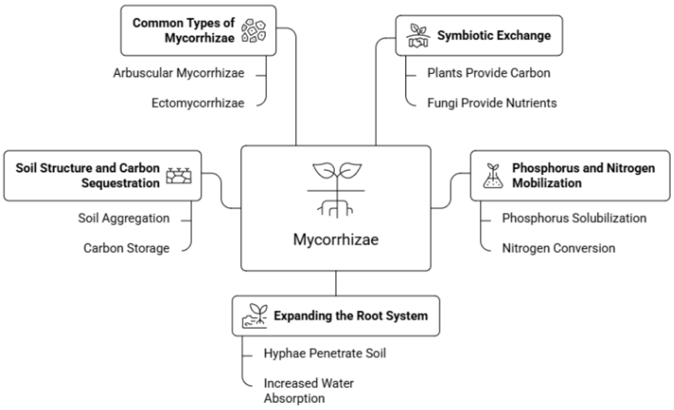

Figure 1: Mycorrhizae symbiotic associations act as central hubs for terrestrial nutrient cycling

2. Types of Mycorrhizae

Mycorrhizal associations are classified based on the structural relationship between fungal hyphae and plant roots. Although several forms exist, the major categories include arbuscular mycorrhizae, ectomycorrhizae, ericoid mycorrhizae, and orchid mycorrhizae. Each type exhibits unique structural and functional characteristics and is associated with particular groups of plants.

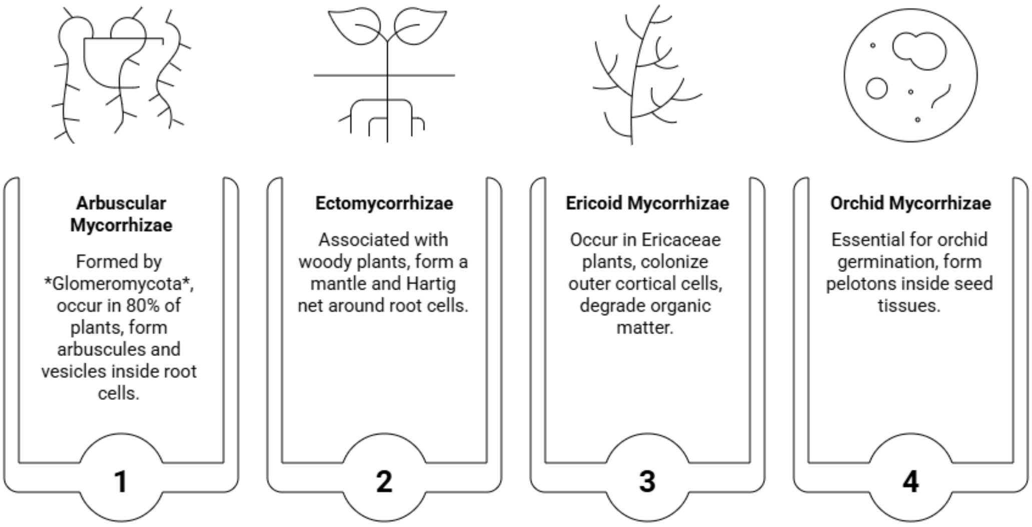

Figure 2: Types of Mycorrhizae

2.1 Arbuscular Mycorrhizae (AM)

Arbuscular mycorrhizae (AM), also known as endomycorrhizae, are the most ancient and widespread form of mycorrhizal association. They are formed by fungi belonging to the phylum *Glomeromycota* and occur in nearly 80% of terrestrial plant species, including most agricultural crops, grasses, herbs, and tropical plants (Schüßler & Walker, 2011; Stürmer *et al.,* 2018).

The hallmark of AM fungi is the formation of highly branched structures called arbuscules inside the cortical cells of plant roots. These structures create an extensive interface for nutrient exchange between the plant and the fungus. AM fungi may also form **vesicles**, which function as storage organs for lipids and nutrients. The fungal hyphae extend outward into the surrounding soil, effectively increasing the absorptive surface area of the plant root system (Garg & Chandel, 2011; Cargill *et al.,* 2025). This extensive hyphal network enhances nutrient acquisition, especially phosphorus uptake, which is often limited in soil due to low mobility. AM fungi also improve plant access to micronutrients such as zinc and copper and increase water absorption under drought conditions. Because of their broad host range and ecological importance, AM fungi are widely used as biofertilizers in sustainable agricultural systems (Lanfranco *et al.,* 2016).

2.2 Ectomycorrhizae (ECM)

Ectomycorrhizae are predominantly associated with woody plant species, especially forest trees such as pines, oaks, birches, and eucalyptus. They are formed mainly by fungi from the *Basidiomycota* and *Ascomycota*. Unlike arbuscular mycorrhizae, ectomycorrhizal fungi do not penetrate the root cortical cells. Instead, they form a dense fungal sheath or mantle around the root surface and a network of hyphae called the Hartig net, which grows between root cortical cells. This arrangement allows efficient nutrient exchange while maintaining cellular integrity.

ECM fungi possess a strong capacity to access organic nutrient pools through the secretion of extracellular enzymes that break down complex organic compounds. This ability is particularly important in forest ecosystems where nutrients are often locked in organic matter. Ectomycorrhizae are therefore highly efficient in acquiring nitrogen and phosphorus from nutrient-poor forest soils (Pritsch & Garbaye, 2011).

These fungi also protect host roots from pathogens, enhance drought tolerance, and influence soil carbon storage, making them crucial components of forest ecosystem stability.

2.3 Ericoid Mycorrhizae

Ericoid mycorrhizae occur mainly in plants of the family Ericaceae, including heathers, blueberries, and cranberries. These plants are commonly found in acidic, infertile soils with high organic matter content. Ericoid fungi colonize the outer cortical cells of fine roots and enable plants to access nitrogen and phosphorus from complex organic substrates. They produce enzymes capable of degrading lignin-rich organic matter, giving host plants a competitive advantage in nutrient-poor environments (Liu, *et al.,* 2026).

2.4 Orchid Mycorrhizae

Orchid mycorrhizae are essential for the germination and development of orchid plants. Orchid seeds are extremely small and lack sufficient nutrient reserves. Consequently, they rely entirely on fungal symbionts for carbon and nutrient supply during early developmental stages. The fungal partner penetrates the seed tissues and forms coiled structures known as **pelotons**, through which nutrients are transferred to the developing embryo. Without this symbiotic interaction, orchid seeds fail to germinate in natural conditions (Dearnaley *et al.,* 2016; Wang *et al.,* 2024).

3. Ecological Roles of Mycorrhizae in Plant Communities

Mycorrhizae profoundly influence the composition, diversity, productivity, and resilience of plant communities. Their ecological roles extend from enhancing individual plant performance to regulating community-level interactions.

3.1 Enhancement of Plant Nutrition and Growth

One of the most fundamental functions of mycorrhizae is the improvement of plant nutrient acquisition and overall growth. The fungal hyphae extend far into the soil matrix beyond the rhizosphere, effectively increasing the absorptive surface area of plant roots. This enables plants to access water and essential nutrients from a much larger volume of soil than roots alone can explore. Phosphorus is the nutrient most significantly enhanced by mycorrhizal associations due to its low mobility and frequent fixation in soils (Bagyaraj *et al.,* 2015). Mycorrhizal fungi efficiently absorb phosphate ions and transport them directly to plant roots. In addition to phosphorus, these fungi facilitate the uptake of nitrogen, potassium, sulfur, and various micronutrients through their extensive hyphal networks (Wahab *et al.,* 2023).

As a result of improved nutrient acquisition, plants exhibit increased biomass production, enhanced root and shoot development, improved reproductive success, and greater survival under nutrient-deficient conditions. Thus, mycorrhizae play a crucial role in optimizing plant growth and productivity.

3.2 Influence on Plant Diversity

Mycorrhizal fungi play a crucial role in shaping plant diversity by influencing competitive interactions and resource distribution within plant communities. Plants associated with highly efficient mycorrhizal partners often gain enhanced access to nutrients and water, which can alter species dominance, abundance, and patterns of coexistence. This symbiotic advantage may help less competitive species persist alongside dominant ones, thereby supporting biodiversity (Hart *et al.,* 2003; Tedersoo *et al.,* 2020).

A key mechanism underlying this influence is the formation of common mycorrhizal networks (CMNs), which physically connect the roots of multiple plants through interconnected fungal hyphae. These underground networks facilitate the transfer of resources and information among plants. Through CMNs, carbon can be transferred from mature, photosynthetically active plants to young seedlings, nutrients can be redistributed across different individuals, and chemical signals related to stress or pathogen attack can be communicated (Ullah *et al.,* 2024). These interactions enhance seedling establishment, reduce competitive exclusion, and promote species coexistence, ultimately contributing to the maintenance and stability of plant community diversity (Figueiredo *et al.,* 2021; Karimi-Jashni & Yazdanpanah, 2023).

3.3 Community Stability and Stress Tolerance

Mycorrhizae play a vital role in enhancing community stability by improving plant tolerance to a wide range of abiotic stresses, including drought, salinity, heavy metal toxicity, and temperature extremes. Through their extensive hyphal networks, mycorrhizal fungi increase water absorption and help maintain cellular hydration during water-deficit conditions. They also regulate ion balance by controlling the uptake and distribution of essential and toxic ions, thereby protecting plants from salinity and metal stress (Wahab *et al.,* 2023).

In addition to abiotic stress tolerance, mycorrhizae provide protection against soil-borne pathogens through multiple mechanisms. They compete with harmful microbes for root colonization sites, thereby limiting pathogen entry. Furthermore, they induce systemic resistance in host plants by activating defense-related pathways and enhancing the production of protective compounds. Mycorrhizal fungi may also produce antimicrobial substances that directly inhibit pathogenic organisms. Collectively, these functions enhance plant health and resilience, reduce mortality under stress conditions, and contribute to the overall stability and sustainability of plant communities (Begum *et al.,* 2019).

3.4 Role in Ecological Succession

Mycorrhizae play a crucial role in ecological succession by facilitating the establishment and growth of both pioneer and late-successional plant species. In disturbed, degraded, or nutrient-poor soils, mycorrhizal fungi enhance nutrient availability, particularly phosphorus and nitrogen, and improve water uptake, thereby increasing plant survival and establishment success. Their presence accelerates vegetation recovery by promoting early colonization and supporting the gradual development of complex plant communities (Liu & Zhao, 2023).

As succession progresses, different types of mycorrhizal associations help sustain plant diversity and ecosystem functioning by improving nutrient cycling and soil structure. These fungi also contribute to the stabilization of soil aggregates and the development of a healthy rhizosphere, which is essential for long-term ecosystem restoration. This role is particularly significant in reforestation programs, mine spoil reclamation, grassland restoration, and wetland rehabilitation, where mycorrhizae act as key biological agents in restoring ecological balance and promoting sustainable ecosystem development (Owiny & Dusengemungu, 2024).

3.5 Soil Structure Improvement

Mycorrhizal fungi play a significant role in improving soil structure through both physical and biochemical mechanisms. Their extensive hyphal networks bind soil particles together, creating stable aggregates that enhance soil integrity. Additionally, these fungi secrete glomalin, a sticky glycoprotein that acts as a natural "soil glue," further stabilizing aggregates and improving soil cohesion over time.

Improved soil aggregation leads to better soil aeration, allowing roots and soil organisms to access sufficient oxygen for metabolic activities. It also enhances water infiltration and retention, reducing surface runoff and improving moisture availability for plants. Furthermore, well-structured soil facilitates deeper root penetration, enabling plants to explore larger soil volumes for nutrients and water. Increased aggregate stability also provides resistance to soil erosion caused by wind and water. Overall, mycorrhizae contribute to the development of a healthy soil environment that supports plant growth, microbial activity, and long-term ecosystem sustainability (Fan *et al.,* 2022).

4. Role of Mycorrhizae in Nutrient Cycling

Mycorrhizae are integral to nutrient cycling in terrestrial ecosystems, particularly in the cycling of phosphorus, nitrogen, carbon, and micronutrients.

4.1 Phosphorus Cycling

Phosphorus is an essential macronutrient required for key plant metabolic processes such as energy transfer (ATP), nucleic acid synthesis, and membrane formation. However, its availability in soil is often limited because it readily forms insoluble complexes with calcium, iron, and aluminum (Malhotra *et al.,* 2018). Mycorrhizal fungi play a crucial role in enhancing phosphorus availability by mobilizing it through several mechanisms, including the excretion of organic acids that solubilize bound phosphorus, production of phosphatase enzymes that release phosphate from organic compounds, and extensive hyphal networks that explore phosphorus-rich microsites beyond root zones. This symbiotic association significantly improves phosphorus uptake and reduces nutrient limitation in terrestrial ecosystems (Rawat *et al.,* 2021; Tian *et al.,* 2021).

4.2 Nitrogen Cycling

Mycorrhizal fungi play a vital role in nitrogen cycling by facilitating the uptake of nitrogen from both organic and inorganic sources present in the soil. Ectomycorrhizal fungi, in particular, are highly efficient as they produce extracellular enzymes capable of breaking down complex organic compounds such as proteins and amino acids in litter and soil organic matter. This enzymatic activity releases usable forms of nitrogen, which are then absorbed and transferred to host plants. Additionally, their extensive hyphal networks enhance nitrogen exploration beyond the root zone. Thus, mycorrhizae effectively connect decomposition processes with plant nutrient uptake, improving nitrogen availability and overall ecosystem productivity (Shah *et al.,* 2026).

4.3 Carbon Cycling

Mycorrhizal fungi play a significant role in carbon cycling by acting as a bridge between plants and soil systems. Plants allocate a substantial portion of their photosynthetically derived carbon (photosynthates) to mycorrhizal partners, transferring it belowground through root-fungal associations (Shah *et al.,* 2026). This carbon fuels fungal growth, metabolism, and the expansion of hyphal networks, which in turn contribute to the formation and stabilization of soil organic matter. Mycorrhizae influence carbon dynamics by enhancing carbon sequestration in soils, promoting the stabilization of soil organic carbon through the formation of aggregates, and regulating microbial respiration rates (Finlay & Söderström, 1992). Consequently, they are crucial in maintaining the terrestrial carbon balance and mitigating climate change effects.

4.4 Micronutrient Cycling

Mycorrhizal fungi enhance the uptake of micronutrients such as Zinc, Copper, Iron, Manganese. Mycorrhizal fungi play a crucial role in the cycling and uptake of essential micronutrients in plant-soil systems. They significantly enhance the absorption of micronutrients such as zinc, copper, iron, and manganese, which are often present in low concentrations or in forms not readily available to plants (Kumar *et al.,* 2016). Through their extensive hyphal networks, mycorrhizae explore a larger volume of soil beyond the root zone, accessing nutrient-rich microsites that roots alone cannot reach. Additionally, these fungi release organic acids and chelating compounds that solubilize bound micronutrients, making them more accessible for plant uptake. These micronutrients are vital for various physiological and biochemical processes, including enzyme activation, chlorophyll synthesis, photosynthesis, and overall plant metabolism. By improving micronutrient acquisition, mycorrhizal associations contribute to enhanced plant growth, stress tolerance, and ecosystem productivity (Sathiyadash *et al.,* 2017).

5. Agricultural and Environmental Significance

The ecological functions of mycorrhizae have significant applications in both agriculture and environmental management, particularly in promoting sustainability and resource efficiency. These symbiotic associations enhance plant growth, improve soil health, and contribute to ecosystem stability. Their ability to facilitate nutrient cycling, water uptake, and soil structure makes them valuable tools in modern agroecosystems and restoration practices.

5.1 Sustainable Agriculture

Mycorrhizal inoculation is increasingly recognized as an eco-friendly approach to improving nutrient use efficiency in crops, thereby reducing reliance on chemical fertilizers. By enhancing the uptake of essential nutrients such as phosphorus and micronutrients, mycorrhizae support better plant growth and development (Fan *et al.,* 2022). The benefits include higher crop productivity, improved drought tolerance due to enhanced water absorption, better soil fertility through increased microbial activity, and reduced fertilizer input, which lowers production costs and environmental pollution. Overall, the use of mycorrhizae contributes to the development of sustainable and resilient farming systems.

5.2 Ecosystem Restoration

Mycorrhizae play a vital role in ecosystem restoration by enhancing the establishment, survival, and growth of native plant species in degraded and disturbed habitats. In soils that are nutrient-poor, eroded, or biologically depleted, mycorrhizal associations help plants overcome stress by improving nutrient and water uptake. Their extensive hyphal networks also contribute to soil aggregation and stabilization, reducing erosion and improving soil structure (Tedersoo *et al.,* 2020). Additionally, mycorrhizae support the re-establishment of beneficial soil microbial communities, thereby accelerating ecological succession. By strengthening plant resilience to environmental stresses such as drought, salinity, and heavy metal toxicity, mycorrhizal fungi serve as effective bio-tools for restoring degraded ecosystems and promoting long-term ecological balance.

5.3 Climate Change Mitigation

Mycorrhizae play an important role in climate change mitigation by enhancing soil carbon storage and improving plant resilience to environmental stress. Through their symbiotic association with plant roots, they facilitate the transfer of carbon from plants to the soil, where it is stored as stable organic matter (Nie *et al.,* 2024). This process contributes to long-term carbon sequestration, helping to reduce atmospheric carbon dioxide levels. Additionally, mycorrhizal fungi improve plant tolerance to stresses such as drought, temperature extremes, and nutrient limitations, enabling vegetation to survive and function under changing climatic conditions. Their role in maintaining soil structure and microbial activity further supports ecosystem stability (Wahab *et al.,* 2023). Thus, mycorrhizae contribute both to climate change adaptation and mitigation by strengthening ecosystem resilience and enhancing carbon cycling processes.

5.4 Bioremediation

Certain mycorrhizal fungi play a significant role in bioremediation by enhancing plant tolerance to toxic pollutants, particularly heavy metals such as lead, cadmium, and arsenic. These fungi form symbiotic associations with plant roots and help in immobilizing or sequestering harmful metals within their hyphal structures, thereby reducing their bioavailability and toxicity to the host plant (Boorboori & Zhang, 2022). Additionally, mycorrhizae can alter the chemical environment of the rhizosphere through the release of organic acids and other compounds, which aid in the detoxification or transformation of contaminants. This interaction supports phytoremediation processes, where plants, along with their associated microbes, are used to stabilize, extract, or degrade pollutants from contaminated soils (Dhalaria *et al.,* 2020).

Consequently, mycorrhizal fungi serve as effective and eco-friendly tools in restoring polluted environments and improving soil health.

6. Future Perspectives and Challenges

Despite the well-established importance of mycorrhizae in ecosystem functioning, several challenges limit their widespread application. Environmental variability, such as changes in soil type, temperature, moisture, and land-use practices, can significantly influence fungal performance and symbiotic efficiency. Additionally, the quality and effectiveness of commercial mycorrhizal inoculants are often inconsistent due to differences in strain selection, formulation, and storage conditions. Another major limitation is the lack of large-scale field applications and standardized protocols for their use in diverse agroecosystems. Furthermore, many molecular and physiological mechanisms underlying plant–mycorrhizal interactions are still not fully understood, particularly under stress conditions. Future research should focus on advancing molecular tools, improving inoculant technology, and developing region-specific application strategies. Integrating mycorrhizal management into agriculture, forestry, and ecological restoration programs will be essential for achieving sustainable and resilient ecosystems.

Conclusion

Mycorrhizae are indispensable to plant communities and ecosystem functioning. Their influence on nutrient acquisition, soil health, biodiversity, and nutrient cycling underscores their ecological and economic importance. As sustainable solutions are sought for agriculture, climate resilience, and ecosystem restoration, mycorrhizae offer immense promise as natural partners in achieving environmental sustainability.

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SUSTAINABLE AGRICULTURE: SOIL DYNAMICS, MICROBIAL INTERACTIONS, AND BIOTECHNOLOGICAL INNOVATIONS FOR FOOD SECURITY

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Abstract

Sustainable agriculture has emerged as a vital strategy to address the interconnected challenges of climate change, food security, and environmental sustainability. This chapter explores the multifaceted dimensions of sustainable agriculture, emphasizing the synergistic relationship between soil health, microbial ecosystems, and technological innovation. It provides a comprehensive overview of pedogenesis, highlighting the physical, chemical, and biological processes involved in soil formation and the essential role of organic matter in maintaining soil fertility and structure. The chapter further examines the complexity of soil biological systems, particularly the role of microorganisms in driving bio-geo-chemical cycles such as nitrogen and carbon cycling, which are fundamental to nutrient availability and ecosystem stability. Additionally, the significance of phytohormones in regulating plant growth, development, and stress responses is discussed in relation to soil health and environmental conditions.

A detailed analysis of phytopathology and plant disease management strategies is presented, focusing on the transition from conventional chemical-based approaches to sustainable alternatives, including biocides, biofertilizers, and integrated biological control methods. Furthermore, the chapter highlights recent advancements in agricultural biotechnology, particularly the application of Ti plasmids and genetic engineering techniques, which contribute to the development of stress-resistant and high-yielding crop varieties.

Overall, this work underscores the importance of integrating ecological principles with modern technological tools to develop resilient agricultural systems capable of ensuring long-term productivity, environmental conservation, and global food security

Keywords: Sustainable Agriculture; Soil Microbiology; Phytopathology; Biocides; Biofertilizers; Climate Resilience; Food Security.

Introduction

Sustainable agriculture has emerged as a comprehensive and adaptive framework designed to address the intertwined challenges of food security, environmental degradation, and socio-economic sustainability. In the context of rapid population growth and intensifying climate variability, agricultural systems are under unprecedented pressure to increase productivity while minimizing ecological footprints. This paradigm emphasizes the integration of ecological principles, resource-use efficiency, and technological innovations to maintain long-term agricultural productivity without compromising the health of natural ecosystems [1,2].

At the core of sustainable agriculture lies soil, a complex and dynamic natural resource that functions as the primary medium for plant growth. Soil acts as an interface where physical structure, chemical composition, and biological activity converge to regulate nutrient availability, water retention, and root development. It comprises approximately 45% mineral matter, 5% organic matter, and 50% pore space filled with water and air, forming a balanced system that sustains plant and microbial life. The maintenance of this balance is crucial, as even minor disruptions in soil composition can significantly impact crop productivity and ecosystem stability [1,3].

Soil fertility is governed by a combination of inherent properties and dynamic biological processes. Organic matter plays a pivotal role by improving soil structure, enhancing water-holding capacity, and serving as a reservoir of essential nutrients such as nitrogen, phosphorus, and sulfur. Additionally, soil microorganisms—including bacteria, fungi, actinomycetes, algae, and protozoa—form intricate ecological networks that drive nutrient cycling through processes like mineralization, immobilization, nitrogen fixation, and decomposition. These microbial communities not only sustain soil fertility but also contribute to plant health by producing growth-promoting substances and suppressing pathogens [4,5].

Nutrient cycling, particularly the nitrogen, carbon, and phosphorus cycles, is fundamental to sustainable agricultural systems. These biogeochemical cycles ensure the continuous transformation and availability of essential elements required for plant growth. For instance, nitrogen-fixing bacteria such as *Rhizobium* and *Azotobacter* convert atmospheric nitrogen into ammonia, making it accessible to plants, while decomposers recycle organic residues into simpler forms. Such processes highlight the importance of maintaining soil biodiversity to ensure efficient nutrient turnover and ecosystem resilience [5,6].

In recent decades, advancements in agricultural biotechnology have significantly contributed to sustainable practices. The development of biofertilizers and biopesticides has provided environmentally friendly alternatives to synthetic agrochemicals, reducing soil and water pollution while enhancing crop productivity. Genetic engineering techniques, including the use of Ti plasmids and gene transfer technologies, have enabled the development of transgenic crops with improved resistance to pests, diseases, and abiotic stresses such as drought and salinity. These innovations not only increase yield potential but also contribute to resource conservation and climate resilience [7,8].

Furthermore, sustainable agriculture promotes integrated disease and pest management strategies that combine biological, cultural, and minimal chemical approaches. The use of beneficial microorganisms, crop rotation, and resistant varieties helps reduce dependency on synthetic pesticides, thereby preserving environmental quality and biodiversity. Similarly, conservation practices such as reduced tillage, organic amendments, and water-efficient irrigation techniques enhance soil structure, reduce erosion, and improve long-term productivity [2,9].

The transition toward sustainable agricultural systems is essential for achieving global food security while addressing environmental challenges such as climate change, soil degradation, and biodiversity loss. By integrating soil science, microbial ecology, and modern biotechnology, sustainable agriculture offers a resilient and adaptive pathway for future food production systems. A deeper understanding of these interconnected processes is therefore critical for developing innovative strategies that ensure agricultural sustainability and ecological balance [1,10].

2. Soil Formation and Pedogenesis

Soil formation, or paedogenesis, is a continuous and complex process through which parent rock material is transformed into a biologically active and fertile medium capable of supporting plant life. This transformation is governed by the interaction of five major factors: parent material, climate, organisms, topography, and time. Together, these factors influence the physical disintegration of rocks, chemical alterations, and biological enrichment that ultimately lead to soil development [1,3].

Pedogenesis involves a series of interrelated processes such as weathering, mineralization, humification, and the formation of organo-mineral complexes. These processes not only determine soil texture and structure but also regulate nutrient availability and microbial activity. The efficiency of these transformations directly impacts agricultural productivity and ecosystem sustainability [2,4].

2.1 Processes of Soil Formation

Table 1: Major Processes Involved in Soil Formation

Process	Description	Significance in Agriculture
(a) Weathering	Breakdown of rocks into smaller particles through physical (temperature, wind, water), chemical (oxidation, hydrolysis, carbonation), and biological (microorganisms, lichens) processes	Initiates soil formation and releases essential minerals
(b) Mineralization	Conversion of organic matter into inorganic nutrients such as nitrates and phosphates	Makes nutrients available for plant uptake
(c) Humification	Formation of stable organic matter (humus) from decomposed plant and animal residues	Improves soil fertility, structure, and water retention
(d) Organo-mineral Complex Formation	Interaction between clay minerals and organic matter forming stable aggregates	Enhances nutrient holding capacity and soil stability

2.2 Factors Affecting Soil Formation

Soil formation is controlled by multiple environmental and biological factors that interact over time:

Table 2: Factors Influencing Pedogenesis

Factor	**Role in Soil Formation**
Parent Material	Determines initial mineral composition and texture
Climate	Influences weathering rate, moisture availability, and temperature
Organisms	Includes plants, microbes, and animals contributing to organic matter and nutrient cycling
Topography	Affects drainage, erosion, and soil depth
Time	Determines the maturity and profile development of soil

2.3 Soil Profile Development

Soil profile development is a fundamental outcome of pedogenesis, reflecting the long-term interaction of physical, chemical, and biological processes acting upon parent material. As soil evolves, it differentiates into a series of distinct horizontal layers known as soil horizons, each characterized by unique morphological, physical, chemical, and biological properties. These horizons collectively form the soil profile, which serves as a vertical record of soil-forming processes and plays a crucial role in determining soil fertility, water dynamics, and plant growth potential [1,2].

The development of soil horizons occurs through processes such as eluviation (removal of materials like clay, iron, and organic compounds from upper layers) and illuviation (accumulation of these materials in lower layers). Over time, these translocations lead to the formation of well-defined layers that differ in color, texture, structure, porosity, and nutrient content. The extent of horizon development depends on environmental factors such as climate, vegetation, topography, and time, with mature soils exhibiting more pronounced and differentiated horizons compared to young soils [2,3].

2.3.1 Soil Horizons and Their Characteristics

A typical soil profile consists of five major horizons designated as O, A, B, C, and R. Each horizon contributes uniquely to soil functionality and plant growth.

Table 3: Soil Horizons and Their Properties

Horizon	**Description**	**Physical & Chemical Characteristics**	**Agricultural Significance**
O Horizon	Organic surface layer composed of decomposing plant and animal residues	High organic matter, dark color, loose structure, high microbial activity	Acts as a nutrient reservoir and supports microbial diversity
A Horizon (Topsoil)	Mineral layer enriched with humus	Granular structure, high fertility, moderate porosity, rich in nutrients	Primary zone for root growth, seed germination, and nutrient uptake

B Horizon (Subsoil)	Zone of accumulation (illuviation) of clay, iron, and minerals	Denser structure, lower organic matter, higher mineral content	Stores nutrients and water; supports deeper root systems
C Horizon	Partially weathered parent material	Coarse texture, low biological activity, minimal organic content	Acts as a source of minerals and influences soil texture
R Horizon	Unweathered bedrock	Hard, compact, no biological activity	Determines soil type and parent material characteristics

3. Soil Microbial Ecology and Functional Dynamics

Soil is not merely a physical substrate but a highly dynamic and complex biological system often referred to as a “living ecosystem.” It harbours an enormous diversity of microorganisms, including bacteria, fungi, actinomycetes, algae, protozoa, and nematodes, which collectively regulate essential ecological processes. These microorganisms play a pivotal role in organic matter decomposition, nutrient cycling, and the maintenance of soil fertility, making them indispensable for sustainable agriculture [1].

The soil microbial community forms an intricate network of interactions that governs the transformation of nutrients into plant-available forms. These biological processes are strongly influenced by environmental factors such as soil moisture, pH, temperature, and aeration, which determine microbial diversity, population dynamics, and functional efficiency.

3.1 Soil Microbial Diversity and Functions

Soil microorganisms contribute significantly to ecosystem functioning by performing specialized biochemical processes. Bacteria and fungi dominate soil biomass and are primarily responsible for the decomposition of organic residues, while actinomycetes degrade complex organic compounds such as cellulose and lignin.

Table 4: Major Soil Microorganisms and Their Functions

Microorganism	Role in Soil	Agricultural Importance
Bacteria	Decomposition, nitrogen fixation, nutrient cycling	Enhance soil fertility and plant growth
Fungi	Breakdown of organic matter, mycorrhizal associations	Improve nutrient and water uptake
Actinomycetes	Decomposition of resistant compounds	Contribute to humus formation
Algae & Cyanobacteria	Photosynthesis, nitrogen fixation	Improve soil organic content
Protozoa & Nematodes	Predation and regulation of microbes	Maintain microbial balance

3.2 Soil as a Biological Network

Soil functions as a natural "biological laboratory" where diverse microorganisms interact continuously to sustain essential ecosystem processes. The dynamics of microbial populations are regulated through complex relationships such as predator–prey interactions, competition for nutrients, and various forms of symbiosis. Within this system, cyanobacteria play a crucial role in nitrogen fixation by converting atmospheric nitrogen into plant-available forms, while Pseudomonas species enhance soil fertility through phosphate solubilisation, making otherwise unavailable phosphorus accessible to plants. Additionally, actinomycetes contribute significantly to the decomposition of organic residues through their filamentous growth, breaking down complex compounds into simpler nutrients. Collectively, these microbial interactions ensure efficient nutrient recycling, maintain soil health, and support sustainable agricultural productivity

3.3 Microbial Interactions in Soil

Microbial ecology is defined by a range of interactions that determine soil stability and productivity:

Table 5: Types of Microbial Interactions

Interaction Type	Description	Example
Mutualism	Both organisms benefit	Rhizobium-legume symbiosis
Commensalism	One benefits, other unaffected	Soil bacteria using plant exudates
Synergism	Cooperative interaction	Microbial consortia in decomposition
Competition	Organisms compete for resources	Nutrient competition among microbes
Antibiosis	Production of inhibitory substances	Antibiotic production by fungi
Parasitism	One benefits, other harmed	Pathogenic microbes

These interactions regulate microbial population dynamics and maintain ecological balance within the soil system.

4. Chemical Messengers and Plant Growth Regulation

Plant growth and development are controlled by chemical regulators known as phytohormones, which are synthesized in small quantities but exert profound physiological effects.

4.1 Types of Phytohormones and Functions

Table 6: Major Phytohormones and Their Roles

Hormone	Function	Agricultural Significance
Auxins	Cell elongation, apical dominance	Root development
Gibberellins	Stem elongation, seed germination	Crop growth enhancement
Cytokinins	Cell division, delay senescence	Improved yield
Ethylene	Fruit ripening	Post-harvest management
Abscisic Acid	Stress response, stomatal closure	Drought resistance

The activity of these hormones is closely linked with soil conditions, particularly nutrient availability and microbial activity, highlighting the interdependence between soil biology and plant physiology.

5. Nutrient Cycling in Soil Ecosystems

Nutrient cycling is a cornerstone of sustainable agriculture, ensuring the continuous availability of essential elements required for plant growth.

5.1 Nitrogen Cycle

The nitrogen cycle involves several microbial processes that convert atmospheric nitrogen into biologically usable forms.

Table 7: Steps in Nitrogen Cycle

Process	Description	Role
Nitrogen Fixation	Conversion of N_2 to ammonia	Makes nitrogen available
Nitrification	Conversion of ammonia to nitrates	Plant uptake
Assimilation	Incorporation into plant tissues	Growth and metabolism
Denitrification	Conversion back to N_2	Maintains balance

5.2 Carbon and Other Cycles

In addition to the nitrogen cycle, other biogeochemical cycles such as carbon, phosphorus, and sulfur play equally vital roles in sustaining soil fertility and ecosystem functioning. The carbon cycle regulates atmospheric CO_2 levels and drives energy flow through processes like photosynthesis and respiration, thereby influencing global climate and productivity. The phosphorus cycle is essential for cellular functions, as it supports the synthesis of ATP, nucleic acids, and phospholipids, although its availability largely depends on the weathering of rocks and microbial activity. Similarly, the sulfur cycle contributes to the formation of essential amino acids and proteins, playing a key role in plant metabolism and growth. Together, these interconnected cycles operate in a coordinated manner to ensure continuous nutrient availability, maintain ecological balance, and support sustainable agricultural systems.

6. Phytopathology and Disease Management

Phytopathology deals with plant diseases caused by pathogens such as fungi, bacteria, viruses, and nematodes. These diseases can significantly reduce crop yield and quality.

6.1 Types of Plant Disease Symptoms

Plant diseases manifest through a variety of visible and physiological symptoms that reflect disruptions in normal plant growth and metabolism. Among the most common symptoms, necrosis refers to the death of plant tissues, often appearing as dark, dry lesions caused by pathogen infection or toxin production. Chlorosis is characterized by the yellowing of leaves due to the loss or degradation of chlorophyll, typically resulting from nutrient deficiencies or pathogenic interference with photosynthesis. Hypertrophy involves abnormal enlargement or overgrowth of plant tissues or cells, often induced by pathogens that alter hormonal balance, leading to structures such as galls or tumors. In contrast, hypoplasia denotes reduced growth or underdevelopment of plant tissues, resulting in stunted growth due to limited cell division or elongation. Collectively, these symptoms serve as key diagnostic indicators in phytopathology, helping to identify disease causes and assess their impact on plant health and agricultural productivity

6.2 Methods of Disease Control

Table 8: Plant Disease Control Strategies

Method	Approach	Examples
Physical	Heat, radiation	Hot water treatment
Chemical	Fungicides, antibiotics	Bordeaux mixture
Biological	Beneficial microbes	Pseudomonas, Streptomyces

7. Eco-Friendly Agricultural Inputs

Eco-friendly agricultural inputs are central to sustainable farming systems, as they minimize environmental impact while maintaining crop productivity and soil health. These inputs rely on natural biological processes and renewable resources to enhance nutrient availability, control pests, and improve overall ecosystem balance. By reducing dependence on synthetic chemicals, they contribute to long-term soil fertility, biodiversity conservation, and safer food production systems.

7.1 Biocides

Biocides offer an environmentally safe alternative to conventional chemical pesticides by utilizing naturally occurring microorganisms and plant-derived compounds for pest and disease control. Microbial agents such as *Bacillus thuringiensis* (Bt) act by disrupting the digestive systems of insect pests, leading to their effective control without harming non-target organisms. Similarly, botanical extracts like neem contain bioactive compounds that function as repellents, growth regulators, and feeding inhibitors for a wide range of pests. These eco-friendly approaches not only reduce chemical residues in the environment but also minimize the risk of pest resistance development, thereby supporting sustainable crop protection strategies.

7.2 Bio Fertilizers

Bio fertilizers are living microbial inoculants that enhance soil fertility by increasing the availability of essential nutrients through natural biological processes. Key microorganisms involved include Rhizobium, which forms symbiotic associations with leguminous plants to fix atmospheric nitrogen; Azospirillum, which promotes plant growth and nitrogen fixation in non-leguminous crops; and Cyanobacteria, which contribute to nitrogen enrichment in aquatic and paddy field ecosystems. These beneficial microbes improve nutrient uptake, stimulate plant growth through the production of growth-promoting substances, and enhance soil structure. As a result, bio fertilizers provide a sustainable and cost-effective alternative to chemical fertilizers while maintaining ecological balance.

8. Biotechnology in Agriculture

Modern biotechnology has significantly transformed agricultural practices by introducing advanced techniques that improve crop productivity, resilience, and sustainability. Genetic engineering enables the transfer of desirable traits into plants using tools such as Ti plasmids, which act as vectors for gene insertion. This has led to the development of transgenic crops with enhanced resistance to pests, diseases, and environmental stresses such as drought and salinity. Additionally, the transfer of nitrogen-fixing genes into non-leguminous crops represents a promising approach to reducing dependence on synthetic fertilizers. These biotechnological innovations not only increase agricultural efficiency but also support environmentally sustainable farming systems by optimizing resource utilization and minimizing ecological damage.

Conclusion

The integration of soil microbial ecology, nutrient cycling, plant physiological processes, and biotechnological advancements forms the foundation of sustainable agriculture. A comprehensive understanding of these interconnected systems enables the development of resilient agricultural practices that enhance productivity while preserving environmental integrity. By adopting eco-friendly inputs and innovative technologies, it is possible to achieve long-term soil health, improved crop performance, and global food security. Sustainable agriculture thus represents a balanced approach that aligns agricultural development with ecological conservation and future sustainability goals.

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CLIMATE SMART AGRICULTURE FOR SUSTAINABLE FOOD SECURITY: A REVIEW

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Abstract

Alternate climate poses an enormous danger to global food protection and the sustainability of agriculture. This case calls for innovative farming techniques that can improve resilience lower green-residence gas emissions, and assist meals protection dreams. Climate Smart Agriculture (CSA) is diagnosed as a proactive method to tack-ling problems associated to climate change and food safety via improving resilience, lowering greenhouse gas emissions, and aiding the united States's development and meals protection [1]. Sustainable food manufacturing is turning into vital, and a shift from conventional practices to extra responsible options aiming to generate nutritious, safe, and on hand meals while minimizing environmental affects is crucial. This review examines the interconnections among agriculture, food protection, and sustainability, that specialize in current demanding situations, improvements, and techniques to cope with those critical troubles. It discusses the significance of sustainable meals manufacturing technology in assembly worldwide food call for while addressing problems concerning weather exchange. Some of the key technology encompass precision agriculture, hydroponics, aquaponics and vertical farming. Precision agriculture makes use of era to decorate farming efficiency by using accumulating facts on soil and water versions and optimizing practices like planting, fertilization, and irrigation. Climate Smart Agriculture (CSA), a comprehensive method geared toward improving agricultural performance and sustainability at the same time as addressing the demanding situations of climate trade. It examines the financial benefits of CSA for adopters in comparison to standard farming strategies and assesses CSA's function in mitigating climate trade, adapting to its effects, and enhancing food protection.

Keywords: Climate Change, Sustainable Agricultural Practices, Resilience, Food Security, Sustainable Food Manufacturing, Progressive Techniques.

Introduction

Agriculture has been a cornerstone of human civilization, supplying the critical meals, fibre, and assets for survival, economic development, and societal advancement. As the worldwide population is projected to attain nearly 10 billion by 2050, making sure meals protection—the supply, accessibility, usage, and balance of the meals supply, has turn out to be one of the most pressing challenges of our time [2]. The complicated courting among agriculture and food safety underscores the significance of sustainable agricultural practices that beautify productiveness, conserve herbal resources, and protect ecosystems. But contemporary agriculture faces multifaceted challenges, such as climate exchange, land degradation, water scarcity, and socioeconomic inequalities, which together threaten its capability to satisfy the developing global call for food [3].

In the mid-20th century, India confronted excessive food shortages and depended notably on imports. The Green Revolution (1960–1970s) introduced high-yielding variety (HYV) seeds, improved irrigation infrastructure, and chemical fertilizers. This transformation led to significant increases in wheat and rice production, making India self-sufficient in food grains. By 1978, wheat production increased from 12 million tons (1965) to over 36 million tons [4]. But the Green Revolution additionally had environmental results, such as soil degradation and groundwater depletion, and difficult long-term sustainability. this example illustrates how agricultural advancements can enhance food protection but ought to be balanced with sustainability concerns. Ethiopia skilled one of the deadliest famines (1983–1985) in history, due to extended drought and political instability. Agriculture in Ethiopia was closely rain-fed, leaving it pretty prone to weather variability. Crop disasters and cattle losses led to extensive starvation, with over four hundred deaths [5]. This tragedy underscored the significance of constructing climate-resilient agricultural systems, which include irrigation, drought-resistant crops, and early caution systems, to shield food security. The case highlights how agriculture's vulnerability to environmental factors immediately affects meals protection in weather-sensitive regions. No matter its confined land place, the Netherlands has become an international leader in agricultural exports through precision farming technologies. improvements such as greenhouse farming, automatic irrigation, and information-driven crop management have enabled farmers to maximise yields at the same time as minimizing useful resource use. For instance, Dutch farmers use 90% less water for growing greens than worldwide averages [6]. This situation demonstrates how generation-pushed agricultural structures can beautify productivity and sustainability, contributing to food safety globally.

In spite of development, sizeable demanding situations persist. climate change remains a tremendous hazard to food security, with excessive weather activities disrupting agricultural productiveness and supply chains [7,8,9]. Regulatory frameworks should evolve to trade climate-resilient farming practices and adaptive control strategies. The developing global populace and transferring nutritional choices additionally stress agricultural systems, necessitating non-stop innovation and coverage advancements. Technological developments, such as biotechnology and digital agriculture, offer promising answers and introduce regulatory complexities. Genetically Modified Organisms (GMOs) and precision farming technologies can decorate productiveness and useful resource efficiency [10]. But their adoption requires strong regulatory mechanisms to cope with protection worries and public perceptions. Bridging the regulatory gaps among developed and developing nations is equally important. Capacity-constructing tasks, along with technical training and financial assist, can empower growing countries to implement and put into effect powerful guidelines, contributing to worldwide food security [11].

Demanding Situations Dealing with Agriculture and Food Protection

Climate change is one of the maximum good-sized threats to worldwide food protection and sustainability within the 21st century [12,13,14]. As global temperatures push upward, weather styles shift, and severe weather occasions grow to be greater common, the complex balance of agricultural systems is more and more disrupted, with profound implications for worldwide meals systems and environmental sustainability. Weather modifications, precipitation patterns, and the frequency of severe climate activities, along with droughts and floods, without delay affect crop yields and farm animals' productivity. For example, research have proven that a 2°C affluent in global temperatures may want to lessen the yields of main crops like wheat, rice, and maize by up to 25% in a few regions [14, 15,16]. Additionally, growing sea degrees and elevated salinization of coastal soils pose risks to agricultural lands, in particular in low-mendacity regions [49]. Agriculture is liable to climate versions. Rising temperatures and modifications in precipitation patterns at once have an effect on crop yields, farm animals health, and soil fertility. Extended droughts, extreme heatwaves, and flooding can lessen agricultural productiveness by way of detrimental crops, disrupting planting schedules, and increasing pest and disorder outbreaks. As an instance, staple plants like wheat, rice, and maize, the backbone of the worldwide food deliver, are specifically liable to warmness pressure, leading to reduced yields and accelerated manufacturing expenses.

Furthermore, transferring climate zones force farmers to adapt through altering cropping styles or relocating agricultural activities, which won't continually be viable. Weather exchange exacerbates food lack of confidence by means of disrupting the provision, accessibility, and affordability of meals. Reduced crop yields and farm animals' productiveness growth food fees, disproportionately affecting low-profits populations. Extreme climate occasions like hurricanes and floods similarly strain food supply chains by means of detrimental infrastructure and disrupting transportation networks. Regions already grappling with food insecurity, along with sub-Saharan Africa and South Asia, are in particular liable to these effects. Similarly, climate-brought about displacement of communities can cause multiplied competition for resources, further exacerbating food shortage in affected regions [17]. Sustainability in agriculture hinges at the green use of herbal resources, environmental stewardship, and resilience to external shocks. Climate trade undermines those ideas with the aid of accelerating soil degradation, depleting water sources, and threatening biodiversity. For example, unpredictable rainfall patterns and extended droughts expend freshwater substances, intensifying opposition for water between agricultural, commercial, and domestic makes use of. In addition, the lack of biodiversity because of habitat destruction and changing ecosystems weakens herbal procedures, along with pollination and pest control, that are important for sustainable farming systems. Mitigating the effect of weather change on agriculture, food safety, and sustainability calls for a multi-faceted approach [18], along with:

- **CSA:** Practices that increase resilience, consisting of agroforestry, conservation agriculture, and precision farming, can facilitate farmer's variation to converting environments at the same time as lowering greenhouse gasoline emissions.
- **Financing in Research and Innovation:** It's miles important to foster climate-resilient crop sorts, enhance irrigation competence, and innovate virtual technology for weather observing and early alert systems.
- **Policy Reinforces:** Governments and worldwide worries have to highlight policies that boost sustainable land and water control, incentivize renewable strength use in agriculture, and offer financial and technological cooperation to farmers.
- **Global Alliance:** Directing climate change's effect on agriculture expects shared action, such as worldwide agreements, information sharing, and financing for adjustment and mitigation proposals in exposed regions.

Climate trade, food security, and sustainability confront the mission of pressing and groundbreaking resolutions via deciding on resilience, sustainability, and fairness in agricultural tactics, humankind can safeguard food safety for imminent generations at the same time as dismissing agriculture's ecological trajectory. Directing on weather exchange in agriculture is an responsibility for persistence and an opening to generate an extra sustainable and rightful global food system.

Principles of Climate Smart Agriculture

Climate Change Mitigation and Adaptation

Mitigation is action to lessen greenhouse gas emissions and restrict the quantity of warming our planet will revel in. *Adaptation* is action to help people adjust to the current and future effects of climate change.

- **Mitigation Centres on the Basis Reason of Weather Trade:** the warmth-trapping greenhouse gases humans are adding to the atmosphere faster than our planet can soak up them. those may be addressed by way of decreasing the assets of greenhouse gasoline emissions, or improving "sinks" of greenhouse gases that dispose of them from the atmosphere.
- **Reducing Resources**: Nearly three-quarters of humans'' greenhouse gas emissions come from burning fossil fuels like coal, oil and natural fuel, so mitigation often specializes in changing those fuels with other resources of electricity, like renewables and nuclear power. Mitigation also can address other sources of greenhouse gases: protective forests from being reduce down, for example, or gathering methane from landfills.

- **Enhancing Sinks**: different kinds of mitigation, like developing new forests and designing and constructing "direct air capture" structures, paintings by taking greenhouse gases out of the environment every now and then known as "carbon removal". These procedures are difficult to do at a totally massive scale, and that they do no longer do away with the want to notably decrease our emissions. Still, government just like the Intergovernmental Panel on climate trade agree that a few carbon removals will be needed to head off the worst climate exchange situations.

The very last goal of mitigation is to prevent the buildup of greenhouse gases inside the atmosphere altogether, and start drawing them down. The Paris agreement of 2015 set worldwide objectives for mitigation, with nearly every us of a in the world agreeing to zero out their greenhouse gas emissions in time to halt global warming at no extra than 2° C, and ideally at no more than 1.5° C. Nowadays, however, mitigation is not on the right track to satisfy either of those desires. In reality, no matter formidable pledges and speedy progress in sectors like easy strength, greenhouse fuel emissions are nonetheless rising global.

Failure to mitigate climate alternate will simply make it greater vital to conform. So far, but, policymakers have not kept up with this urgent want. Most funding to deal with weather alternate international has been spent on mitigation, with simplest a small percentage given to variation. At the same time as all international locations will want to both mitigate and adapt to climate trade, a few have a long way extra resources to achieve this than others. without monetary and technological resource, low- and middle-profits international locations are not going to adapt quick sufficient to store their people from serious complication. A renewed commitment to mitigation and adaptation these days may be properly really worth the investment. The sooner the world stops the upward push of greenhouse gases, and shields people from the warming we have already prompted, the much less we will in the long run ought to spend to stabilize our weather, and the greater lives and livelihoods we will save along the way.

Food Security: Ensuring meals protection is crucial for ensuring that everybody has get right of entry to ok, secure, and nutritious meals that supports everyday activities and promotes typical health. Food safety can be finished through local production or by obtaining surplus meals from other regions (Ehrlich *et al.,* 1993). It accommodates four essential dimensions: availability, get entry to, food usage, and balance availability relates to the amount of food accessible inside country or region, including local production, imports, production, imports, food reserves, and useful resource.

- Access refers the physical, economic, and social way to be had to acquire meals.
- Food utilization entails consuming secure and nutritious meals that satisfies nutritional wishes.
- Balance significances the chronic availability, get admission to, and proper use of food through the years (Simon, 2012).

Furthermore, climate exchange gives great threats to all four dimensions, highlighting the need for included strategies that foster resilience and adaptableness inside food structures.

Improving Food Safety and Nutrition via the Adoption of CSA Practices

CSA is increasingly identified as an approach to relieve the influences of climate change on agriculture while fostering extra resilient groups and improving international food safety. Many of the most urgent development demanding situations of our time are the threats that weather alternate poses to food and nutrients security [19]. Climate change, coupled with structural and institutional challenges, exacerbates food insecurity, in particular in Sub-Saharan Africa and other growing areas. Shrinking agricultural land [20,21], declining soil fertility [22], a growing populace, low productiveness [23], and continual rural poverty avoid the development of sustainable agricultural practices. In those areas, growing drought frequencies, moving climate styles, and a heavy reliance on rain-fed agriculture have resulted in declining crop yields, decreased food availability, and economic instability for farming groups.

Moreover, weather trade has the capability to impact each the quality and availability of micronutrient-rich ingredients [24]. Variability in weather in a roundabout way influences meals safety and nutrients by way of diminishing food best, increasing costs, and disrupting distribution networks [25]. Expanded carbon dioxide concentrations are reducing the nutrient density in crops, especially important minerals and bioactive compounds. The shift in the direction of excessive-yielding, much less nutritious crop types, mixed with changing farming practices, further contributes to the decline in food exceptional. This worsening state of affairs exacerbates malnutrition and nutrient deficiencies, specifically among vulnerable populations in growing countries [26].

Addressing the consequences of weather exchange on meals protection and nutrition requires adopting CSA practices. Those practices bridge weather change model with meals manufacturing, supplying a course to stepped forward food protection [27]. In growing countries, wherein smallholder farmers face extensive challenges which includes limited land and weather alternate impacts, CSA offers a crucial possibility to decorate livelihoods [28]. Key CSA techniques include selling regenerative agriculture, crop diversification, biochar utility, and agroforestry, all of which improve soil fitness and reduce greenhouse gasoline emissions.

Soil fitness is important to crop nutrients, at once influencing each crop yield and nutrient content material. by using helping farmers with climate-resilient technologies and sustainable practices such as precision agriculture and regenerative agriculture technology, we are able to assist reverse declining meals nice trends. improved agricultural productiveness because of CSA also can raise household incomes, enhance self-sufficiency in meals production, and reinforce food safety. households that undertake CSA practices are much more likely to look progressed food consumption, greater nutritional range, and more desirable usual meals protection.

Climate exchange disrupts meals markets and threatens the food supply; but these dangers may be mitigated by means of enhancing farmers' adaptive capacity and enhancing aid use efficiency. An included technique to weather trade mitigation, related to nearby, national, and worldwide collaboration, is crucial. Governments and stakeholders should work collectively to strengthen weather risk control, lessen vulnerability, and construct resilience via complete monetary, social, and environmental techniques. As mentioned by [29], weather-resilient pathways need to focus on proof-based totally answers, strengthening local establishments, harmonizing agricultural and weather rules, and integrating climate and agricultural financing. This included technique sticks out by emphasizing adaptable and context-driven solutions supported by means of modern rules and financing mechanisms.

Conclusion

In conclusion, the interplay between agriculture, food security, and sustainability is significant to addressing the developing demanding situations of population boom, weather trade, and aid barriers. Integrating revolutionary technologies, which include genetic engineering, virtual agriculture, and water management systems, is similarly critical to optimizing useful resource use and mitigating risks. Achieving worldwide food security demands collaborative efforts among policymakers, researchers, and stakeholders to set up resilient meals' structures prioritizing equitable get admission to, monetary viability, and environmental stewardship. the agricultural sector can ensure long-term food security while maintaining the planet's ecological integrity by using balancing productiveness and sustainability

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LAC CULTURE: A MODEL FOR SUSTAINABLE AGRICULTURE IN INDIA

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1. Introduction

In recent decades, sustainable agriculture has transitioned from a peripheral concern to a central pillar of agricultural discourse in India, due to mounting ecological pressures, progressive depletion of soil fertility, and widening socio-economic inequities across rural landscapes. The intensification of conventional farming practices, often reliant on chemical inputs and monoculture systems, has compromised environmental integrity. It has also increased the vulnerability of farming communities to climatic uncertainties. In this context, the need for resilient, low-input, and ecologically attuned agricultural models has become both urgent and indispensable.

The National Education Policy 2020 (NEP-2020) further reinforces this paradigm shift by advocating the meaningful integration of indigenous knowledge systems with contemporary scientific understanding. It calls for pedagogical approaches that are not merely theoretical but grounded in experiential learning, local relevance, and sustainability-oriented innovation. Such a vision creates a fertile intellectual and practical space for the revival and scientific validation of traditional agro-ecological practices that have sustained communities for generations.

Within this evolving framework, lac culture assumes particular significance as a distinctive and time-honored agro-biological enterprise. It represents a rare confluence of entomology, forestry, and rural livelihood systems, functioning in close harmony with natural ecosystems. Unlike input-intensive agricultural models, lac cultivation is inherently adaptive and minimally intrusive, relying largely on the natural interaction between host trees and lac insects. This system not only supports biodiversity but also exemplifies a sustainable mode of resource utilisation that aligns seamlessly with the principles of ecological balance and circular economy.

Lac itself is a remarkable natural product—a resinous secretion produced by the scale insect *Kerria lacca,* which has been utilised in the Indian subcontinent for centuries. Historical references to lac can be traced to ancient Sanskrit texts, underscoring its long-standing cultural and economic relevance. In contrast to synthetic resins derived from petrochemical sources, lac is entirely biodegradable, non-toxic, and renewable, thereby positioning it as an environmentally superior alternative in an era increasingly defined by sustainability imperatives.

India continues to occupy a pre-eminent position in global lac production, contributing a substantial share to the international supply. More importantly, lac culture serves as a critical livelihood support system for millions of forest-dependent Tribal communities, smallholders, and marginal farmers. It offers a supplementary yet dependable source of income without necessitating extensive land modification or capital investment. As such, lac culture not only embodies ecological sustainability but also advances socio-economic inclusivity, making it a compelling model for sustainable agriculture in contemporary India (*Sharma & Ramani, 2008; Yogi et al., 2021*).

2. Biology of Lac Insect

Biology, Metamorphosis, and Life Cycle of the Lac Insect

The lac insect, *Kerria lacca*, represents a highly specialized form of scale insect within the order Hemiptera and family Kerriidae. Its biological organization reflects a remarkable degree of adaptation to a sedentary, plant-dependent mode of life. Unlike many free-living insects, it derives nourishment directly from the phloem sap of host plants and, in doing so, produces a natural resin that holds considerable ecological and economic significance. The intimate association between the insect and its host illustrates a finely balanced biological relationship shaped through long evolutionary refinement.

1. Taxonomic Lineage and Systematic Nomenclature

The lac insect, *Kerria lacca*, stands as a masterwork of evolutionary specialization within the order Hemiptera. Classified under the suborder Sternorrhyncha and the family Kerriidae, its taxonomic journey is rooted in the early observations of James Kerr (1782), who originally designated it *Coccus lacca*. Modern systematic understanding is largely built upon the foundational frameworks of Targioni-Tozzetti (1884) and the rigorous refinements of Varshney (1977). While it shares the superfamily Coccoidea with other scale insects, *Kerria lacca* is distinguished by its extreme commitment to a sedentary lifestyle and its unique biological capacity to synthesize and secrete a complex resinous covering. This secretion is the only known natural resin of animal origin recognized by science.

2. Morphological Architecture and Dimorphism

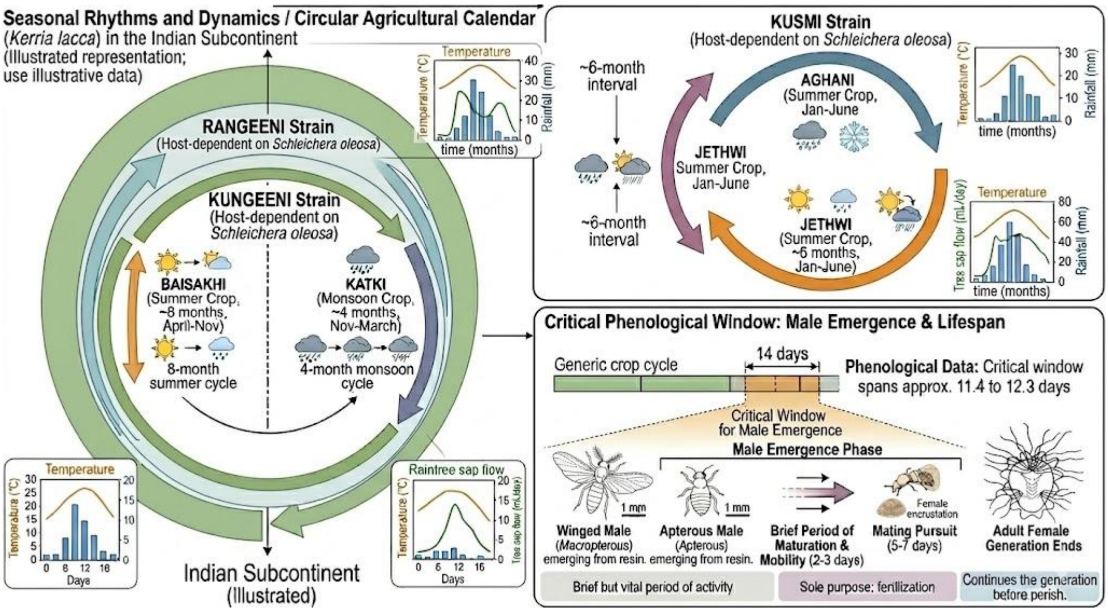
The physical appearance of *K. lacca* provides one of the most striking illustrations of sexual dimorphism in the arthropod kingdom. The adult female is a study in biological reductionism; she is a soft-bodied, globular, bag-like organism, measuring roughly 4.0 to 5.0 mm in length and 2.0 to 3.0 mm in width (Glover, 1937). Having traded locomotion for reproductive efficiency, she lacks wings, legs, and functional eyes, possessing only vestigial antennae. Female anatomy is dominated by a sophisticated stylet fiber bundle, an intricate feeding apparatus with a clypeolabral shield approximately 141 μm by 91.5 μm (Ahmad *et al.,* 2012), designed to tap into the host's lifeblood (phloem). In stark contrast, the adult male is a transient, delicate creature measuring just 1.2 to 1.5 mm. Whether winged (macropterous) or wingless (apterous), the male is equipped with sensory antennae and functional legs, yet entirely lacks mouthparts. His existence is a brief, non-feeding odyssey dedicated solely to the pursuit of fertilization (Mohanta *et al.,* 2014).

3. Metamorphic Transition and Ontogeny

The developmental journey of *K. lacca* follows a modified hemimetabolous trajectory, usually concluding a full generational cycle within 6 to 8 months. This process begins with the mass production of eggs, typically 200 to 500 per female, though favorable seasons may see this surge to 1,000 (Sharma *et al.,* 2015). Upon hatching, the "crawlers" or first-instar nymphs, minute, boat-shaped pioneers measuring about 0.6 mm by 0.25 mm, embark on the only mobile phase of their lives. For a fleeting window of 3 to 5 days, they navigate the host's topography to find succulent twigs. Once anchored, their transformation becomes more dramatic: females undergo three molts into a permanent sedentary form, while males progress through four stages, including a "pseudo-pupal" phase that mirrors complete metamorphosis. Throughout the 8 to 12-week nymphal period, these insects operate as tiny chemical factories, secreting a mixture of resins, wax, and dyes from dermal glands to construct their protective lac cells (Ramani, 2005).

4. Seasonal Rhythms and Crop Dynamics

The life of the lac insect depends upon climate and the host plant's internal rhythms. In the Indian subcontinent, two distinct biological strains, Kusmi and Rangeeni, dictate the agricultural calendar. The Rangeeni strain follows the sun and rain through the *Baisakhi* (8-month summer cycle) and *Katki* (4-month monsoon cycle). The Kusmi strain, primarily associated with the *Schleichera oleosa* tree, yields the *Aghani* and *Jethwi* crops over roughly 6-month intervals. Recent phenological data (Aditya & Ktalam, 2026) suggest that the critical window for male emergence spans approximately 11.4 to 12.3 days, a brief but vital period of activity that ensures the continuation of the generation before the males inevitably perish.



5. Ecological Associations and Geographical Footprint

While *Kerria lacca* is inherently polyphagous—documented on over 400 host species—its commercial and biological success is tethered to a select few "primary" hosts. Trees such as *Butea monosperma* (Palas), *Schleichera oleosa* (Kusum), and *Ziziphus mauritiana* (Ber) provide the optimal nutrient profile required for high-density resin production. This delicate insect-plant synergy is most vibrant across the tropical belt of India, particularly in Jharkhand, Chhattisgarh, Madhya Pradesh, and West Bengal. Contemporary research (2025–2026) emphasizes that the health of the host plant is the primary determinant of "colonization density," with the most robust female populations reaching concentrations of 8.40 to 11.60 cells/cm² on premier host twigs (Aditya & Ktalam, 2026; Sharma, 2017).

Biological Significance

From a broader perspective, the biology of the lac insect exemplifies an intricate and highly specialized form of insect–plant interaction. Its sedentary existence, protective resin secretion, and synchronized developmental cycle collectively represent a strategy finely tuned to maximize survival and reproductive success within a constrained ecological niche.

Moreover, the insect's ability to convert plant-derived nutrients into a durable, protective, and commercially valuable substance reflects a unique biological innovation. In doing so, it bridges the domains of ecology and economy, reinforcing its importance within sustainable agroforestry systems.

Host Plants and Distribution of Lac Insect

Lac insects exhibit a notable degree of host preference, though they are not strictly monophagous and may colonize a range of plant species under suitable ecological conditions. Nevertheless, successful lac cultivation depends upon a limited number of well-recognized host plants that provide optimal nutritional support and physiological compatibility for insect growth and resin production. Among the most economically significant hosts are *Butea monosperma* (Flame of the forest – Palas), *Acacia arabica* Willd (Babul), *Acacia catechu* Willd (Khair), *Cajanus cajan* (Linn.) Millsp. (Arhar; Tur.) , *Ficus benghalensis* Linn. Bar (Banyan tree), *Ficus cunia* Buch. Ham. Khunia; Jharphali, *Ficus lacor* Buch. Ham. Pilkhan, *Ficus racemosa* Linn. Gular, *Ficus religiosa* Linn. (Pipal), *Leea crispa* Linn. Bnn-Chalta, *Leea robusta* Roxb. Galeni. *Schleichera oleosa* (Lour.) Oken. (Kusum), *Ziziphus mauritiana* Lam. (Ber) and *Ziziphus xylopyra* Willd. – Ghont. These species have long been favored in traditional and scientific lac cultivation systems owing to their ability to sustain dense insect populations and yield high-quality resin.

The relationship between the lac insect and its host plant is both exclusive and functionally significant. The nutritional composition of the host, particularly the quality and flow of phloem sap, exerts a direct influence on insect development, survival, and resin secretion. Variations in host physiology can lead to apparent differences in both the quantity and physicochemical properties of the lac produced. For instance, certain hosts are associated with superior resin quality, characterized by desirable attributes such as color, hardness, and purity, while others may yield comparatively lower-grade material (Sharma, 2017). Consequently, the careful selection and management of host plants remain fundamental to achieving consistent productivity and commercial value.

Equally important is the natural abundance of suitable host trees within these landscapes, often occurring in forested or semi-forested environments. The coexistence of lac insects with these host species within such ecosystems facilitates a form of cultivation that is inherently aligned with ecological processes. Unlike conventional agricultural systems that rely heavily on land modification and external inputs, lac culture operates within the existing vegetative framework, thereby minimizing environmental disturbance.

When incorporated into agroforestry systems, lac cultivation assumes an even greater significance. By integrating lac host trees with crops, farmers can optimize land use, enhance overall productivity, and diversify income sources. Such systems contribute to soil conservation, improve microclimatic conditions, and support biodiversity by maintaining a varied landscape structure. Furthermore, lac culture offers a productive means of utilizing marginal and degraded lands that may be unsuitable for intensive cropping, thereby transforming otherwise underutilized resources into economically viable assets.

In this manner, the distribution and host associations of the lac insect not only determine the biological success of the species but also support the viability of lac cultivation as a sustainable and ecologically significant agricultural practice. The strategic management of host plants, combined with favorable environmental conditions, thus forms the cornerstone of efficient lac production and its long-term sustainability.

4. Lac Cultivation Practices

Lac Cultivation Practices

Lac cultivation represents a sophisticated synergy between human stewardship and natural biological processes, a practice rooted in the ancestral wisdom of forest-dependent tribal communities and further validated by modern scientific inquiry. Rather than being a purely mechanistic agricultural operation, lac culture represents a subtle and context-sensitive practice in which timing, ecological awareness, and careful observation are of supreme importance. Its continued relevance in contemporary agriculture lies in this very synthesis of indigenous wisdom and modern scientific understanding, which together enable a sustainable and resilient production system.

At the outset, the selection of appropriate host plants assumes critical importance, as the vitality and physiological condition of the host directly influence both insect establishment and resin yield. Preference is invariably given to healthy, mature, and disease-free trees exhibiting vigorous growth, as these provide a stable and nutritionally adequate substrate for the lac insect. This is followed by thoughtful pruning, carried out at carefully determined intervals with the specific aim of inducing the growth of tender, actively metabolizing shoots. Such shoots are particularly favorable for the settlement of lac insect crawlers owing to their enhanced phloem activity and nutrient availability (Sharma & Ramani, 2008). In this sense, pruning is not merely a mechanical intervention but a strategic measure designed to synchronize plant physiology with insect requirements.

The subsequent stage of inoculation constitutes the most delicate and decisive phase in the cultivation cycle. This process involves the intentional transfer of lac insects to prepared host plants through the use of brood lac, small segments of twigs bearing mature, gravid females nearing the culmination of their life cycle. These brood sticks are carefully affixed to freshly pruned branches, thereby enabling the newly emerged crawlers to disperse naturally and colonise suitable feeding sites. The success of inoculation is highly dependent upon precise timing, as it must coincide not only with the emergence of the crawler stage but also with the optimal physiological state of the host plant. Any deviation in timing may adversely affect settlement efficiency and subsequent yield (Sharma *et al.,* 2016).

Within the Indian context, lac cultivation is traditionally classified into two principal strains Kusmi and Rangeeni each distinguished by its ecological preferences, host associations, and qualitative attributes of the resin produced. The Kusmi strain, commonly reared on hosts such as *Schleichera oleosa*, is widely regarded for yielding lac of superior quality, typically characterised by a lighter hue and enhanced commercial value. Conversely, the Rangeeni strain, cultivated on hosts including *Butea monosperma* and *Ziziphus mauritiana*, exhibits greater ecological adaptability and resilience, albeit with some variation in resin quality (Sharma, 2017). The selection strains depend on environmental conditions and market considerations.

Effective crop management necessitates sustained vigilance and informed intervention, particularly with regard to the control of pests and predators. Lac insects are vulnerable to a range of natural enemies, including parasitic wasps belonging to families such as Encyrtidae and Eulophidae, as well as predatory lepidopteran larvae. These organisms, if left unchecked, may cause substantial damage to the insect populations and, consequently, to the resin yield. In response, cultivators adopt an integrated approach to pest management, combining traditional practices such as the removal of infested brood with more structured measures, including the use of protective netting and the conservation of ecological balance within the system (Sandeep, 2015; Mohanta *et al.,* 2014).

One of the most striking features of lac culture is its inherently low-input and environmentally compatible nature. Unlike many conventional agricultural systems, it does not rely much upon chemical fertilizers, synthetic pesticides, or intensive irrigation regimes. Instead, it operates largely within the parameters of natural ecological processes, drawing upon the intrinsic productivity of host plants and the adaptive capacity of the lac insect. This not only reduces production costs but also minimizes environmental impact, rendering lac cultivation particularly suitable for Tribals and marginal farmers and ecologically sensitive regions (Sharma & Ramani, 2008).

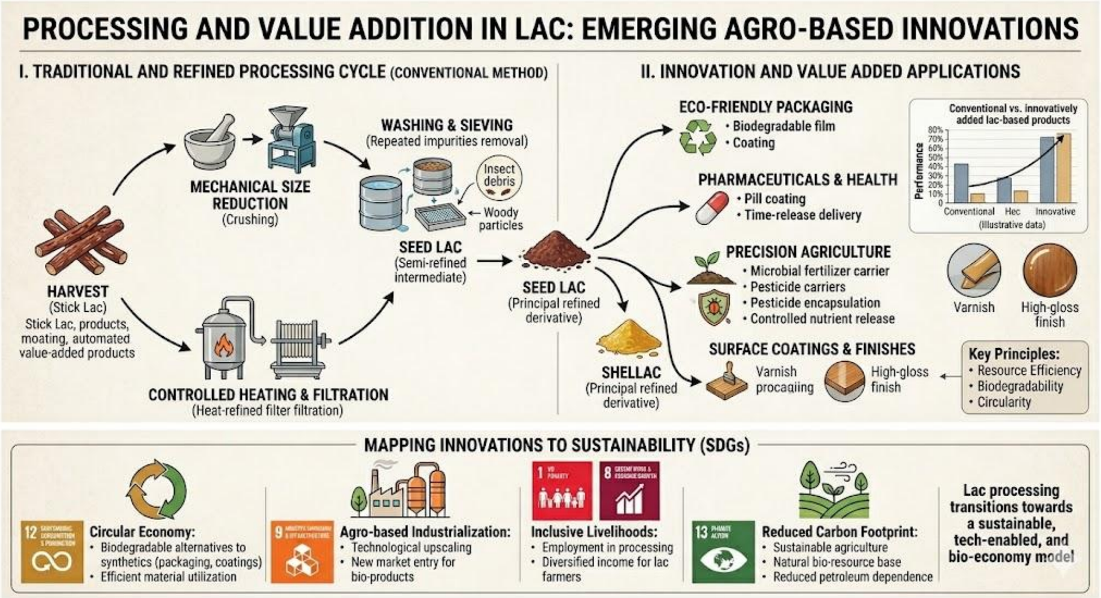
In essence, lac cultivation may be regarded as a model of harmonious coexistence between biological systems and human management. It demonstrates that economic productivity need not be achieved at the expense of ecological integrity. Rather, through informed and sensitive management, it is possible to derive sustained livelihoods while maintaining the health and resilience of the surrounding ecosystem. In this regard, lac culture offers a compelling example of sustainable agricultural practice, well aligned with contemporary environmental and developmental priorities.

5. Processing and Value Addition

Processing and Value Addition in Lac: Emerging Agro-Based Innovations

The transformation of raw lac into commercially valuable products represents a crucial stage in the overall lac value chain, wherein traditional practices are increasingly being complemented by scientific refinement and technological innovation. Following harvest, the resinous encrustation produced by lac insects, commonly referred to as stick lac, undergoes a sequence of carefully regulated processing operations aimed at improving both its purity and functional performance.

Conventionally, this process begins with mechanical size reduction, wherein the hardened encrustations are crushed into smaller fragments. This is followed by repeated washing and sieving to remove residual impurities, including insect debris, woody particles, and other extraneous matter. The material thus obtained, known as seed lac, constitutes a semi-refined intermediate. Further purification is achieved through controlled heating and filtration, ultimately yielding shellac, the principal and most widely utilized derivative of lac (Sharma & Ramani, 2008; Sen *et al.,* 2020).



Shellac occupies a distinctive niche among natural polymers, owing to its biodegradable nature, excellent film-forming ability, and inherent adhesive properties. These characteristics have long supported its use across a broad spectrum of industries, including surface finishing, electrical insulation, pharmaceutical coatings, and food glazing. In recent years, however, a growing global emphasis on sustainability has renewed interest in shellac as a viable alternative to petroleum-derived polymers. Within the domains of green chemistry and bio-based materials science, shellac is increasingly recognized for its potential to contribute to environmentally responsible manufacturing practices (Gandini, 2011; Thakur *et al.,* 2018).

Beyond its established applications, lac is now being re-evaluated through the lens of innovation, particularly in relation to agro-based value addition. Present-day research has begun to reposition lac as a versatile biomaterial with considerable promise in advanced technological applications. For example, shellac-based composites are currently under investigation for use in biodegradable packaging systems, where they offer a sustainable substitute for conventional plastic materials. Notably, shellac films have demonstrated favorable barrier properties against moisture and gaseous exchange, rendering them suitable for food preservation and controlled release packaging solutions (Siracusa *et al.,* 2008; Nair *et al.,* 2020). In the pharmaceutical sector, shellac has gained prominence as a naturally derived enteric coating material. Its pH-responsive solubility and biocompatibility make it particularly suitable for the formulation of controlled drug delivery systems, enabling the selective release of active compounds within targeted regions of the gastrointestinal tract. Such developments highlight the growing relevance of lac-derived materials within the expanding field of biomedical applications (Patel *et al.,* 2017).

In addition to shellac, the processing of lac yields two important products Lac dyes and Lac wax, each of which is attracting renewed scientific and commercial interest. Lac dye, derived from anthraquinone compounds, is increasingly being explored as a natural alternative to synthetic colorants in textiles, cosmetics, and food products. In light of tightening environmental regulations and consumer preference for non-toxic materials. Such natural pigments are gaining prominence for their biodegradability and reduced ecological footprint (Shahid *et al.,* 2013).

Lac wax, meanwhile, is emerging as a material of considerable industrial relevance. Traditionally utilised in polishes and finishing agents, it is now being investigated for applications in cosmetics, biodegradable coatings, and even bio-lubricants. Its physicochemical properties make it suitable for surface modification and protective formulations, thereby extending its utility into more advanced industrial domains (Yilmaz *et al.,* 2015).

From an agro-based innovation standpoint, the integration of lac processing with rural enterprise development offers significant opportunities for enhancing value chains and promoting sustainable livelihoods. The establishment of decentralised, small-scale processing units—supported by appropriate technological inputs—can generate employment, reduce post-harvest losses, and improve income stability among forest-dependent communities. Moreover, the diversification of lac-derived products, ranging from eco-friendly adhesives and coatings to bio-composites and functional materials, strengthens the economic resilience of lac cultivation while aligning with global sustainability objectives.

Emerging interdisciplinary research, particularly at the interface of materials science and green engineering, further underscores the future potential of lac-based polymers. Studies exploring nanocomposites, bio-resins, and functional coatings derived from lac suggest that this natural material may play an increasingly significant role within the evolving bioeconomy. Its renewable origin, coupled with its versatile chemical properties, positions lac as a promising candidate for next-generation biodegradable materials (Thakur *et al.,* 2018; Mohanty *et al.,* 2021).

In summary, the processing and value addition of lac have undergone a notable transformation—from largely artisanal practices to increasingly sophisticated, innovation-driven systems. This progression not only enhances the commercial value of lac but also situates it firmly within the broader discourse on sustainable materials and circular economic models. As research continues to expand its range of applications, lac is poised to emerge as a key bio-resource in the transition towards environmentally responsible industrial development.

6. Economic Importance

Economic Importance of Lac Culture

Lac culture occupies a position of considerable socio-economic importance within the rural and tribal landscapes of India, where it functions not merely as an auxiliary activity but, in many instances, as a vital livelihood strategy. Its inherently labor-intensive character renders it particularly well suited to regions where access to mechanized agriculture is limited, thereby facilitating the absorption of local labor and generating employment across multiple stages of production, processing, and marketing. In this respect, lac cultivation contributes meaningfully to income security among marginal farmers and forest-dependent communities, who often rely on seasonal and diversified sources of livelihood.

A defining strength of lac culture lies in its close compatibility with forest ecosystems and agroforestry practices. Unlike conventional agricultural enterprises that frequently necessitate extensive land transformation and external inputs, lac cultivation is conducted on standing host trees, thereby allowing communities to derive the economic benefits without compromising ecological integrity. This feature enables the diversification of income streams, particularly in regions where agricultural productivity is constrained by soil quality or climatic variability. Consequently, lac culture provides a resilient and adaptive livelihood option that aligns with both environmental sustainability and rural development objectives.

Estimates suggest that several million households across India are directly or indirectly engaged in lac-related activities, encompassing cultivation, primary processing, value addition, and trade. The economic significance of the sector is thus not confined to primary producers alone but extends across an interconnected value chain that supports traders, processors, artisans, and small-scale entrepreneurs (Yogi *et al.,* 2021). In this manner, lac culture contributes to the creation of a decentralized rural economy characterized by localized production and distributed economic benefits.

At the international level, lac and its derivatives occupy a distinctive niche in worldwide markets, primarily owing to their natural origin, biodegradability, and environmentally benign properties. With globally increasing environmental awareness and regulatory constraints on synthetic materials, products such as shellac, lac dye, and lac wax have seen increased demand across industries, including food processing, pharmaceuticals, cosmetics, and surface coatings. This growing preference for sustainable materials has enhanced the export potential of lac, positioning India as a key supplier within the global value chain.

Equally significant is the role of lac culture in supporting cottage and small-scale industries, particularly in rural and semi-urban settings. The relatively low capital requirements associated with lac processing and value addition make it accessible to small entrepreneurs, self-help groups, and cooperative societies. Such enterprises not only generate employment but also contribute to skill development, local capacity building, and economic empowerment. In many instances, lac-based industries serve as a foundation for women-led initiatives and community-driven enterprises, thereby fostering inclusive growth and social equity (Roy & Sharma, 2010; Jaiswal, 2015).

From a broader developmental perspective, lac culture strengthens the socio-economic fabric of rural communities by integrating economic activity with a deep-rooted care for the natural environment. It exemplifies a model of development in which resource use is both productive and sustainable, ensuring that economic gains are achieved without undermining environmental stability. As such, lac culture aligns closely with contemporary policy priorities centered on rural livelihoods, sustainable resource management, and inclusive economic growth.

In summary, the economic importance of lac culture extends beyond its immediate financial returns. It represents a multifaceted system that generates employment, supports rural industries, enhances export potential, and promotes environmentally responsible development. Its continued expansion and modernization hold considerable promise for strengthening the resilience and sustainability of India’s rural economy.

7. Lac Culture and Sustainable Agriculture

From the standpoint of sustainability, lac culture represents a remarkably balanced and ecologically attuned agricultural system, distinguished by its ability to reconcile economic productivity with environmental stewardship. Unlike many conventional agricultural practices that impose considerable strain on natural resources, lac cultivation operates in close harmony with existing ecosystems, thereby maintaining ecological integrity while simultaneously generating livelihood opportunities. This dual capacity renders it an exemplary model of sustainable agriculture, particularly within India's socio-ecological context.

A central attribute of lac culture is its contribution to biodiversity conservation. The system is intrinsically dependent upon the preservation of host tree species such as *Butea monosperma* and *Schleichera oleosa*, which form integral components of forest and agroforestry ecosystems. By incentivizing the protection and propagation of these species, lac cultivation indirectly sustains a wide range of associated flora and fauna. Furthermore, the presence of lac insects fosters intricate ecological interactions involving predators, parasitoids, and microbial communities, thereby reinforcing ecosystem stability and resilience (Sharma *et al.,* 2006; Mohanta *et al.,* 2014).

In the context of the United Nations Sustainable Development Goals (SDGs), this ecological dimension aligns closely with SDG 15: Life on Land, which emphasizes the conservation and sustainable use of terrestrial ecosystems. Lac culture, by promoting tree conservation and biodiversity, contributes meaningfully to this global objective.

The arboreal nature of lac cultivation also enhances its environmental value through carbon sequestration, as host trees function as long-term carbon sinks. By capturing atmospheric carbon dioxide and storing it in biomass, these trees contribute to the mitigation of climate change. This aspect is particularly significant in light of global efforts to reduce greenhouse gas emissions and transition towards climate-resilient agricultural systems (Nair *et al.,* 2010). Accordingly, lac culture directly supports SDG 13: Climate Action, highlighting its relevance in addressing one of the most pressing environmental challenges of our time.

Equally noteworthy is the manner in which lac culture embodies the principles of a circular economy, wherein resources are utilized efficiently, and waste generation is minimised. The system is largely dependent on renewable biological inputs and generates valuable by-products such as lac dye and lac wax, ensuring that minimal material is discarded. This efficient utilization of resources resonates with SDG 12: Responsible Consumption and Production, which advocates sustainable resource management and reduced environmental impact.

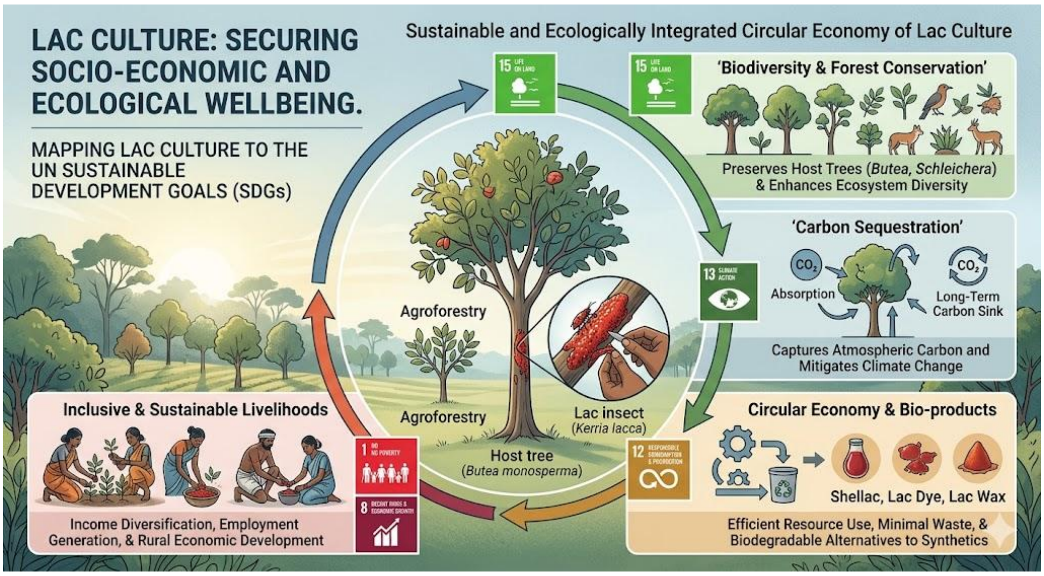
The integration of lac cultivation within agroforestry systems further strengthens its sustainability credentials. By combining host trees with agricultural crops, farmers can optimize land use, diversify income streams, and enhance ecological resilience. Such systems contribute to improved soil stability, reduced erosion, and better water retention, particularly in fragile and degraded landscapes. Moreover, the reduced reliance on synthetic inputs lowers the risk of environmental contamination, thereby safeguarding both ecosystem and human health. These attributes collectively align with SDG 2: Zero Hunger, through sustainable agricultural practices, and SDG 15: Life on Land, through ecosystem restoration.

From a socio-economic perspective, lac culture plays a significant role in promoting inclusive and sustainable livelihoods, particularly among tribal and marginal farming communities. Its labor-intensive nature generates employment across various stages of production and processing, while its compatibility with forest ecosystems allows for income generation without ecological degradation. This contribution is directly linked to SDG 1: No Poverty and SDG 8: Decent Work and Economic Growth, as it supports income diversification and rural economic development.

In a broader developmental sense, lac culture may be viewed as an exemplar of ecological intensification, wherein productivity is enhanced not through increased external inputs but through the intelligent management of natural processes. Its capacity to deliver multiple ecosystem services

including biodiversity conservation, carbon sequestration, soil stabilization, and livelihood support underscores its importance in advancing sustainable development objectives at both national and global levels.

In conclusion, lac culture embodies a holistic and integrative approach to agriculture that aligns closely with the United Nations Sustainable Development Goals. By simultaneously addressing ecological, economic, and social dimensions of sustainability, it offers a viable and scalable pathway towards a more resilient and environmentally responsible agricultural future.



8. Environmental and Ecological Significance

Environmental and Ecological Significance of Lac Culture

The ecological significance of lac culture extends far beyond its immediate economic utility, encompassing a wide spectrum of biological interactions that contribute to the stability and functioning of terrestrial ecosystems. At its core, lac cultivation is embedded within a multi-tiered trophic framework, wherein the lac insect, Kerria lacca, interacts intricately with its host plants, natural enemies, and associated microbial communities. These interactions are not merely incidental but represent a finely regulated ecological network that sustains biodiversity and promotes ecosystem resilience.

Host plants form the primary structural and nutritional foundation of this system, supplying the phloem sap upon which lac insects depend. In turn, lac insects support a diverse assemblage of organisms, including predators and parasitoids, particularly hymenopteran wasps and lepidopteran larvae that regulate insect populations through natural biological control. Additionally, microbial communities associated with both the insect and host plants contribute to nutrient cycling, plant health, and physiological processes. The cumulative outcome of these interdependent relationships is the maintenance of ecological equilibrium, wherein population dynamics are naturally balanced, and biodiversity is preserved (Mohanta *et al.,* 2014; Sharma *et al.,* 2006).

Such ecological complexity confers a degree of resilience upon lac-based systems, allowing them to absorb and adapt to environmental fluctuations more effectively than simplified monocultural systems. The preservation of these intricate relationships supports biodiversity at multiple levels: genetic, species, and ecosystem, thereby reinforcing the stability and sustainability of the landscape. This aligns with broader ecological theories that emphasize the importance of trophic diversity and functional redundancy in maintaining ecosystem integrity (Tilman *et al.,* 2014; Cardinale *et al.,* 2012).

A particularly noteworthy aspect of lac ecology is the role of lac insects as bio-indicators of environmental health. Their survival, reproduction, and resin productivity are highly sensitive to variations in climatic parameters such as temperature, humidity, and rainfall, as well as to changes in host plant condition and environmental quality. Consequently, fluctuations in lac insect populations or resin yield may serve as early indicators of ecological disturbance, including habitat degradation, pollution, or climatic stress. Such responsiveness renders lac insects valuable tools for ecological monitoring and environmental assessment (Raman, 2014; Nair *et al.,* 2010).

In addition to their role as indicators, lac-based systems contribute to broader ecological processes at the landscape level. The maintenance of host trees within agroforestry frameworks enhances carbon sequestration, supports soil stabilization, and facilitates nutrient cycling. These systems also provide habitat and refuge for a variety of organisms, thereby increasing landscape heterogeneity, a key determinant of ecological resilience (Jose, 2009; Nair *et al.,* 2010). By integrating production with conservation, lac culture exemplifies a sustainable land-use model that minimizes ecological disruption while maximizing ecosystem services.

Furthermore, the ecological sustainability of lac culture is reinforced by its minimal reliance on external inputs. The absence of synthetic fertilizers and pesticides reduces the risk of soil and water contamination, thereby preserving the environmental quality. This feature is particularly significant in the context of sustainable agriculture, where reducing chemical inputs is a major priority.

In summary, lac culture represents a biologically intricate and ecologically harmonious system that contributes to biodiversity conservation, ecosystem stability, and environmental monitoring. Its capacity to sustain complex trophic interactions, function as a sensitive indicator of ecological change, and support essential ecosystem services positions it as a valuable component of sustainable agroforestry and conservation strategies. As environmental challenges continue to intensify, such nature-aligned systems assume increasing importance in the pursuit of long-term ecological resilience and sustainability.

9. Government Initiatives and Policy Support

Institutional Support, Policy Framework, and Educational Integration of Lac Culture

In India, the sustained development and contemporary relevance of lac culture are underpinned by a coordinated framework of institutional research, extension services, and policy support mechanisms. A central role in this regard is played by the National Institute of Secondary Agriculture (NISA) (Formerly known as the Indian Institute of Natural Resins and Gums (IINRG)), which functions as the premier national institute dedicated to the scientific advancement of lac and allied natural resins. Through its interdisciplinary research programmes, the institute has made significant contributions to the refinement of cultivation techniques, improvement of lac strains, pest and disease management strategies, and the development of value-added products.

Equally important is its extension mandate, which facilitates the transfer of scientific knowledge to cultivators through training programmes, field demonstrations, and participatory outreach initiatives. While these efforts have had a measurable impact in key lac-producing regions, it is important to recognize that the wider dissemination of improved technologies and practices still requires strengthening to achieve broader national coverage (Kumar & Sharma, 2018; Sharma & Ramani, 2008).

Complementing these institutional efforts, a range of governmental programmes focused on tribal welfare, rural livelihoods, and non-timber forest products (NTFPs) have contributed to the promotion of lac cultivation as a viable income-generating activity. These initiatives typically provide a combination of capacity building, financial assistance, input support, and facilitation of market access. However, it is important to note that such interventions are often region-specific, with stronger implementation observed in states such as Jharkhand, Chhattisgarh, and parts of Madhya Pradesh, where lac cultivation is traditionally practiced.

Programmes implemented through agencies such as the National Rural Livelihoods Mission (NRLM), along with allied initiatives including tribal development schemes and forest-based enterprise promotion programmes, have contributed to strengthening community-based lac enterprises in selected regions. Nevertheless, lac is not uniformly prioritized across all such programmes at the national level, and its inclusion often depends upon local resource endowments and policy emphasis (Jaiswal, 2015; Government of India, 2020).

From an economic and developmental standpoint, these policy interventions contribute not only to income generation but also to broader objectives of inclusive growth and rural resilience. By encouraging decentralized production systems and small-scale processing units, they support local entrepreneurship, reduce distress-driven migration, and enhance the socio-economic status of marginalized communities. At the same time, the emphasis on sustainable utilization of forest resources ensures that economic benefits are realized without compromising ecological stability.

In parallel with these institutional and policy frameworks, the integration of lac culture into educational systems has emerged as a promising, albeit still evolving, development—particularly in the context of the National Education Policy 2020 (NEP-2020). The policy advocates a shift towards experiential, multidisciplinary, and skill-oriented education, with a strong emphasis on contextual relevance and sustainability. Within this framework, lac culture offers considerable potential as a pedagogical tool that bridges the disciplines of zoology, environmental science, and rural development.

The incorporation of lac culture into academic curricula can enable students to engage meaningfully with real-world agro-ecological systems, thereby deepening their understanding of concepts such as insect–plant interactions, biodiversity conservation, and sustainable resource management. Field-based exposure, practical training in lac cultivation, and engagement with value-addition processes can enhance both technical competence and entrepreneurial capacity. However, it must be acknowledged that such curricular integration is presently limited and in a developmental phase, requiring systematic institutional adoption and curriculum design.

From a skill development perspective, lac culture presents opportunities across a broad spectrum of competencies, including agroforestry management, biological pest regulation, post-harvest processing, and product innovation. These competencies are not only academically relevant but also aligned with emerging employment opportunities in rural and bio-based sectors. Consequently, the inclusion of lac culture within NEP-aligned educational frameworks holds significant promise for fostering a workforce that is both environmentally informed and economically productive.

In conclusion, the advancement of lac culture in India is best understood as the outcome of a synergistic interaction between scientific research, targeted policy interventions, and emerging educational initiatives. Institutions such as the Indian Institute of Natural Resins and Gums provide the scientific foundation, while governmental programmes offer varying degrees of implementation support depending on regional priorities. Concurrently, educational frameworks such as NEP-2020 create opportunities for knowledge dissemination and skill development, although their full potential in this domain remains to be realized. Together, these elements constitute a dynamic yet evolving ecosystem that supports the sustainable growth of lac culture, reinforcing its importance as both an economic resource and a pedagogical asset in contemporary India.

10. Constraints and Challenges in Lac Culture

Notwithstanding its considerable ecological and economic promise, lac culture in India continues to be constrained by a range of interrelated environmental, biological, and socio-economic challenges. These limitations, if left inadequately addressed, have the potential to undermine both productivity and long-term sustainability, thereby restricting the broader expansion of the sector.

Foremost among these constraints is the increasing influence of climatic variability, which exerts a profound impact on the biology and productivity of the lac insect, Kerria lacca. Fluctuations in temperature, irregular rainfall patterns, and prolonged dry spells can disrupt the synchronization between insect life cycles and host plant physiology. Given that lac insects are highly sensitive to environmental conditions, even minor deviations from optimal climatic parameters may adversely affect crawler emergence, settlement success, and resin secretion. Extreme weather events, such as heat waves or unseasonal rains, may further exacerbate mortality rates, leading to substantial reductions in yield (Papnai, 2017; Sharma *et al.,* 2016).

In addition to climatic stress, biotic pressures, particularly those arising from pests and diseases, constitute a significant impediment to lac production. Lac insects are vulnerable to a diverse array of natural enemies, including parasitic hymenopterans and predatory lepidopteran larvae, which can cause extensive damage if not effectively managed. While these interactions form part of a natural ecological balance, their proliferation under certain conditions can lead to significant population decline. The absence of widespread adoption of integrated pest management strategies, coupled with limited access to timely advisory services, often results in preventable yield losses (Mohanta *et al.,* 2014; Sandeep, 2015).

Equally important are the market-related constraints that affect the economic viability of lac cultivation. The sector is characterized by price volatility, largely driven by fluctuations in supply, demand, and international market conditions. Small-scale producers, who constitute the majority of lac cultivators, are particularly vulnerable to such instability due to their limited bargaining power and lack of access to real-time market information. Furthermore, the absence of well-organized and transparent supply chains often compels farmers to rely on intermediaries, thereby reducing their share of the final market value (Roy & Sharma, 2010).

Although research institutions have developed improved cultivation techniques and management practices, their dissemination remains uneven across regions. As a result, many farmers continue to rely on traditional methods that, while valuable, may not always yield optimal results under changing environmental conditions. This gap in knowledge transfer is further compounded by inadequate training infrastructure and limited institutional reach in remote or forested areas (Kumar & Sharma, 2018).

From a structural perspective, the underutilization of available host resources also represents a missed opportunity. A significant proportion of potential host trees in India remains unexploited for lac cultivation, largely due to a lack of awareness, insufficient technical guidance, and limited institutional support. Addressing this gap could substantially enhance production without necessitating additional land-use change.

In a broader sense, these challenges highlight the need for a more integrated and responsive approach to lac development, one that combines scientific innovation with effective extension, market reform, and climate-resilient strategies. Strengthening farmer capacity, improving access to organized markets, and enhancing institutional coordination will be essential to overcoming existing constraints and unlocking the full potential of lac culture.

In conclusion, while lac culture offers a compelling model of sustainable and inclusive agriculture, its continued growth is contingent upon the systematic resolution of these environmental, biological, and socio-economic challenges. Holistically addressing these issues will not only improve productivity and income stability but also reinforce the resilience of lac-based agroforestry systems in the face of emerging global uncertainties.

11. Future Prospects and Innovations

Future Prospects and Innovations in Lac Culture

The future trajectory of lac culture is likely to be shaped by a judicious synthesis of time-tested traditional practices and contemporary scientific innovation. While indigenous knowledge continues to provide a strong operational foundation, the incorporation of modern technological advances offers considerable scope for enhancing both productivity and product quality. In this regard, emerging developments in biotechnology, genetic improvement, and ecological pest management are expected to play a pivotal role in strengthening the resilience and efficiency of lac-based production systems.

Recent advances in biological sciences have opened new avenues for the selective improvement of lac insect strains to achieve higher resin yield, improved quality parameters, and greater tolerance to environmental stress. Although conventional selection methods have long been employed, there is increasing interest in the application of molecular tools to better understand genetic variability and host–insect interactions. Such approaches hold promise for the development of strains that are better adapted to changing climatic conditions and capable of sustaining stable production across diverse agro-ecological zones (Sharma, 2021; Mohanty *et al.,* 2021).

Parallel to genetic improvement, the refinement of integrated pest and disease management strategies represents another critical area of innovation. The adoption of ecologically based pest control methods—including biological control agents, habitat management, and behavioural interventions—can significantly reduce crop losses while maintaining environmental integrity. These approaches are particularly important in lac systems, where the use of synthetic chemicals is neither desirable nor practical. Advances in ecological modelling and monitoring technologies may further enhance the precision and effectiveness of such interventions.

Equally significant is the expanding scope for value addition and product diversification. With increasing global emphasis on sustainable and bio-based materials, lac is gaining renewed attention as a versatile natural polymer. Research into novel lac-derived products, including biodegradable composites, functional coatings, and bio-based adhesives, is opening new industrial avenues. Improved processing technologies—such as controlled thermal refinement, solvent-free purification methods, and nano-scale material modification—are further enhancing the functional properties of lac, thereby broadening its application spectrum (Thakur *et al.,* 2018; Sen *et al.,* 2020).

From a market perspective, the rising international demand for environmentally benign and biodegradable materials presents a significant opportunity for the expansion of the lac sector. As industries increasingly seek alternatives to petroleum-derived products, lac-based materials are well-positioned to occupy a niche within the global bioeconomy. This transition is further supported by evolving consumer preferences, which favor natural and sustainably sourced products across sectors such as food, cosmetics, pharmaceuticals, and packaging.

However, the realization of this potential will depend upon the implementation of strategic policy interventions and sustained research investment. Strengthening institutional linkages between research organizations, extension agencies, and market stakeholders will be essential to ensure the effective translation of scientific advances into field-level applications. Additionally, targeted policies aimed at improving market access, stabilizing prices, and supporting small-scale processors can enhance the economic viability of lac cultivation.

In the context of the National Education Policy 2020 (NEP-2020), there is also considerable scope for integrating these innovations into academic and skill development programmes. By exposing students to emerging technologies and entrepreneurial opportunities within the lac sector, educational institutions can play a vital role in fostering innovation-driven growth.

In conclusion, the future of lac culture lies not in the replacement of traditional practices but in their thoughtful augmentation through scientific and technological advancement. By combining ecological sustainability with innovation-led development, lac culture has the potential to evolve into a dynamic and globally relevant bio-based industry. With appropriate policy support, research investment, and capacity building, it can emerge as a key contributor to sustainable agriculture, rural livelihoods, and the broader circular economy.

Summary: The Renaissance of Lac Culture in Sustainable Agriculture

In recent decades, Indian agriculture has undergone a profound paradigm shift, pivoting from resource-intensive monocultures toward resilient, ecologically attuned models. Driven by the imperative to reverse soil depletion and mitigate climate volatility, this transition finds a potent ally in lac culture. The National Education Policy 2020 (NEP-2020) reinforces this trajectory by formalizing the integration of indigenous knowledge with modern scientific inquiry, creating a multidisciplinary framework where traditional practices are rigorously validated. Lac, a natural biodegradable resin secreted by the insect *Kerria lacca*, represents a rare confluence of entomology, forestry, and rural sociology. It provides a supplementary, low-input livelihood for millions of marginal farmers while maintaining the biological integrity of the landscape.

The biological foundations of this system are a masterclass in evolutionary adaptation. As sessile organisms, lac insects derive nourishment from the phloem sap of specific host trees—most notably *Butea monosperma* (Palas), *Schleichera oleosa* (Kusum), and *Ziziphus mauritiana* (Ber). The life cycle is defined by striking sexual dimorphism and the synchronized emergence of "crawlers" that colonize host branches to produce dense, protective resinous encrustations. Beyond its economic value, this system functions as a critical carbon sink and a sensitive bio-indicator of environmental health. Because cultivation relies on standing timber rather than deforestation, it incentivizes the preservation of forest cover and sustains complex trophic networks, aligning seamlessly with the United Nations Sustainable Development Goals (SDGs) regarding climate action and terrestrial biodiversity.

Cultivation itself is a sophisticated synthesis of seasonal rhythms and human stewardship. Practitioners manage two primary strains—Kusmi and Rangeeni—through precise pruning and inoculation cycles to optimise yields. The value chain has evolved far beyond the forest floor; raw "stick lac" is now refined into shellac, a high-performance natural polymer. Contemporary innovations in green chemistry are repositioning lac derivatives as superior, eco-friendly alternatives to petroleum-based plastics in pharmaceutical enteric coatings, biodegradable food packaging, and advanced bio-lubricants. This transition from an artisanal craft to a cornerstone of high-tech biomaterial science bolsters the global export potential of India, which currently commands the majority of the world's supply.

Ultimately, lac culture serves as a decentralized engine for socio-economic resilience. It is inherently inclusive, requiring negligible capital investment and providing a vital financial safety net for forest-dependent and tribal communities. While institutional support from bodies like the National Institute of Secondary Agriculture (NISA) provides a scientific anchor, the sector must still navigate challenges such as climatic instability and market price volatility. Prospects lie in the integration of molecular biotechnology for strain enhancement and the deployment of digital extension services. By augmenting time-honored traditions with cutting-edge innovation, lac culture emerges as a compelling, scalable model for an environmentally responsible and socially equitable agricultural future.

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SUSTAINABLE AGRICULTURE IN A CHANGING CLIMATE

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Abstract

Global agricultural systems are seriously threatened by climate change, which has an impact on food security, ecological stability, and productivity. By combining social justice, economic viability, and environmental preservation, sustainable agriculture has become a vital tactic to address these issues. This chapter examines how agriculture and climate change are related, emphasizing technical advancements, policy frameworks, and climate-resilient practices. With special attention to emerging nations like India, it highlights the significance of climate-smart agriculture and sustainable food systems.

Keywords: Sustainable Agriculture, Climate Change, Food Security, Climate Resilience, Climate-Smart Agriculture.

1. Introduction

Agriculture is one of the most climate-sensitive sectors, directly influenced by temperature, precipitation, and extreme weather events. Climate change has intensified these variables, leading to reduced crop productivity, increased variability in yields, and heightened risks for farmers (Wang, 2025).

Globally, the demand for food is expected to increase significantly due to population growth, requiring agricultural production to rise substantially by 2050 despite environmental constraints (Wang, 2025). Increasing food production while reducing environmental deterioration becomes a dual problem as a result. By encouraging resource-efficient and ecologically responsible farming methods, sustainable agriculture offers a chance to reach this equilibrium.

2. Concept and Principles of Sustainable Agriculture

Farming practices that satisfy current food and fiber demands without jeopardizing the capacity of future generations to satisfy their own needs are referred to as sustainable agriculture. It is built upon three interrelated pillars: social justice, economic profitability, and environmental sustainability.

Key principles include maintaining soil health, conserving water resources, enhancing biodiversity, and reducing reliance on chemical inputs. These approaches not only improve productivity but also enhance ecosystem resilience and long-term sustainability (Barua & Mitra, 2024).

Additionally, sustainable agriculture encourages the fusion of conventional wisdom with cutting-edge scientific discoveries, allowing for flexible and site-specific solutions.

3. Climate Change and Its Impact on Agriculture

Climate change that effects agriculture are changes in temperature, precipitation patterns, and the frequency of extreme weather. Crops are subjected to biotic and abiotic stressors as a result of these changes. Rising temperatures and water scarcity reduce crop yields and affect plant physiological processes, while unpredictable rainfall patterns increase the risk of droughts and floods (Barua & Mitra, 2024). In addition, changing climatic conditions alter pest and disease dynamics, further threatening agricultural productivity.

These impacts are particularly severe in developing countries where agriculture is predominantly rain-fed and highly vulnerable to climate variability. As a result, food security is increasingly at risk, especially among smallholder farmers (Alobwede & Muasya, 2026).

4. Climate-Resilient and Climate-Smart Agriculture

Enhancing agricultural systems' ability to adjust to and recover from climate-related shocks is the main goal of climate-resilient agriculture. Climate-Smart Agriculture (CSA) is a well-known framework in this regard.

CSA aims to achieve three main objectives: increasing agricultural productivity, enhancing resilience to climate change, and reducing greenhouse gas emissions (Steenwerth *et al.,* 2014).

Agricultural diversification, conservation agriculture, better water management, and the use of stress-tolerant agricultural types are examples of CSA practices. These methods enhance long-term sustainability while simultaneously lowering susceptibility to climate shocks.

Research indicates that CSA plays a crucial role in improving food security and livelihoods, particularly in regions where agriculture is highly climate-dependent (Regmi & Paudel, 2024)

5. Role of Technology in Sustainable Agriculture

Climate resilience and sustainable agriculture are greatly influenced by technological innovation. Increased output, less environmental effect, and efficient resource usage are all made possible by modern agricultural technologies.

Precision agriculture, which utilizes sensors, satellite data, and geographic information systems, allows farmers to optimize the use of water, fertilizers, and pesticides. Similarly, digital technologies such as artificial intelligence and the Internet of Things enable real-time monitoring and decision-making.

Biotechnology also plays a significant role by developing crop varieties that are resistant to drought, heat, and pests. These innovations contribute to sustainable intensification, allowing higher productivity with fewer inputs (Wang, 2025).

6. Sustainable Agriculture and Food Security

The four dimensions of food security are availability, accessibility, use, and stability. All of these aspects are disrupted by climate change, which has an impact on food pricing, supply systems, and crop output.

By boosting productivity, enhancing resource efficiency, and stabilizing food systems, sustainable agriculture improves food security. By encouraging diverse agricultural systems and lowering reliance on monoculture techniques, it also enhances nutritional security.

Climate-smart agricultural practices have been shown to improve yields and farm incomes, thereby enhancing food accessibility and reducing poverty (Ghosh, 2019).

7. Indian Perspective on Sustainable Agriculture

India is extremely sensitive to climate change because of its sizable agrarian population. The nation has put in place a number of programs to support sustainable agriculture, such as resource conservation strategies and climate-smart farming methods.

Programs such as climate-smart villages and sustainable agricultural missions aim to enhance resilience and improve productivity. Adoption of practices such as micro-irrigation, organic farming, and integrated farming systems has shown positive outcomes in terms of yield stability and income generation (Ghosh, 2019).

However, challenges such as limited awareness, financial constraints, and institutional barriers continue to hinder widespread adoption.

8. Challenges and Constraints

Adoption of sustainable agriculture confronts a number of obstacles despite its potential. These include poor policy backing, high initial expenses of technology, and limited access to resources and information.

The majority of the agricultural labor force in developing nations is made up of smallholder farmers, who frequently lack the capacity to embrace cutting-edge technologies. Furthermore, the adoption of sustainable methods is further constrained by socioeconomic variables including market access and land fragmentation.

Governments, academic institutions, and stakeholders must work together to address these issues.

9. Future Prospects and Way Forward

Innovation, resilience, and sustainability must be integrated if agriculture is to survive. Investments in research and development, policies that promote sustainable practices, and programs that increase farmers' capacity are crucial.

New strategies for improving sustainability include agroecology, regenerative agriculture, and digital farming. Enhancing international collaboration and information exchange will also be essential to changing agricultural systems.

A comprehensive strategy that takes into account social, economic, and environmental factors is needed to create sustainable food systems.

Conclusion

Sustainable agriculture is essential for ensuring food security in a changing climate. By integrating climate-resilient practices, technological innovations, and supportive policies, it is possible to build agricultural systems that are both productive and environmentally sustainable. The transition to sustainable agriculture is not only necessary but urgent, as it holds the key to feeding the future while preserving natural resources for generations to come.

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BEYOND SELF REPORTS: A PSYCHOLOGICAL EVALUATION OF BEHAVIOUR-BASED MEASURES OF PRO-ENVIRONMENTAL ACTION AND THEIR RELEVANCE TO SUSTAINABILITY

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1. Introduction: Behaviour at the Core of Sustainability

Human behaviour lies at the core of environmental degradation and sustainability transitions. Psychological processes such as decision-making, motivation, and value orientation shape whether individuals engage in pro-environmental actions.

The global challenges of climate change, food insecurity, and environmental degradation are no longer driven solely by technological or policy limitations—they are deeply rooted in human behaviour. In the context of sustainable agriculture and climate resilience, individual and collective choices related to consumption, resource use, and environmental responsibility play a decisive role.

Pro-environmental behaviour (PEB), broadly understood as actions that contribute to environmental preservation, has gained increasing attention across disciplines. Whether it is farmers adopting sustainable practices, consumers shifting toward eco-friendly food systems, or communities supporting conservation initiatives, behavioural change remains central to achieving long-term sustainability.

However, a persistent challenge in this field is not just promoting such behaviours, but accurately measuring them. Without reliable measurement, designing effective interventions for climate-resilient agriculture and sustainable food systems becomes difficult.

2. The Measurement Problem in Pro-Environmental Behaviour

Traditionally, research in environmental psychology has relied heavily on self-report measures—questionnaires where individuals describe their own behaviours, attitudes, or intentions. While useful, these methods are often limited by:

- Social desirability bias
- Overestimation of environmentally friendly actions
- Weak connection to actual real-world behaviour

This is particularly problematic when translating research into domains like agriculture or food security, where actual behavioural outcomes, not intentions, determine sustainability impact.

In response to these concerns, recent methodological developments have attempted to capture "consequential behaviour"—that is, behaviour involving real effort, trade-offs, or outcomes.

3. WEPT: A Behaviour-Based Approach

One such innovation is the Work for Environmental Protection Task (WEPT)**,** developed as a web-based experimental method to assess pro-environmental behaviour through effort-based decision-making**.**

WEPT represents a behavioural decision-making paradigm that operationalizes pro-environmental behaviour through effort-based cost and consequence-driven reinforcement.

Unlike traditional surveys, WEPT requires participants to perform a cognitively demanding task (such as identifying numerical patterns). Their effort translates into real monetary contributions to environmental causes, thereby introducing a tangible consequence.

What makes WEPT particularly interesting is its attempt to simulate a key real-world dilemma:

Would individuals invest personal effort or resources for environmental benefit?

This structure reflects everyday sustainability decisions—such as whether a farmer adopts labour-intensive sustainable practices or whether consumers choose eco-friendly but less convenient options.

4. Key Mechanisms Underlying WEPT

WEPT operates on two fundamental behavioural dimensions:

a. Behavioural Cost

Participants must invest time and cognitive effort. As the task becomes more demanding, willingness to continue typically decreases.

b. Environmental Impact

Higher perceived impact (e.g., greater donations per task) increases motivation to engage.

Empirical findings suggest a clear behavioural trade-off:

- Increased effort reduces participation
- Increased environmental benefit enhances engagement

This mirrors real-world sustainability decisions where individuals constantly negotiate between personal cost and environmental gain**.**

5. Relevance to Sustainable Agriculture and Food Systems

Although WEPT originates in environmental psychology, its implications extend meaningfully into the domain of sustainable agriculture and food security**.**

a. Farmer Decision-Making

Farmers often face trade-offs similar to those simulated in WEPT:

- Higher effort (organic practices, water conservation)
- Delayed or uncertain rewards
- Understanding how behavioural costs influence decisions can inform:
- Policy incentives
- Adoption strategies for sustainable technologies

b. Consumer Behaviour in Food Systems

Consumers choosing sustainable food options encounter:

- Higher prices
- Limited availability
- Habitual resistance

WEPT-like frameworks help explain why intentions do not always translate into action, a major barrier in sustainable consumption.

c. Climate Resilience

Climate-resilient practices often require:

- Immediate effort
- Long-term benefits

Behavioural tools like WEPT highlight the importance of making environmental outcomes more visible and immediate to encourage adoption.

6. Strengths of WEPT as a Measurement Tool

WEPT contributes to sustainability research in several important ways:

- Moves beyond hypothetical responses to observable behaviour
- Incorporates real consequences, improving internal validity
- Uses repeated trials, allowing dynamic behavioural analysis
- Captures effort–impact trade-offs, central to sustainability decisions

These features make it a valuable experimental tool for studying behavioural dimensions of environmental action.

7. Critical Limitations in Real-World Application

Despite its strengths, WEPT has notable limitations when viewed through the lens of agriculture and climate systems:

a. Limited Generalizability

Most studies use student samples, which may not represent:

- Farmers
- Rural populations
- Diverse socio-economic groups

b. Low Ecological Validity

The task (number screening) does not resemble real-life environmental decisions such as:

- Crop selection
- Water management
- Waste reduction

c. Immediate Reinforcement Bias

In WEPT, environmental benefits are immediate and visible. In reality:

- Climate benefits are delayed
- Feedback loops are unclear

This discrepancy may overestimate real-world pro-environmental behaviour.

d. Context-Specific Behaviour

WEPT captures behaviour in a controlled setting but fails to reflect:

- Habitual actions
- Cultural influences
- Structural constraints

8. Beyond WEPT: Toward Integrated Behavioural Measurement

For meaningful application in sustainable systems, behavioural measurement must go beyond single-method approaches.

More comprehensive frameworks should include:

- Self-report scales (e.g., ecological behaviour scales)
- Field observations in real agricultural settings
- Consumption-based measures covering acquisition, use, and disposal
- Technology adoption metrics

Particularly relevant is the concept of environmentally responsible consumption, which integrates behaviour across the entire lifecycle of resource use—highly applicable to food systems.

9. Implications for Policy and Practice

- Understanding behavioural dynamics has direct implications for sustainability interventions:
- Designing incentives that reduce perceived effort
- Making environmental benefits visible and immediate
- Integrating behavioural insights into agricultural extension programs
- Promoting context-specific interventions rather than one-size-fits-all solutions

Behavioural tools like WEPT can support policy design, but only when combined with real-world data and socio-cultural understanding.

Conclusion

The transition toward sustainable agriculture and climate-resilient food systems depends not only on innovation and policy, but on human behaviour.

The Work for Environmental Protection Task represents a meaningful step toward capturing real behavioural tendencies by introducing effort-based and consequence-driven decision-making into research.

However, its limitations highlight an important reality:

No single method can fully capture the complexity of pro-environmental behaviour.

Future research must move toward integrated, context-sensitive, and interdisciplinary approaches that bridge laboratory insights with real-world sustainability challenges.

Only then can behavioural science effectively contribute to building resilient agricultural systems and ensuring long-term food security.

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