Advances in Sustainable Agriculture and Allied Sciences

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Bhumi Publishing

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Editors

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PREFACE

As Editors, we take great pride in presenting *Advances in Sustainable Agriculture and Allied Sciences*, a scholarly compilation that reflects the evolving dimensions of agriculture in the context of global sustainability challenges. The agricultural sector today is confronted with multifaceted pressures arising from climate variability, shrinking natural resources, environmental degradation, and the increasing demand for safe and nutritious food. These realities necessitate innovative, science-driven, and ecologically balanced solutions.

This volume has been conceptualized with the objective of bringing together diverse perspectives from experts across agriculture and its allied sciences. The chapters included herein address contemporary themes such as sustainable crop production, soil health management, integrated pest and nutrient management, climate-resilient agriculture, precision farming, biotechnology interventions, fisheries and animal husbandry advancements, agroforestry systems, and sustainable food processing technologies. The integration of modern tools such as artificial intelligence, remote sensing, and data-driven decision-making further highlights the transformative potential of technology in promoting resilient agricultural systems.

From the editors' perspective, sustainability is not merely a concept but a practical framework that harmonizes productivity, environmental conservation, economic viability, and social responsibility. The allied sciences significantly contribute to this framework by enhancing resource efficiency, supporting rural livelihoods, and strengthening food and nutritional security.

We sincerely appreciate the valuable contributions of all authors, reviewers, and collaborators who have enriched this volume with their research insights and field experiences. It is our hope that this book will serve as a meaningful academic resource for researchers, students, policymakers, and practitioners, and will stimulate further dialogue and innovation in sustainable agricultural development.

We trust that this volume will contribute positively toward shaping a resilient, inclusive, and sustainable agricultural future.

- Editors

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CLIMATE RESILIENCE AND SUSTAINABLE LIVELIHOODS

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Abstract

Agriculture is increasingly challenged by climate change, land degradation, declining soil fertility, and livelihood insecurity of farming communities. Extreme weather events such as droughts, floods, heat waves, and erratic rainfall have made conventional mono-cropping systems more vulnerable and less reliable. In this context, agroforestry has emerged as a sustainable land-use system that integrates trees with crops and/or livestock on the same land management unit. Agroforestry systems enhance climate resilience by improving soil health, conserving water, sequestering carbon, and diversifying farm income. This chapter discusses the concept and components of agroforestry systems, their functioning, tools and practices used, and their role in supporting climate resilience and sustainable livelihoods. The advantages, limitations, and future prospects of agroforestry are also elaborated, highlighting its importance as a climate-smart and farmer-friendly approach for sustainable agricultural development.

Keywords: Agroforestry, Climate Resilience, Sustainable Livelihoods, Tree-Based Farming Systems, Soil Conservation, Climate-Smart Agriculture.

Introduction

Climate change has emerged as one of the most serious challenges facing agriculture worldwide. Rising temperatures, unpredictable rainfall patterns, frequent droughts, floods, and increased incidence of pests and diseases have significantly affected crop productivity and farm incomes. Small and marginal farmers, who depend heavily on rain fed agriculture, are particularly vulnerable to these climatic risks. Conventional agricultural systems dominated by mono-cropping and intensive input use often lack resilience and are unable to cope effectively with environmental stresses.

Agroforestry offers a viable and sustainable alternative by integrating trees with crops and livestock in a complementary manner. It is a traditional practice in many parts of the world but has gained renewed attention due to its potential to address contemporary challenges related to climate change, environmental degradation, and livelihood insecurity. By combining perennial woody components with annual crops, agroforestry systems provide ecological stability, economic diversification, and social benefits.

From a sustainable agriculture perspective, agroforestry contributes to climate adaptation and mitigation while supporting food security and income generation. It improves farm productivity, enhances ecosystem services, and strengthens farmers' capacity to cope with climatic uncertainties. Therefore, agroforestry systems are increasingly recognized as an important component of climate-resilient and sustainable agricultural development.

Concept of Agroforestry Systems

Agroforestry is defined as a land-use system in which woody perennials such as trees and shrubs are deliberately integrated with agricultural crops and/or livestock on the same land unit, either simultaneously or sequentially. The key principle of agroforestry is the purposeful interaction between different components to achieve ecological and economic benefits.

Agroforestry systems are designed to optimize the use of natural resources such as land, water, sunlight, and nutrients. Trees play a crucial role in modifying the microclimate, improving soil structure, recycling nutrients from deeper soil layers, and providing multiple products such as fuelwood, fodder, fruits, timber, and non-timber forest products. When properly managed, agroforestry systems enhance overall system productivity and sustainability compared to mono-cropping systems.

Components of Agroforestry Systems

i) Tree Component

Trees form the backbone of agroforestry systems. Depending on the objectives, different tree species are selected for timber, fuelwood, fodder, fruits, or soil improvement. Deep-rooted trees help in nutrient recycling and water uptake from deeper soil layers, reducing competition with crops when appropriately spaced and managed.

ii) Crop Component

Annual or perennial crops are grown in association with trees. These may include cereals, pulses, oilseeds, vegetables, or fodder crops. Crop selection depends on climatic conditions, soil type, and the degree of shade tolerance. Proper crop-tree combinations are essential to minimize competition and maximize complementary interactions.

iii) Livestock Component

In some agroforestry systems, livestock such as cattle, goats, or sheep are integrated. Trees provide fodder and shade, while livestock contribute manure, enhancing nutrient cycling. This integration supports diversified livelihoods and efficient resource use.

iv) Soil and Water Resources

Soil and water are critical components of agroforestry systems. Tree roots improve soil structure, enhance infiltration, and reduce erosion. Leaf litter and organic residues add organic matter, improving soil fertility and moisture retention.

Types and Tools of Agroforestry Systems

Agroforestry systems vary based on ecological conditions, farmer objectives, and management practices. Common types include agrisilviculture (trees with crops), silvopasture (trees with pasture and livestock), and agri-horticulture (fruit trees with crops). Tools and practices used in agroforestry include contour planting, mulching, pruning, lopping, and spacing management.

Simple tools such as pruning knives, sickles, and hand saws are used for tree management, while soil and water conservation structures like bunds and trenches support moisture conservation. Improved planting material and nursery techniques also play a key role in successful agroforestry establishment.

Working Mechanism of Agroforestry Systems

Agroforestry systems function through positive interactions among their components. Trees reduce wind speed and temperature extremes, creating a favorable microclimate for crops. Their deep root systems access nutrients and water from lower soil layers, which are later returned to the surface through leaf fall and decomposition.

Crops benefit from improved soil fertility, reduced moisture stress, and protection from climatic extremes. Livestock utilize crop residues and tree fodder, while their manure enriches the soil. This integrated functioning enhances system resilience, reduces dependency on external inputs, and ensures stable productivity under variable climatic conditions.

Role of Agroforestry in Climate Resilience

Agroforestry enhances climate resilience by buffering farms against climatic shocks. Trees act as windbreaks, reduce evapotranspiration, and improve water use efficiency. Increased organic matter improves soil water-holding capacity, helping crops withstand dry spells.

Agroforestry systems also contribute to climate change mitigation by sequestering carbon in tree biomass and soil. The diversified nature of these systems reduces the risk of complete crop failure, ensuring food and income security even under adverse climatic conditions.

Benefits to the Farming Community

Agroforestry provides multiple benefits to farmers. It diversifies income sources through the production of timber, fruits, fodder, and fuelwood alongside crops. This diversification reduces economic risk and enhances livelihood security.

The system improves soil fertility, reduces input costs, and enhances long-term productivity. Farmers benefit from improved resilience to climate variability and reduced vulnerability to market and environmental shocks. Agroforestry also generates employment opportunities and supports sustainable rural livelihoods.

Advantages of Agroforestry Systems

Agroforestry systems offer several advantages, including improved soil health, enhanced biodiversity, efficient resource use, and climate resilience. They support sustainable intensification by increasing productivity per unit area without degrading natural resources. Agroforestry also promotes ecological balance and long-term sustainability of farming systems.

Limitations and Challenges

Despite its benefits, agroforestry faces certain challenges. Initial establishment requires time and investment, and returns from trees are often delayed. Inappropriate species selection and poor management can lead to competition between trees and crops. Lack of awareness, technical knowledge, and policy support may also limit adoption among farmers.

Future Prospects of Agroforestry

The future of agroforestry is promising, particularly in the context of climate change and sustainable development goals. Improved research on species combinations, climate-resilient tree varieties, and management practices can enhance system performance. Policy support, incentives, and integration of agroforestry into climate and agricultural programmes can accelerate adoption. Agroforestry has the potential to play a key role in climate-smart agriculture and sustainable livelihood development.

Conclusion

Agroforestry systems represent a holistic and sustainable approach to addressing the challenges of climate change, environmental degradation, and livelihood insecurity. By integrating trees with crops and livestock, agroforestry enhances ecological stability, economic resilience, and social well-being. Although challenges exist, the long-term benefits of agroforestry outweigh the limitations. With appropriate research, extension support, and policy interventions, agroforestry can significantly contribute to climate-resilient agriculture and sustainable livelihoods.

Summary

Agroforestry integrates trees, crops, and sometimes livestock to create diversified and resilient farming systems. These systems improve soil health, conserve water, sequester carbon, and enhance farm income. Agroforestry strengthens climate resilience and supports sustainable livelihoods, particularly for small and marginal farmers. Despite certain constraints, agroforestry holds immense potential as a climate-smart and sustainable agricultural practice for the future.

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DIGITAL AGRICULTURE:

APPLICATIONS OF ARTIFICIAL INTELLIGENCE IN AGRICULTURE

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Abstract

Agriculture is facing unprecedented challenges due to climate change, shrinking natural resources, rising input costs, and increasing food demand from a growing population. Traditional farming practices, though rich in experience and indigenous knowledge, often lack precision and timely decision-making under complex and variable conditions. Digital agriculture has emerged as a transformative approach that integrates digital technologies with agricultural practices to enhance productivity, sustainability, and resilience. Artificial Intelligence (AI) plays a central role in digital agriculture by enabling intelligent data analysis, pattern recognition, prediction, and decision support. AI applications in agriculture range from crop monitoring and pest detection to yield prediction, smart irrigation, and market intelligence. This chapter presents a comprehensive overview of digital agriculture with a specific focus on applications of artificial intelligence in agriculture. It discusses the major components, AI tools, working mechanisms, and benefits to the farming community, advantages, limitations, future prospects, and the overall contribution of AI-driven agriculture towards sustainable agricultural development.

Keywords: Digital Agriculture, Artificial Intelligence, Smart Farming, Precision Agriculture, Decision Support Systems, Sustainable Agriculture.

Introduction

Agriculture has always been influenced by uncertainty arising from weather variability, pest and disease outbreaks, soil heterogeneity, and market fluctuations. Farmers traditionally rely on experience, observation, and generalized extension advisories to manage crops. While these approaches remain important, they are often insufficient to address the increasing complexity of modern agriculture, especially under changing climatic and socio-economic conditions.

Digital agriculture represents a shift from experience-based farming to data-driven and knowledge-based farming. It involves the use of digital tools such as sensors, satellites, mobile applications, data platforms, and automation technologies to support agricultural decision-making. Artificial intelligence is a key enabling technology within digital agriculture that allows machines to learn from data, recognize patterns, and generate recommendations or predictions.

In agriculture, AI does not replace farmers but enhances their decision-making capacity. By providing timely, location-specific, and crop-specific advisories, AI helps farmers optimize input

use, reduce risks, and improve productivity. In countries like India, where small and marginal farmers dominate, AI-based digital agriculture has immense potential to bridge knowledge gaps, strengthen extension services, and improve farmers' income and resilience.

Concept of Digital Agriculture and Artificial Intelligence

Digital agriculture refers to the application of digital technologies across the agricultural value chain, including planning, production, post-harvest management, marketing, and value addition. It focuses on collecting large volumes of data from diverse sources and converting them into actionable information for farmers and stakeholders.

Artificial intelligence is a branch of computer science that enables systems to perform tasks that normally require human intelligence, such as learning, reasoning, problem-solving, and decision-making. In agriculture, AI systems analyze complex datasets related to soil, crops, weather, pests, and markets to support precision and site-specific farming. AI models continuously improve their accuracy by learning from new data and feedback, making them highly suitable for dynamic agricultural environments.

Major Components of AI-Based Digital Agriculture

i) Data Collection Systems

Data is the foundation of AI-driven agriculture. Data is collected from multiple sources, including soil testing laboratories, weather stations, satellites, drones, farm machinery, and farmers' field records. These datasets capture information on soil properties, crop growth stages, weather parameters, and management practices.

ii) Sensors and Internet of Things (IoT)

Sensors deployed in agricultural field's measure real-time parameters such as soil moisture, temperature, humidity, and nutrient status. Through IoT networks, these sensors transmit continuous data to digital platforms. Real-time monitoring enables timely interventions and efficient resource management.

iii) Remote Sensing and Imaging Technologies

Remote sensing technologies use satellite and drone imagery to monitor large agricultural areas. AI algorithms analyze these images to assess crop health, detect stress symptoms, estimate biomass, and identify pest or disease incidence. This allows early detection of problems that may not be visible to the naked eye.

iv) Data Processing and AI Platforms

Collected data is processed using cloud-based platforms where AI and machine learning algorithms analyze patterns and relationships. These platforms integrate multiple datasets and generate insights that support farm-level decision-making.

v) Decision Support and Advisory Systems

AI-based decision support systems translate analytical outputs into simple advisories for farmers. These advisories are delivered through mobile applications, SMS, voice messages, or web portals in local languages, making them accessible to a wide range of farmers.

Applications of Artificial Intelligence in Agriculture

i) Crop Planning and Variety Selection

AI tools analyze historical yield data, soil characteristics, and climatic conditions to support crop and variety selection. This helps farmers choose suitable crops and varieties for specific locations and seasons, reducing production risks.

ii) Precision Nutrient Management

AI-based systems recommend precise fertilizer doses based on soil fertility status, crop demand, and growth stage. This improves nutrient use efficiency, reduces fertilizer wastage, and minimizes environmental pollution.

iii) Smart Irrigation Management

AI integrates sensor data and weather forecasts to optimize irrigation scheduling. Water is applied only when and where required, improving water use efficiency and reducing energy consumption.

iv) Pest and Disease Detection

Image-based AI tools analyze photographs of crop leaves and stems to identify pest and disease symptoms. Early detection enables timely control measures, reducing yield losses and pesticide use.

v) Yield Prediction and Crop Monitoring

AI models predict crop yields by analyzing crop growth data, weather patterns, and management practices. Accurate yield estimates help farmers and policymakers plan storage, procurement, and marketing strategies.

vi) Market Intelligence and Price Forecasting

AI tools analyze market trends, demand-supply dynamics, and price movements to provide market intelligence. This helps farmers decide the best time and place to sell their produce, improving income realization.

Working Mechanism of AI Applications in Agriculture

The functioning of AI in agriculture involves a systematic process. Initially, data is collected from multiple field-level and external sources. The data is then cleaned and standardized to ensure quality. AI algorithms analyze the processed data to identify patterns and relationships. Based on this analysis, the system generates predictions, alerts, or recommendations. These outputs are communicated to farmers through user-friendly digital interfaces. Continuous data flow and farmer feedback enable AI systems to learn and improve over time.

Benefits of AI-Based Digital Agriculture to the Farming Community

AI-driven digital agriculture empowers farmers with accurate, timely, and location-specific information. It supports precision farming, reducing unnecessary input use and lowering production costs. Timely advisories help farmers manage climatic risks, pests, and diseases effectively.

For small and marginal farmers, AI tools act as virtual advisors, providing access to expert knowledge that may otherwise be unavailable. Improved yield prediction and market intelligence

enhance income stability. Overall, AI-based digital agriculture strengthens farmers' decision-making capacity and promotes sustainable livelihoods.

Advantages of Artificial Intelligence in Agriculture

The major advantages of AI applications in agriculture include enhanced productivity, efficient resource utilization, reduced production risks, and improved environmental sustainability. AI enables real-time monitoring, early warning systems, and data-driven decisions. It also supports climate-smart agriculture by optimizing water and nutrient use and reducing greenhouse gas emissions.

Limitations and Challenges

Despite its potential, AI-based agriculture faces several challenges. Limited digital literacy among farmers, inadequate digital infrastructure, high initial investment costs, and data privacy concerns can restrict adoption. AI models may also perform poorly in regions with limited or unreliable data. Addressing these challenges requires capacity building, inclusive design, infrastructure development, and supportive policies.

Future Prospects of Artificial Intelligence in Agriculture

The future of AI in agriculture is promising due to rapid advancements in machine learning, automation, robotics, and renewable energy integration. AI-powered autonomous machinery, advanced climate risk assessment models, and real-time decision support systems are expected to become more widespread. In India, integrating AI tools with extension services, farmer producer organizations, and government programmes can accelerate adoption and ensure inclusive benefits. Continued research, public-private partnerships, and policy support will be crucial for scaling AI-driven digital agriculture.

Conclusion

Artificial intelligence is transforming agriculture by enabling intelligent, data-driven, and precise farming practices. As a core component of digital agriculture, AI supports informed decision-making, improves resource efficiency, and enhances resilience to climatic and market uncertainties. While challenges related to cost, infrastructure, and skills remain, the long-term benefits of AI applications in agriculture are substantial. With appropriate institutional support and farmer-centric implementation, AI-driven digital agriculture can significantly contribute to sustainable agricultural development, food security, and improved farmers' income.

Summary

Digital agriculture, supported by artificial intelligence, represents a paradigm shift in modern farming systems. AI applications in agriculture include crop planning, nutrient and water management, pest and disease detection, yield prediction, and market intelligence. These technologies help farmers optimize resource use, reduce risks, and improve productivity. Despite certain limitations, the future prospects of AI in agriculture are highly encouraging, making it a vital tool for achieving sustainable and resilient agricultural systems.

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CUTICLE AND INSECT COLORATION –
PHYSIOLOGICAL ROLES AND DEFENSIVE ADAPTATIONS

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Abstract

Insect coloration is a multifaceted biological trait arising from the intricate interaction between cuticle architecture, pigment chemistry, microstructural organization, and environmental influences. Unlike many other animals, insects express most external coloration through the cuticle, a non-living extracellular matrix composed of chitin, proteins, lipids, and pigments that simultaneously provides mechanical protection and optical functionality. This chapter integrates current knowledge on the structural and biochemical basis of insect cuticle coloration and examines its physiological, defensive, ecological, and evolutionary significance. Color production in insects occurs through pigmentary mechanisms primarily involving melanins, carotenoids, ommochromes, and pteridines and through structural coloration generated by nanoscale cuticular architectures such as multilayers, diffraction gratings, and photonic crystal-like arrangements. Pigmentary coloration is closely linked to physiological processes including cuticle hardening, desiccation resistance, immune defense, ultraviolet protection, and signaling, while structural coloration produces iridescent and metallic hues that enhance visual communication and predator deterrence. Increasing evidence demonstrates that pigments and structural elements often act synergistically, with pigments enhancing optical contrast and structural stability. Cuticle coloration plays vital roles in thermoregulation, hydric balance, and immunity, with darker, melanized cuticles frequently associated with reduced water loss, increased pathogen resistance, and improved performance in cooler or arid environments. Ecologically, coloration mediates key defensive strategies such as camouflage, aposematism, and mimicry, reducing predation risk and enhancing survival. These traits are shaped by genetic regulation and environmental plasticity, reflecting adaptive responses to habitat conditions, predation pressure, and climate variability. Overall, insect cuticle coloration represents a highly integrated adaptive system balancing physiological function, defense, and ecological interaction. Advances in molecular genetics and imaging technologies continue to reveal how cuticle biosynthesis and color regulation contribute to insect fitness, diversification, and resilience, offering valuable insights into evolutionary biology and potential biomimetic applications.

Keywords: Insect Cuticle, Coloration Mechanisms, Pigmentary And Structural Coloration, Defensive Coloration and Ecological Adaptation

1. Introduction

The insect cuticle is a multifunctional biological structure that determines insect survival, ecological success, and evolutionary diversification. Acting as both a mechanical exoskeleton and a dynamic physiological interface, the cuticle provides structural support, protection from physical and chemical stressors, and resistance to microbial invasion, while mediating interactions between insects and their environment (Vincent & Wegst, 2020; Andersen, 2023). Among its diverse roles, the generation of body coloration is one of the most visually conspicuous and biologically significant functions of the insect cuticle.

Insects exhibit remarkable diversity in body coloration, ranging from cryptic and subdued hues that facilitate camouflage to vivid, contrasting patterns that function as visual signals (Stevens & Ruxton, 2019; Garg *et al.,* 2024). This diversity arises from complex interactions among genetic regulation, cuticle composition, pigment biosynthesis, and microstructural organization. Consequently, insect coloration is not merely ornamental but an emergent property of the cuticle that integrates physiological performance with adaptive and defensive strategies (True, 2021).

The insect cuticle is a highly specialized extracellular matrix composed primarily of chitin, cuticular proteins, lipids, and pigments. Beyond forming a protective barrier, it generates most externally visible colors in insects (Duan *et al.,* 2025). Pigment-based coloration arises through the deposition of melanins, ommochromes, pteridines, and carotenoids within distinct cuticular layers, whereas structural coloration results from nanoscale arrangements in the epicuticle and exocuticle that manipulate light via reflection, interference, and diffraction (Vukusic & Stavenga, 2021; Wilts *et al.,* 2020). The interaction of pigmentary and structural mechanisms accounts for the extraordinary chromatic diversity observed across insect taxa.

Cuticle-mediated coloration is closely linked to physiological regulation. Variations in pigmentation and cuticular structure influence thermoregulation by altering solar radiation absorption and reflectance, thereby affecting body temperature, metabolic efficiency, and habitat suitability (Clusella-Trullas *et al.,* 2021). In addition, cuticular pigmentation and surface lipids contribute to water balance by reducing cuticle permeability and enhancing resistance to desiccation, particularly in insects inhabiting arid or climatically variable environments (Gibbs & Rajpurohit, 2023). Melanin deposition further contributes to cuticle sclerotization, increasing mechanical strength and providing protection against ultraviolet radiation and oxidative stress (Andersen, 2023).

Coloration also plays a central role in defense and ecological interaction. Cryptic coloration and disruptive patterning reduce detectability by visual predators, whereas conspicuous aposematic colors function as warning signals indicating toxicity or unpalatability (Stevens & Ruxton, 2019; Skelhorn *et al.,* 2021). These visual signals are frequently reinforced by chemical defenses sequestered or synthesized within the cuticle. Mimicry systems further illustrate the adaptive value of coloration, enabling non-defended species to gain protection by resembling defended models (Kikuchi *et al.,* 2022).

Advances in molecular genetics, genomics, and high-resolution imaging have strengthened understanding of how cuticle architecture, pigment biosynthetic pathways, and microstructural organization generate adaptive color phenotypes shaped by environmental and evolutionary pressures (Matsuoka *et al.,* 2021; Nature Communications, 2024). This chapter synthesizes current knowledge on insect cuticle structure, mechanisms of coloration, and their integrated physiological and defensive roles, emphasizing the cuticle as a dynamic adaptive system enhancing insect fitness and resilience.

2. Cuticle Architecture and Composition

The insect cuticle is a stratified, non-living matrix secreted by epidermal cells and composed of multiple layers with distinct structural and functional properties. The epicuticle forms the outermost protective and water-retentive barrier and is rich in lipids, waxes, and hydrocarbons that limit penetration by water, toxins, and microorganisms (Lockey, 2018; Blomquist & Bagnères, 2019). Beneath it lies the procuticle, which is subdivided into the exocuticle and endocuticle and contains chitin microfibrils embedded in a protein matrix arranged in helicoidal lamellae.

2.1 Layered Organization and Barrier Function

The composite architecture of the cuticle confers resistance to abrasion, compression, and penetration, thereby reducing vulnerability to predation and parasitism. Increased cuticle thickness and lamination enhance resistance to mechanical stress, particularly in heavily armored insects such as coleopterans (Vincent *et al.,* 2021). Cuticle chemistry and protein composition influence not only mechanical performance but also optical properties and pigment integration.

2.2 Sclerotization and Cuticular Hardness

Sclerotization is a post-ecdysial process involving enzymatic cross-linking of cuticular proteins through quinone intermediates derived from catecholamines. This process increases hardness, stiffness, and durability of the cuticle and often contributes to inherent dark coloration (Andersen, 2019). Highly sclerotized regions such as the head capsule, mandibles, thoracic plates, and elytra provide armor-like protection against predators and physical damage. Biomechanical studies demonstrate that sclerotized cuticles exhibit increased fracture resistance and load-bearing capacity, although excessive sclerotization may reduce flexibility, highlighting an evolutionary trade-off between protection and mobility.

3. Mechanisms of Color Production

Insect coloration arises through pigmentary mechanisms, structural mechanisms, or a combination of both.

3.1 Pigment-Based Coloration

Pigmentary coloration results from selective absorption of light by chemical compounds deposited within the cuticle during molting and cuticle differentiation (Nation, 2016). Major insect pigments include melanins, carotenoids, ommochromes, and pteridines.

Table 1: Major cuticular pigments in insects and their biological significance

Pigment Type	Primary Colors	Source	Major Physiological/ Defensive Roles
Melanins	Black, brown	Endogenous synthesis	Cuticle hardening, desiccation resistance, immunity, UV protection
Carotenoids	Yellow, orange, red	Diet-derived	Antioxidant activity, sexual signaling, warning coloration
Ommochromes	Red, brown	Endogenous synthesis	Cuticle and eye coloration, visual signaling
Pteridines	Yellow, white, red	Endogenous synthesis	Pigmentation, light reflection, signaling

3.1.1 Melanin-Based Coloration

Melanins are among the most widespread insect pigments, producing black, brown, and dark reddish hues. They are synthesized from tyrosine via enzymatic reactions involving phenoloxidase and related enzymes (True, 2003; González-Santoyo & Córdoba-Aguilar, 2012). Melanin deposition is closely associated with cuticle sclerotization, contributing to mechanical strength of the exoskeleton (Andersen, 2010). Beyond coloration, melanization reduces cuticular permeability, enhances resistance to desiccation (Parkash *et al.,* 2008), and plays a key role in immune defense through pathogen encapsulation (Whitten & Coates, 2022; Insects, 2023). Darker cuticles may also confer protection against ultraviolet radiation and oxidative stress (Frontiers in Zoology, 2025). Functional studies in hemimetabolous insects such as *Oncopeltus fasciatus* demonstrate that RNAi-mediated downregulation of melanin pathway genes alters black patterning in a region-specific manner, highlighting genetic control of aposematic coloration (Liu *et al.,* 2014; Liu *et al.,* 2016).

3.1.2 Carotenoid-Based Coloration

Carotenoids generate yellow, orange, and red coloration. As most insects cannot synthesize carotenoids de novo, these pigments are obtained through diet or symbiotic associations and selectively transported to the cuticle (Nijhout, 1991; Nation, 2016). Carotenoid-based coloration is commonly associated with aposematism and sexual signaling and may function as an honest indicator of physiological condition due to trade-offs between antioxidant use and visual display (Ruxton *et al.,* 2004).

3.1.3 Ommochromes and Pteridines

Ommochromes and pteridines are nitrogen-containing pigments responsible for red, brown, yellow, and white coloration in many insects, particularly Diptera, Lepidoptera, and Hemiptera. In addition to external coloration, these pigments regulate light absorption in compound eyes and enhance visual contrast. Their spatial distribution within the cuticle is tightly regulated during development, enabling species-specific patterns essential for recognition and communication (Nation, 2016; Nature Communications, 2024; Duan *et al.,* 2025).

3.2 Structural Coloration

Structural coloration originates from micro- and nanoscale cuticular architecture rather than pigments. Ordered multilayers, diffraction gratings, and nanoscale lamellae produce iridescent and metallic hues by manipulating incident light (Vukusic & Stavenga, 2021; Nature Communications, 2024). Studies of butterfly wing scales indicate that cytoskeletal scaffolding guides nanostructure formation, directly influencing fine-scale color expression.

3.3 Combined Pigmentary and Structural Coloration

In many insects, pigmentary and structural mechanisms act synergistically. Underlying melanin layers absorb stray light beneath structurally colored regions, increasing color saturation and contrast while maintaining cuticle strength (Kinoshita *et al.,* 2008). Such combined coloration is common in butterflies and beetles and supports mate recognition, predator deterrence, and species-specific signaling.

4. Physiological Functions of Cuticle Coloration

Table 2: Physiological functions associated with insect cuticle coloration

Cuticle trait	Color association	Physiological function	Adaptive significance
Increased melanization	Dark coloration	Reduced water loss	Survival in arid environments
Light pigmentation	Pale coloration	Reduced heat absorption	Adaptation to high temperatures
Structural nanostructures	Iridescent colors	Optical signaling	Mate recognition, predator confusion
Pigment–protein cross-linking	Dark, rigid cuticle	Mechanical strength	Resistance to predators

4.1 Barrier Function and Hydric Balance

Darker, melanin-rich cuticles are typically thicker and less porous, reducing water loss and increasing tolerance to arid conditions. This relationship between pigmentation, cuticle thickness, and desiccation resistance has been documented across multiple insect taxa (Frontiers in Zoology, 2025).

4.2 Thermal Adaptation

Cuticle coloration influences heat absorption and reflectance. Dark insects warm more rapidly in cool environments, whereas lighter coloration minimizes overheating in hot habitats, facilitating ecological adaptation across thermal gradients (Frontiers in Ecology & Evolution, 2024).

4.3 Immune Function

Melanin synthesis is tightly linked to immune responses. The phenoloxidase cascade generates reactive intermediates used in wound healing and pathogen encapsulation, enhancing resistance to fungal and bacterial infections (Whitten & Coates, 2022).

5. Defensive Roles of Cuticle Coloration

Coloration contributes substantially to insect defense by mediating interactions with predators and parasitoids.

5.1 Camouflage and Crypsis

Cryptic coloration and background matching reduce visual detection by predators and are common among herbivorous and ground-dwelling insects (Stevens & Merilaita, 2009).

5.2 Aposematism and Mimicry

Bright, high-contrast coloration functions as an aposematic signal advertising toxicity or unprofitability. Batesian and Müllerian mimicry systems exploit these signals to enhance predator avoidance and reinforce learned associations (Mallet & Joron, 1999; Skelhorn *et al.,* 2021).

5.3 Structural Features Enhancing Defense

Structural adaptations such as ultrablack cuticle maximize light absorption and may disrupt predator visual perception, further enhancing camouflage or deterrence (Beilstein Journal of Nanotechnology, 2024).

6. Chemical, Antimicrobial, and Pathogen Defense

6.1 Cuticular Lipids and Hydrocarbons

Epicuticular hydrocarbons and lipids contribute to waterproofing, chemical communication, and defense by masking cues used by predators and parasitoids (Blomquist & Bagnères, 2019). Certain compounds inhibit spore germination and microbial adhesion, increasing resistance to entomopathogenic fungi (Pedrini *et al.,* 2019).

6.2 Melanization and Immune Integration

Melanization at wound sites integrates cuticular defense with immune signaling. Reactive intermediates produced during melanin synthesis are toxic to invading pathogens, and insects with thinner or poorly melanized cuticles exhibit increased susceptibility to infection (Whitten & Coates, 2022).

7. Ecological, Evolutionary, and Genetic Regulation of Coloration

Cuticular coloration reflects trade-offs among thermoregulation, concealment, communication, and defense. Genetic pathways controlling pigment synthesis and cuticle protein expression interact with environmental factors such as temperature, nutrition, humidity, and population density to produce phenotypic plasticity (Clusella-Trullas *et al.,* 2007; Garg *et al.,* 2024). Temperature-dependent melanism and nutritionally constrained carotenoid coloration illustrate how color traits respond dynamically to environmental conditions, influencing ecological performance and geographic distribution under climate change.

Conclusion

The insect cuticle is a dynamic, multifunctional system integrating mechanical protection, chemical deterrence, immune defense, and visual signaling. Through pigmentary and structural mechanisms, cuticle-based coloration contributes fundamentally to insect physiological regulation, ecological interaction, and evolutionary diversification. Understanding these processes not only advances insect biology but also offers inspiration for biomimetic materials and innovative pest management strategies.
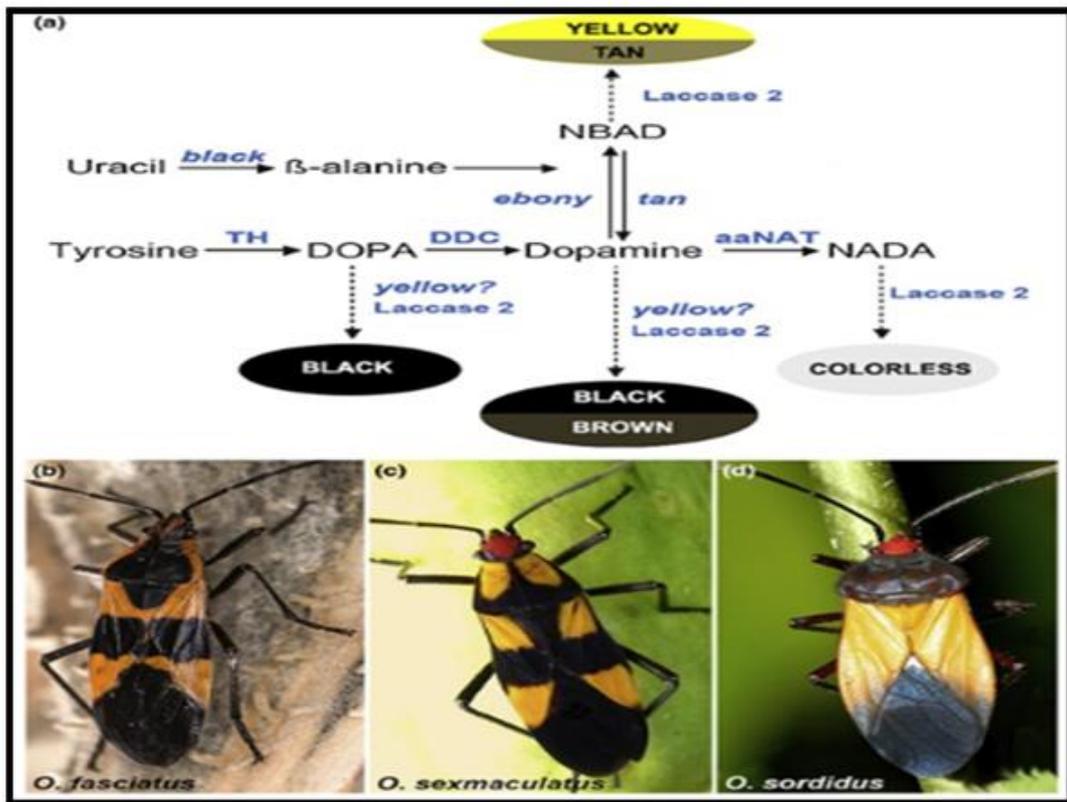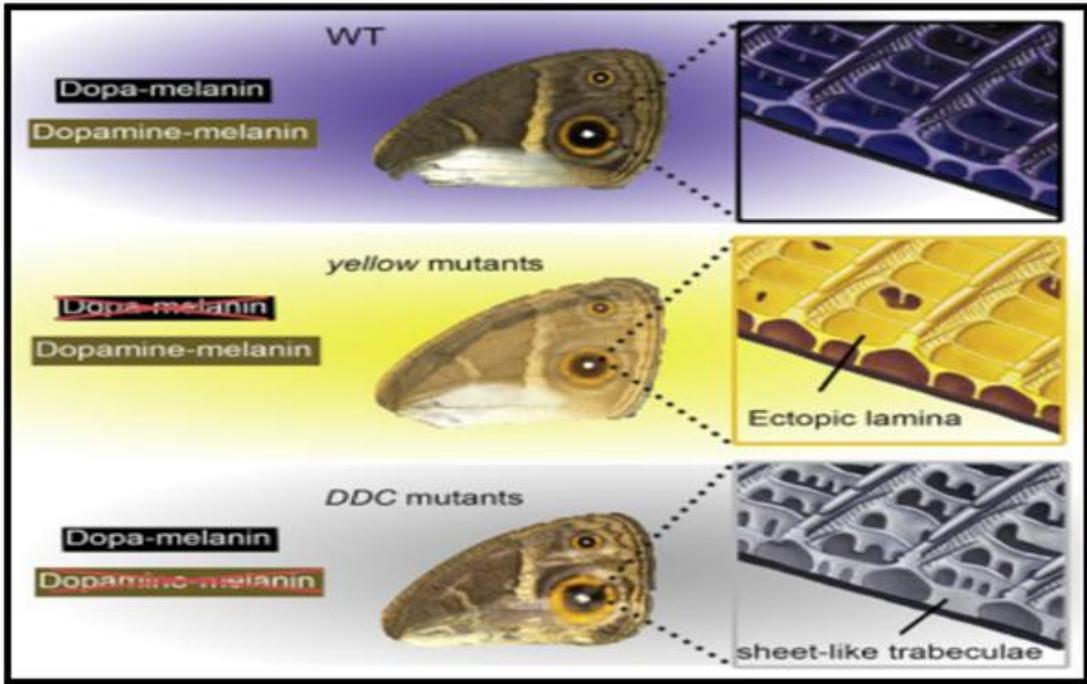
Melanin Pigmentation Pathway
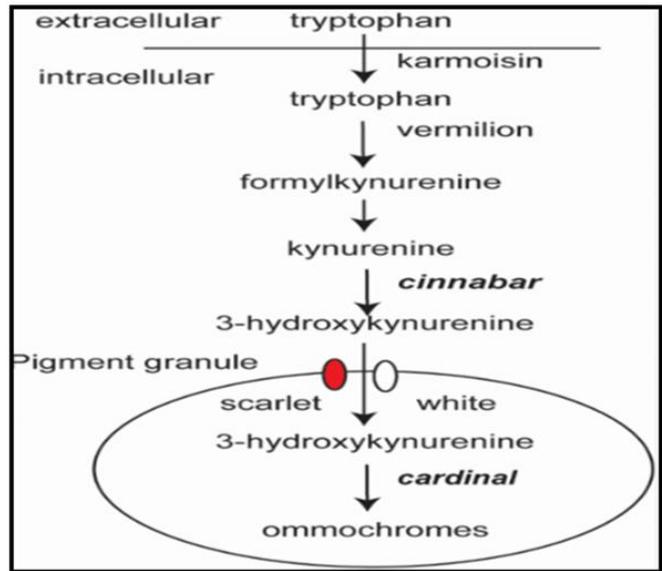
Ommochromes Pigmentation Pathway
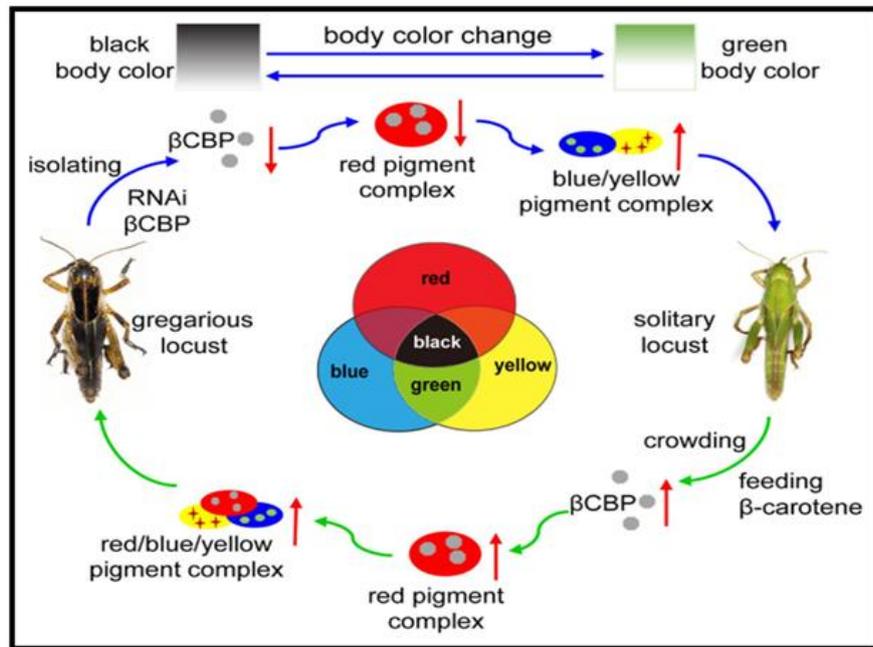
Carotenoids Pigmentation Pathway
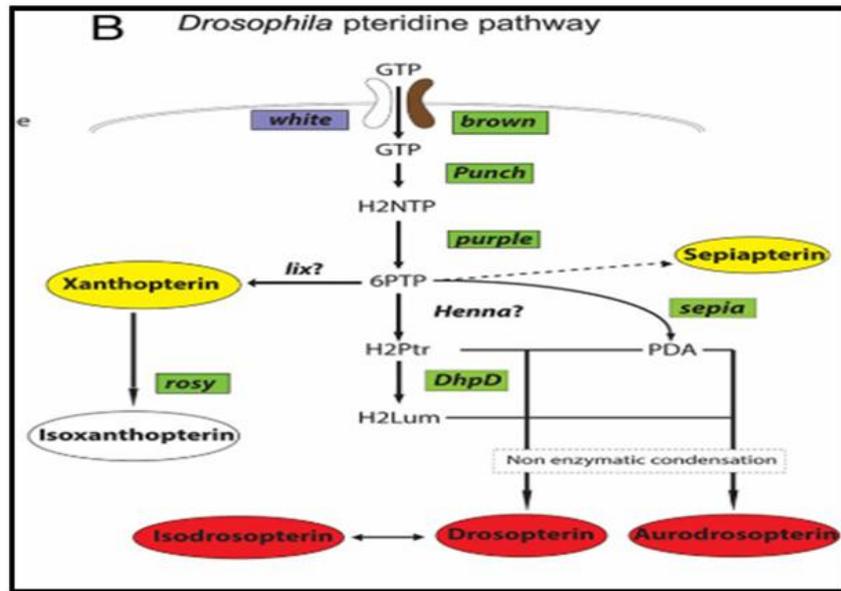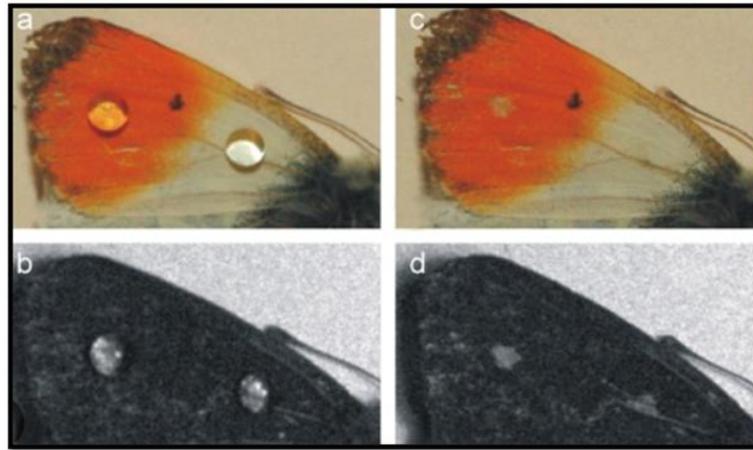
Pteridine Pigmentation Pathway

Camouflage

Mimicry

Aposematism

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LIVESTOCK AND ALLIED DISCIPLINES IN SUSTAINABLE AGRICULTURE

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Abstract

Livestock and allied agricultural enterprises constitute an essential component of sustainable farming systems by enhancing resource efficiency, ecological balance, and farm profitability. The integration of livestock with crop production promotes circular nutrient flows, where crop residues are utilized as animal feed and animal manure enriches soil fertility. Such interactions reduce dependency on synthetic fertilizers, lower production costs, and improve soil health. Sustainable livestock management further emphasizes balanced feeding, pasture-based grazing, preventive healthcare, animal welfare, and scientific manure handling to minimize environmental impacts while maintaining productivity. Allied sectors including dairy farming, poultry rearing, small ruminant production, fisheries, and apiculture diversify income sources, generate year-round employment, and strengthen household food and nutritional security. These enterprises utilize locally available resources and agricultural by-products, contributing to waste reduction and enhanced farm resilience. Moreover, climate-smart practices such as biogas production, carbon sequestration through grasslands, and efficient feed utilization help mitigate greenhouse gas emissions associated with livestock systems. By combining traditional knowledge with modern innovations and supportive policies, livestock-centered integrated farming systems offer a sustainable pathway for improving livelihoods, conserving natural resources, and ensuring long-term agricultural stability. Thus, livestock and allied disciplines are not merely supplementary activities but foundational pillars of sustainable agriculture and rural development.

Keywords: Sustainable Agriculture, Livestock Integration, Crop–Livestock Systems, Resource-Use Efficiency, Agro-Ecosystem Resilience.

Introduction:

Livestock has always been an integral component of agricultural systems rather than a separate enterprise. In traditional farming landscapes, crops, animals, trees, fisheries, and other allied activities functioned together in a mutually supportive cycle where the waste of one component

became the resource of another. Over time, however, specialization and industrialization separated livestock from cropping systems, leading to excessive input use, nutrient imbalances, environmental degradation, and rising production costs. Sustainable agriculture seeks to restore this lost integration by repositioning livestock and allied disciplines as essential pillars of ecological balance, farm profitability, and rural livelihoods.

This chapter discusses how scientifically managed livestock production, when combined with allied sectors such as dairy, poultry, fisheries, apiculture, and waste recycling, contributes to resilient, low input, and climate smart agricultural systems. The emphasis is on approaches that conserve natural resources, enhance animal welfare, reduce environmental footprints, and generate diversified income for farmers.

10.1 Role of Livestock in Sustainable Farming Systems:

Livestock contributes to sustainability through multiple pathways. Animals convert crop residues, grasses, and by-products that are unsuitable for human consumption into milk, meat, eggs, fiber, and manure. This conversion improves resource use efficiency and minimizes waste. In addition, livestock provides draft power, organic manure, and regular income, all of which stabilize smallholder farming systems. From a socioeconomic perspective, livestock acts as a living asset or "mobile bank" for farmers. Animals can be sold during emergencies, reducing vulnerability to crop failure or market fluctuations. Nutritionally, animal products supply high quality proteins, vitamins, and minerals, thereby improving household food security.

Ecologically, well managed livestock supports nutrient cycling. Manure enriches soil organic matter, enhances microbial activity, and improves soil structure. When integrated properly, livestock becomes a regenerative force rather than a polluting agent.

10.2 Integration of Crops and Livestock:

Integrated crop–livestock systems form the backbone of sustainable agriculture. In such systems, crops and animals are planned together rather than managed independently. Crop residues such as straw, Stover, husks, and bran serve as feed, while animal manure returns nutrients to the soil.

This integration provides several advantages:

- Reduced dependence on synthetic fertilizers
- Improved soil fertility and water retention
- Lower feed costs
- Diversified farm income
- Enhanced resilience to climatic variability

For example, after harvesting cereals, livestock can graze crop stubbles, which helps control weeds while providing feed. Similarly, green fodder crops can be included in rotations to restore soil nitrogen and supply balanced nutrition to animals. Such circular resource use reduces both waste and production costs.

10.3 Sustainable Feeding and Nutrition Management:

Feed production accounts for a large portion of livestock related environmental impacts. Therefore, sustainable feeding strategies aim to maximize local resources and minimize external

inputs. The use of crop residues, agro industrial by-products, and fodder trees reduces pressure on cultivated land.

Key practices include:

- Cultivation of perennial fodders and legumes
- Silage and hay preparation for lean seasons
- Use of multi nutrient blocks and mineral mixtures
- Incorporation of tree leaves and shrubs in diets
- Precision feeding based on animal requirements

Balanced nutrition improves feed conversion efficiency, reduces methane emissions per unit of product, and enhances animal health. Feeding animals only what they require prevents wastage and lowers costs. Moreover, indigenous breeds adapted to local feeds often perform better under low input systems than high producing exotic breeds that demand costly concentrate feeds.

10.4 Pasture Based and Grazing Systems:

Grazing systems play a crucial role in sustainable livestock management. Properly managed pastures reduce feed costs, conserve soil, and enhance biodiversity. Rotational grazing, where animals are moved between paddocks, prevents overgrazing and allows vegetation to regenerate.

Benefits of pasture based systems include:

- Improved soil organic carbon through root biomass
- Reduced soil erosion
- Better water infiltration
- Lower dependence on purchased feed
- Enhanced animal welfare

Grasslands also act as carbon sinks, contributing to climate change mitigation. Mixed pastures containing grasses and legumes improve protein content and reduce the need for synthetic nitrogen fertilizers. When animals graze naturally, their behaviour and health improve, reducing stress related diseases.

10.5 Animal Health and Welfare:

Healthy animals are more productive and require fewer chemical inputs such as antibiotics and synthetic drugs. Sustainable livestock production emphasizes preventive healthcare rather than curative treatments. Biosecurity, vaccination, hygiene, and balanced nutrition are fundamental.

Important measures include:

- Clean housing with proper ventilation
- Access to clean water
- Regular health monitoring
- Vaccination and deworming schedules
- Stress free handling

Ethical treatment of animals is increasingly recognized as both a moral responsibility and a production necessity. Stress reduces immunity and productivity, leading to economic losses. Welfare friendly practices ensure better growth, reproduction, and product quality while meeting consumer expectations for ethically produced food.

10.6 Manure Management and Nutrient Recycling:

Animal waste, if mismanaged, becomes an environmental pollutant. However, when properly treated, manure is a valuable resource. Sustainable manure management transforms waste into fertilizer and energy, closing the nutrient loop.

Practices include:

- Composting
- Vermicomposting
- Biogas production
- Slurry application through fertigation

Composted manure improves soil structure, increases water holding capacity, and enhances microbial diversity. Biogas plants convert dung into renewable energy for cooking and lighting, while the slurry serves as a nutrient rich fertilizer. Such systems reduce reliance on fossil fuels and chemical fertilizers, lowering both costs and emissions.

10.7 Dairy Farming in Sustainable Agriculture:

Dairy farming provides regular cash flow and nutritional security. Sustainable dairy systems prioritize indigenous breeds, balanced feeding, hygienic milk production, and efficient waste management. Small scale dairying integrated with crop farming allows farmers to utilize crop residues effectively while supplying manure for fields. Low input dairying reduces feed and medicine costs while ensuring stable returns. Value addition through processing into curd, butter, and cheese increases profitability. Cooperative models enable small farmers to access markets, technical support, and fair pricing.

10.8 Poultry and Small Ruminants:

Poultry, goats, and sheep are well suited to smallholder systems because they require limited space and investment. Backyard poultry provides eggs and meat with minimal inputs. Local breeds are hardy and resistant to diseases. Small ruminants convert shrubs and weeds into valuable products, making them ideal for marginal lands. Their quick reproduction cycles offer rapid income generation. Integrating these animals diversifies production and spreads economic risk.

10.9 Fisheries, Apiculture, and Allied Enterprises:

Allied disciplines complement livestock and crop production. Fish farming in farm ponds improves water use efficiency while providing protein rich food. Integrated fish–duck or fish–poultry systems recycle nutrients naturally. Apiculture enhances pollination, increasing crop yields and biodiversity. Honey and wax provide additional income. Mushroom cultivation, sericulture, and vermiculture also utilize agricultural waste, promoting resource recycling and entrepreneurship. Such diversification strengthens farm resilience and creates year round employment opportunities.

10.10 Climate Change and Environmental Considerations:

Livestock production is often criticized for greenhouse gas emissions. Sustainable approaches address this issue through improved feed efficiency, manure management, and pasture restoration. Reducing methane emissions through better nutrition and adopting biogas systems significantly lowers the carbon footprint.

Carbon sequestration through grasslands and agroforestry further offsets emissions. Integrating trees with livestock provides shade, improves microclimates, and enhances biodiversity. Climate resilient breeds that tolerate heat and diseases are also crucial for future sustainability.

10.11 Socioeconomic and Policy Dimensions:

Livestock supports livelihoods, particularly for women and small farmers. Policies that promote access to veterinary services, credit, insurance, and markets are essential. Capacity building through training and extension services enhances knowledge adoption.

Farmer cooperatives and producer organizations strengthen bargaining power and facilitate collective marketing. Government incentives for biogas, organic manure, and pasture development encourage sustainable practices at scale.

10.12 Future Prospects:

The future of sustainable livestock lies in combining traditional wisdom with modern innovations. Digital tools such as mobile based advisory services, precision feeding systems, and health monitoring sensors can improve efficiency. At the same time, local breeds and ecological principles must be preserved. A holistic approach that integrates livestock with crops, trees, and allied enterprises will ensure food security, environmental protection, and economic stability. Livestock should not be viewed merely as production units but as dynamic components of agroecosystems.

Conclusion:

Livestock and allied disciplines are central to sustainable agriculture. When integrated thoughtfully, animals contribute to nutrient recycling, soil health, income diversification, and resilience against climate and market risks. Sustainable feeding, grazing, healthcare, and waste management practices minimize environmental impacts while enhancing productivity. Allied activities such as dairy, poultry, fisheries, and apiculture further strengthen farm sustainability. Thus, livestock based systems that respect ecological limits, animal welfare, and farmer livelihoods represent a pathway toward truly sustainable agricultural development. By adopting integrated, resource efficient, and climate smart strategies, farmers can achieve productivity without compromising environmental integrity or future generations.

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ROLE OF INSECT COLLECTIONS AND MUSEUMS
IN TAXONOMIC RESEARCH

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Abstract

Insect collections preserved in museums form the foundational infrastructure of taxonomic research. As insects represent the most species-rich group of organisms on Earth, carefully curated reference material is essential for accurate identification, classification, and nomenclatural stability. Museum specimens serve as permanent physical evidence of species existence, enabling researchers to describe new taxa, verify species identities, reassess historical classifications, and test taxonomic hypotheses. By maintaining type specimens and well-documented voucher material, museums ensure reproducibility and long-term reliability in systematic studies. Beyond their central taxonomic role, insect collections function as long-term archives of ecological, geographical and temporal information. Specimen records containing locality, date and habitat data provide valuable insights for reconstructing species distributions, analysing phenological shifts and assessing biodiversity change across decades or centuries. As a result, these collections support research in evolutionary biology, conservation planning, agricultural pest management, invasive species monitoring, biosecurity and climate change science. Despite their scientific importance, insect museums face persistent challenges, including limited funding, declining taxonomic expertise, specimen deterioration and incomplete digitization. Nevertheless, recent technological advancements have significantly expanded their relevance. Developments in molecular techniques allow DNA extraction from historical specimens, strengthening integrative taxonomy by combining morphological and genetic evidence. Large-scale digitization initiatives, high-resolution imaging, and global biodiversity data platforms have improved accessibility and encouraged international collaboration. In a period of accelerating environmental change and documented insect declines, museum collections provide irreplaceable baseline data for understanding biodiversity patterns. Continued institutional support, technological modernization and interdisciplinary collaboration are essential to sustain their scientific and societal value. Insect collections remain indispensable for advancing taxonomic research and safeguarding global biodiversity knowledge.

Keywords: Insect Collections, Taxonomy, Museums, Biodiversity Documentation, Digitalization.

1. Introduction

Insects constitute the most species-rich group of organisms on Earth, representing more than half of all described living species and potentially millions more yet to be discovered. Despite centuries of systematic study, global insect diversity remains incompletely documented, particularly in tropical ecosystems and understudied habitats. The scientific enterprise that seeks to discover, delimit, name, and classify species where taxonomy depends fundamentally on physical reference material. Without preserved specimens, taxonomy would lack its empirical foundation.

Taxonomy is not merely descriptive; it is hypothesis-driven. Species hypotheses are proposed, tested, revised, and sometimes rejected based on comparative evidence. As emphasized by Winston (2007), preserved specimens are indispensable in this process because they allow taxonomic decisions to be verified, challenged, and replicated. Even though new advancements like molecular taxonomy have emerged morphological reference of the specimens is one of the important aspects of taxonomy. The stability and reproducibility of taxonomic knowledge depend on the continued availability of voucher specimens and type material. Without reference collections, species concepts would become subjective and unstable, undermining biological research across disciplines.

Museums and institutional insect collections thus function as repositories of biological evidence. They house the tangible records upon which species names are anchored and through which biodiversity is documented across space and time. These collections are not static archives; rather, they are dynamic research infrastructures that support systematic biology, ecology, conservation science, agriculture, biosecurity and evolutionary research.

Beyond taxonomy, insect collections serve as historical datasets. They preserve records of species distributions, phenological patterns, host associations and morphological variation spanning centuries.

In addition to preserving extinct taxa, museums also contain living species, which helps researchers measure biodiversity loss and reconstruct evolutionary histories. Gupta (2022) documented species richness and distribution across regional and temporal scales, highlighting the relevance of collections in biodiversity accountability. Thus, insect collections represent both scientific infrastructure and cultural heritage.

2. Historical Development of Insect Collections

2.1 Early Natural History Traditions

In the 17th and 18th centuries, early collections of insects emerged with the study of natural history. Over time, institutional museums connected to scientific societies and universities

replaced private cabinets of curiosity that reflected fascination with natural diversity. The significance of voucher specimens and type material was established by pioneering taxonomists like Linnaeus, who mostly relied on specimen-based studies. The rise of systemic biology in 18th century relied heavily on physical specimens to define species and develop classification systems. The concept of type specimen emerged as cornerstone of nomenclatural stability.

2.2 Institutionalization and Expansion

By the 19th century, natural history museums affiliated with universities and scientific societies replaced private cabinets. Colonial expeditions, global trade, and scientific surveys contributed to massive accumulation of insect material. National museums expanded rapidly, assembling comprehensive regional and global collections.

These historical collections laid the groundwork for modern systematics and biogeography. Many specimens gathered during this period remain scientifically valuable today. In fact, historical material is increasingly used to study long-term environmental change, invasive species pathways, and historical distribution baselines. The shift from individual collectors to institutional stewardship marked a critical transition, which made insect collections as an enduring scientific resource rather than personal assemblages.

3. Types of Insect Collections

Insect collection varies in accordance with the purpose, scope and other reasons.

3.1 Research Collections

Research collections are curated primarily for taxonomic and systematic studies. They contain type specimens, voucher specimens, well-documented series essential for species descriptions and revisions and undescribed specimens on which study has to be carries on. The importance of collecting sufficient series, keeping well-prepared specimens and depositing representative voucher specimens in reputable institutions so that published research can be validated and re-examined in the future (Upton and Mantle, 2010). They also note that poorly curated or inadequately preserved material is known to undermine the long-term scientific value of research. Research collection enables species revisionary studies, phylogenetic analysis, comparative morphology and biogeographic investigations. These are essential for clarifying species boundaries and stabilizing nomenclature.

3.2 Reference and Teaching Collections

It is very important that the insects collected must be are prepared, labelled, identified with utmost attention and they have to act as a representative of regional fauna. following the protocols. As these collections support education and helps in training students and routine identifications, often used in universities, museums and extension services to build strong foundational knowledge in taxonomy where accessibility and durability of specimens are essential. They are also used in pest diagnostics and applied entomology. These collections serve as training grounds for future taxonomists and practitioners, ensuring continuity of expertise.

3.3 Regional and Thematic Collections

Some collections focus on specific geographic regions or taxonomic groups (e.g., Lepidoptera of South India, aquatic Coleopterans, agricultural pests). These thematic collections are invaluable for,

- Regional biodiversity assessments
- Pest monitoring
- Endemism studies
- Conservation planning

They often document local faunal histories and may preserve records of species that have declined or disappeared.

4. Museums as Infrastructure for Taxonomic Research

Biological museums are not passive repositories of preserved organisms; they function as active scientific infrastructures that sustain the intellectual framework of taxonomy and systematic biology. The fundamental research infrastructure for taxonomy and associated biological sciences is made up of collections of insects and other biological materials. Insect collections, in particular, represent one of the largest and most information-dense biological archives on Earth. With hundreds of millions of specimens distributed across institutional collections worldwide, entomological museums provide the comparative material necessary for the documentation, verification, and reinterpretation of global biodiversity (Short *et al.,* 2018). More than half a billion preserved specimens and over a million known insect species make up entomological collections, which are the largest of any biological category.

Unlike digital databases or literature records, museum specimens are primary evidence (Suarez and Tsutsui., 2004). They embody morphological characters, geographic provenance, ecological context, and increasingly, genetic material. Taxonomic conclusions are anchored in these specimens, making museums indispensable for maintaining scientific rigor and continuity in species-level research. Thus, museums function simultaneously as:

- Repositories of primary taxonomic evidence
- Historical archives of biodiversity
- Platforms for integrative research
- Nodes in global scientific networks

4.1 Species Discovery and Description

The discovery and formal description of species depend critically on comparative material housed in museums. Nomenclatural stability is ensured by type specimens kept in museums, which act as authoritative reference points for species names and concepts. Species descriptions require examination of morphological variation across populations and comparison with existing taxa, particularly type specimens. Winston (2007) made a compelling case that systematic research that does not use museum artifacts to confirm or refute taxonomic identities cannot be regarded as scientific. This emphasizes how important insect collections are to strict taxonomic

procedures. By comparing physical traits between populations, museum specimens make it easier to find new species. Museum-preserved type specimens guarantee nomenclatural stability. Type specimens serve as the objective reference for species names, ensuring nomenclatural stability. As Sluys (2021) notes, type material preserved in natural history museums provides the ultimate benchmark for species concepts and prevents interpretative drift. Without access to such material, taxonomic revisions risk perpetuating historical errors.

Short *et al.* (2018) stress that entomological collections contain vast amounts of undescribed diversity. Many specimens collected during earlier expeditions remain unidentified or await modern analysis. This phenomenon sometimes referred to as "dark taxa" or "taxonomic backlog", illustrates that museums are not merely archives of known biodiversity but reservoirs of future discovery.

Wheeler *et al.* (2012) further argue that accelerating species discovery requires strengthening museum-based infrastructure, as many undescribed species are already sitting in drawers rather than waiting in the field.

Moreover, integrative taxonomy increasingly combines morphological, ecological, and molecular evidence. Museum specimens provide the morphological baseline against which genetic divergence can be interpreted. In this sense, collections remain central even in genomics-driven systematics.

4.2 Species Identification, Authentication and Revision

In the fields of systematics, ecology, evolutionary biology, natural resource management, biosecurity and biogeography, insect museums serve as authoritative sources. Hockland (2005) highlights that preserved invertebrate collections are essential for accredited identification services and quality assurance in regulatory contexts. In plant health and quarantine systems, museum-based identifications serve as authoritative determinations for invasive or economically significant species.

Gupta (2022) emphasizes that museums often act as the first line of defense in biodiversity documentation and environmental monitoring. This diagnostic function extends beyond taxonomy into applied science, particularly in agriculture and invasive species management.

Comparative series housed in museums allow taxonomists to distinguish between:

- Intraspecific variation
- Geographic polymorphism
- Sexual dimorphism
- True species-level divergence

Such distinctions are critical in groups where morphological differences are subtle. Pyke and Ehrlich (2010) note that museum specimens allow re-evaluation of historical identifications when new diagnostic frameworks emerge, preventing perpetuation of misapplied names. Thus, museums safeguard diagnostic reliability across generations of taxonomists.

Taxonomy is dynamic; when new information becomes available, species conceptions evolve. Researchers can utilize contemporary methods to reexamine historical material in museums.

4.3 Museums – "The Archives"

One of the most significant contributions of insect collections lies in their temporal depth. Specimens collected decades or centuries ago provide baseline data for assessing biodiversity change. Hoberg *et al.* (2009) argue that permanent and curated collections create an empirical archive essential for stabilizing our understanding of biodiversity over time. These archives allow researchers to detect shifts in species distributions, host associations, and ecological interactions. Kharouba *et al.* (2018) demonstrated how historical insect specimens reveal phenological shifts associated with climate warming. Similarly, Meineke *et al.* (2018) showed that herbarium and insect specimens can reveal increasing herbivory patterns over time in response to climate change.

Insects, due to their short generation times and environmental sensitivity, are particularly responsive indicators of ecological change. Museum collections thus serve as retrospective monitoring systems that extend far beyond the lifespan of contemporary field projects. Without museum records, claims of biodiversity loss would lack historical comparison.

4.4 Integrating Morphological and Molecular Data

The importance of museum collections as genetic and genomic resources has grown. Advances in DNA extraction from degraded material allow genomic analysis of specimens collected over a century ago. According to Short *et al.* (2018), habitat devastation and biodiversity loss have made it difficult or impossible to recollect many of the species that are represented in museum holdings thereby, digitization and molecular techniques are transforming entomological collections into integrated biodiversity data platforms. By extracting and analyzing fragmented DNA from ancient specimens, researchers can connect classical morphology-based taxonomy with contemporary phylogenetics and evolutionary biology. Suarez and Tsutsui (2004) predicted that the value of museum specimens would increase as molecular methods advanced. This prediction has proven accurate, as genomic-scale analyses increasingly depend on archived material. Ancient DNA approaches allow researchers to:

- Resolve cryptic species complexes
- Reconstruct phylogenetic relationships
- Assess historical genetic diversity
- Identify extinct lineages

Integrative taxonomy now combines:

- Morphology
- DNA barcoding
- Phylogenomics
- Ecological niche data
- Biogeographic modelling

Museums help in connecting these streams in an efficient way and helps in taking up taxonomy to next level.

5. Applications Beyond Taxonomy

According to Gibb and Oseto, (2019), insect collections are used by a variety of people outside of taxonomists, necessitating flexibility and better communication.

5.1 Conservation Biology

Collections document historical species ranges and abundance patterns. They help identify regions of endemism and conservation priority. Suarez and Tsutsui (2004) highlight that museum data are often the only records for rare or extinct species.

5.2 Climate Change Research

Kharouba *et al.* (2018) and Meineke *et al.* (2018) demonstrate how specimen-based datasets reveal phenological and distributional shifts linked to warming trends. Such long-term data are rare outside museum contexts.

5.3 Agricultural Entomology and Pest Management

Museum reference collections ensure accurate identification of pest species, including cryptic or morphologically similar taxa. Hockland (2005) underscores the importance of validated collections in regulatory diagnostics. Voucher deposition from pest management studies enhances reproducibility and allows future reassessment as taxonomy evolves.

5.4 Invasive Species and Biosecurity

Comparative analysis of museum specimens can determine whether a species is newly introduced or historically present but overlooked. Such distinctions influence management strategies and policy decisions.

6. Digitization and Data Accessibility

Curation, availability and usage of insect collections have all changed dramatically as a result of digitization activities. Less than 2% of insect specimens worldwide have been digitized, but even this small amount of digitalization has significantly increased availability to study (Short *et al.,* 2018). Large-scale data liberation is being made possible by technologies like whole-drawer photography and specimen-level data collecting, and specimen records are being made more widely available through global biodiversity platforms like the Global Biodiversity Information Facility (GBIF).

These digital projects promote taxonomic revisions, biogeographic research and conservation evaluations by enabling researchers to examine distributional, temporal and ecological data at previously unheard-of scales.

Insect museums are now widely available resources because of digitization efforts. Researchers from all over the world can study specimens remotely with the help of high-resolution photography, georeferenced datasets, and open-access platforms. However, digital surrogates do not replace physical specimens. Three-dimensional structures, microscopic characters, and molecular sampling still require direct access to material.

7. Major Entomological Museums

Several institutions worldwide serve as major centers for entomological research and house some of the largest insect collections (Wooden *et al.,* 2024).

Notable Entomology Museums Worldwide:

- **Natural History Museum, London (UK)** – One of the largest global insect collections, including significant type material.
- **National Museum of Natural History (Smithsonian), USA** – Contains one of the world's most extensive entomological collections.
- **Muséum national d'Histoire naturelle, Paris (France)** – Historically important insect collections from early expeditions.
- **Museum für Naturkunde, Berlin (Germany)** – Renowned for historical and type specimens.
- **American Museum of Natural History, New York (USA)** – Major center for systematic entomology.
- **Sphingidae Museum** – Specialized collection of hawk moths (Sphingidae).

Notable Entomology Museums in India:

- **TNAU Insect Museum, Coimbatore** – Houses ~1.14 lakh specimens across thematic sections on insect diversity, biology, beneficial insects, insect–plant interactions and cultural entomology.
- **National Forest Insect Collection (NFIC), Dehradun** – Contains ~300,000 pinned forest insect specimens, one of the largest forest insect repositories in India.
- **National Insect Museum, ICAR–NBAIR, Bengaluru** – A premier agricultural insect collection supporting taxonomy, pest identification, and biosecurity research.
- **Wankhar Entomology Museum, Shillong** – Known for collections of moths, beetles, butterflies and tarantulas.
- **Honey Bee Museum, Ooty** – Focuses on indigenous honey bees and traditional apiculture.

8. Challenges Facing Insect Collections

Insect collections suffer many obstacles despite their scientific significance. Many collection holders lack the resources necessary for long-term conservation, curation, and taxonomic

research, according to (Hockland, 2005). At the same time, the competence needed to maintain and interpret these collections is in risk due to the worldwide shortage of qualified taxonomists. The science of biodiversity is seriously at risk from the possible loss of rare specimens and institutional expertise.

Permanent and well-maintained museum collections are crucial for producing an empirical record that confirms our knowledge of the ecosystem (Hoberg *et al.,* 2009). Insect museums' fundamental role in systematics research may be lost in the absence of consistent institutional and financial support.

Despite their importance, insect museums face challenges including:

- Decline in taxonomic expertise
- Insufficient funding and staffing
- Physical degradation of specimens
- Under representation of tropical biodiversity

Addressing these challenges would require sustained investment and interdisciplinary collaboration.

9. Future Directions

The future of insect collections will increasingly involve the integration of advanced technologies and broader societal engagement. Artificial intelligence and machine learning are beginning to assist in specimen sorting, image recognition, and data management, helping reduce the taxonomic backlog. Automated digitization systems are also improving the speed and accessibility of specimen data worldwide.

Genomic tools will further enhance the scientific value of collections. Improved methods for extracting DNA from preserved specimens allow researchers to combine morphological and molecular evidence in integrative taxonomy. In this way, museums are evolving into both morphological and genetic resource centers.

Citizen science will also play a growing role. Public participation in biodiversity documentation, when properly validated, can complement museum records and expand geographic coverage. Strengthening links between museums and policymakers will ensure that taxonomic knowledge contributes directly to conservation planning, pest management, and biodiversity legislation.

Overall, insect collections are moving toward a more digital, collaborative, and policy-relevant future.

Conclusion

Insect collections and museums provide the essential foundation for taxonomic research. They anchor species names to physical specimens, ensure stability in classification, and allow scientific findings to be verified and re-examined over time.

Beyond taxonomy, these collections document historical biodiversity patterns and support research in conservation, agriculture, climate change, and biosecurity. In a time of rapid environmental change, their value has become even more significant.

Sustained investment, technological advancement, and continued taxonomic expertise are necessary to maintain and strengthen these institutions. Insect museums remain vital scientific infrastructures for understanding, documenting, and protecting global biodiversity.

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AN INTRODUCTION TO CORRELATION AND REGRESSION

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Abstract

Correlation and regression are essential statistical tools used to analyze the relationship between variables. Correlation measures the strength and direction of a linear relationship between two variables, indicating how one variable changes in response to another. Regression, on the other hand, goes a step further by not only measuring this relationship but also predicting the value of a dependent variable based on one or more independent variables

Keywords: Independent Variable, Dependent Variable, Correlation, Regression, Cause and Effect.

Introduction:

It is a common experience in our country that the level of production depends on the monsoon. In a year of good rainfall, the agricultural production is high and when monsoon fail, the agricultural output is low. We also know that farm with assured irrigation are generally a higher productivity per hectare than the un- irrigated one. Many other examples can be given off the relationship between variables. Economic theory teaches us that there is a relationship between income and consumption, cost & output. These all are the examples of two variables. Very often the relationship might extend to three or more variables. For example, productivity per hectare may not be only related to irrigation but also on the quality of seed, pesticides etc. the quantity demanded of a commodity may be related to disposable income, taste, prices of related commodities in addition to its own price. Similarly, in addition to output, production cost is related to wage rate and type of technology used. The consumption expenditure of a household will be related besides household income to household size, consumption habit and social status etc. There are various methods for measuring the relationship existing between the economic variables. The simplest are the correlation and regression analysis.

The measurement of degree of relationship between variables is called simple correlation and the degree of relationship connecting three or more variables is called multiple correlations. The correlation only indicated the degree and direction of relationship between two variables. However, it does not apply to cause-effect relationship, even when there are grounds to believe that casual relationship exist, correlation does not tell us which variable is the cause and which one is the effect. For example, the demand for a commodity and its price will generally be found to be highly co-related. But, the question whether demand depends on price or price depend s on demand is not be answered by correlation. In the example on demand and price, economic theory tells us that other thing being equal, quantity demanded of a commodity depends on its price. It

is possible to test this hypothesis and further to find out by how much on an average is demand expected to change if price change by certain percentage. This is done through regression analysis which describes the functional relationship and enables us to make estimates of one variable from another.

Correlation and Causation: Correlation analysis helps us in determining the degree of relationship between two or more variables. But it does not tell us anything about cause-and-effect relationship. Even a high degree of correlation does not necessarily mean that a relationship of cause and effect exists between the variables. The explanation of a significant degree of correlation may be any one of the following factors:

a. One variable being the cause of other: When variable causes the change of other variable, the variable which is the cause is called the subject or the independent variable and the other variable is called as relative or dependent variable.

b. Both variables being the result of a common cause or both the co-related variables may be influenced by one or more other variables: For example-(i) a high degree of correlation between the yield per hectare of rice and tea may be due to the fact that both are related to the amount of rainfall. But, none of the two variables is the cause of other. (ii) Suppose, the correlation of teacher's salaries and the consumption of liquor over a period of year comes out to be 0.9. This does not prove that neither teachers drink, nor does it prove that liquor sale increases teacher salaries. Instead both variables move together because both are influenced by third variable i.e long run growth in national income and population.

c. Both the variables may be mutually influencing each other so that neither can be designated as the cause and other the effect: There may be high degree of correlation between variables. But, it is very difficult to pin-point as to which the cause is and which the effect is. This is especially likely to be so in case of economic variables. Examples of such variables are such as demand and supply, price and production etc. These are mutually interacting. But, it is also possible that increase demand of a commodity due to growth of population or an upward pressure on price. Now, the cause is the increase demand and effect is price. That means price is a function of demand.

d. Chance: Sometime, it has been seen that between two variables a fair degree of correlation may be observed when one exist in the universe. It is just possible that the existence of correlation may be by-chance or accident. So, such a correlation observed between variables that cannot be casually related is called spurious or non-sense correlation. If there is a cause and effect, there is a correlation linear or otherwise. But, the reverse is not necessarily true. For example- there is a extremely high correlation between series represented by the production of pig and the production of iron. Yet, no one has ever believed that this correlation has any meaning or that it indicated the existence of cause-effect relationship.

Correlation: The term correlation indicates the relationship between two such variables in which with changes in the value of one variable, the value of the other variable also changes. On the other hand, it gives the relationship between two variables whether positive or negative.

Relationship depends upon how thick is the correlation i.e. it is perfect one or limited perfect one.

Measures of Correlation:

1. Scattered diagram;
2. Graphic method;
3. Karl Pearson's coefficient of correlation;
4. Coefficient of rank correlation;
5. Partial correlation coefficient;
6. Zero order correlation coefficient
7. Regression line (method of determining average relationship between variable

1. Scattered Diagram: The scatter diagram helps us to visualize the relationship between two phenomenons**.** It indicates the strength of relationship between two variables. If the point lies close to the line, the correlation is strong, on the other hand, greater dispersion of points about the lines implies weaker correlation. It gives only rough idea of the relationship between variables X&Y.
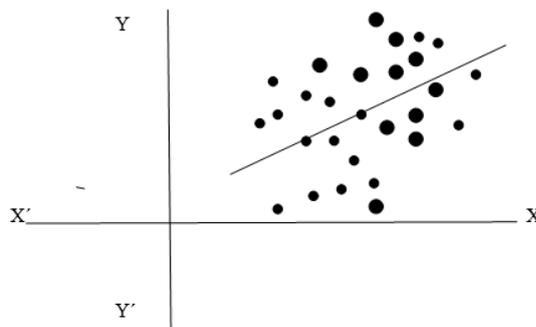
If the values are overlapping then, this measure is not a reliable because it simply gives us perfect correlation or direction of correlation. Correlation should be quantified.

Merits: It is very easy to draw a scattered diagram; it can be easily understood and interpreted; and values of extreme items do not affect this method, such points are always isolate in the diagram.

Demerits: It only gives a visual picture of the relationship of two variables; it only tells us whether there is correlation between the variables and if so, then in which direction positive or negative; it does not gives an idea about the precise degree of relationship as it is not amenable to mathematical treatments.

2. Graphic Method:
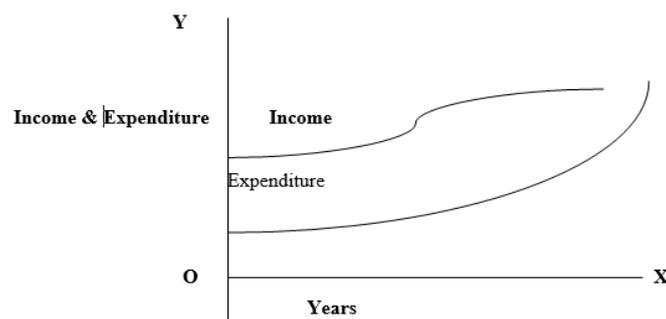
3. Pearson's Coefficient of Correlation: For precise quantitative measurement of the degree of relationship between X&Y, we use Karl Pearson's coefficient of correlation denoted by "r".

$$r_{xy} = \frac{\sum x_i y_i}{\sqrt{\sum x_i^2} \cdot \sqrt{\sum y_i^2}}$$

The value of the correlation coefficient may assume vary from -1 to +1. When r = +ve, It implies that there is a perfect correlation between X&Y. When r = -ve, it implies that there is perfect negative correlation between X&Y. When r =0, then the variables are uncorrelated.

The graphical representation of positive, negative and no correlation are shown below:

Positive Correlation   Negative Correlation   No Correlation
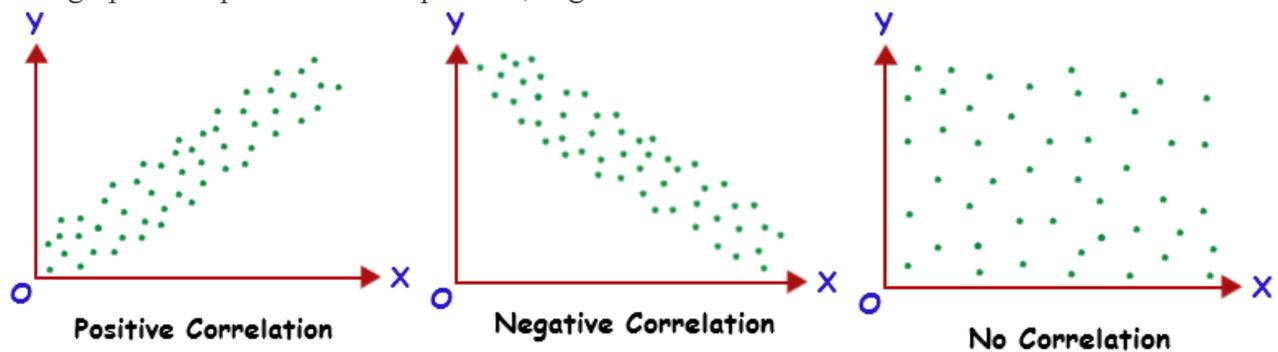
The Pearson correlation coefficient is denoted by the letter "r"

4. Spearmen's Rank Correlation Coefficient: If the variables are of qualitative or binary in nature then, it is possible to use this statistics. Rank correlation coefficient is calculated by the formula given below:

$$r' = \frac{6\sum D^2}{N(N^2-1)}$$

Where, D = difference between rank of corresponding pairs of X&Y.

N =number of observations.

5. Partial correlation coefficient: It measures the relationship between any two variables, when all other variables connected with two are kept constant. The simple correlation coefficient between two variables can be written as:

r_{12} = correlation coefficient between X_1 and X_2.

r_{13} = correlation coefficient between X_1 and X_3

r_{23} = correlation coefficient between X_2 and X_3

Therefore, Partial correlation coefficient between X_1 and X_2 when X_3 is kept constant is given by:

$$r_{12.3} = \frac{r_{12} - (r_{13})(r_{23})}{\sqrt{1 - r_{13}^2} \cdot \sqrt{1 - r_{23}^2}}$$

6. Zero-Order Correlation Coefficient (r_{x1x2}): The relationship between two variables at a time and none of them held constant. For more than two variables, we use partial correlation.

Types of Correlation:

a. **Simple correlation:** Measurement of degree of relationship between variables.

b. **Multiple correlations**: Degree of relationship connecting three or more variables is called multiple correlations.

c. **Positive correlation**: The correlation is said to be positive when the higher values of one variable are associated with the higher values of the other variable. Or when the lower values of one variable are accompanied by the lower values of the other variable. In such cases the movements of the two variables are in the same direction. For example, quantity of commodity supplied and its price. When the price rises, the quantity offered increase and when price fall, the quantity supplied decreases. If all the point lies on a line or curve, the correlation is said to be perfect positive.

d. **Negative or inverse correlation:** It happens, when the higher values of one variable are associated with the lower values of the other variable, the correlation is said to be negative. In such a case, the movements of the two variables are in the opposite direction. For example, quantity demanded and their prices are negatively correlated. If all the points lie on the line or curve, the correlation is said to be perfect negative.

e. **No correlation or zero correlation**: The correlation is said to be zero when two variables tends to change with no connection to each other. In the scattered diagram, the points are dispersed all over the surface of XY plane. For example, one should expect zero correlation between the height of inhabitants of a country and the production of steel or the weight of the students and the color of their hair.
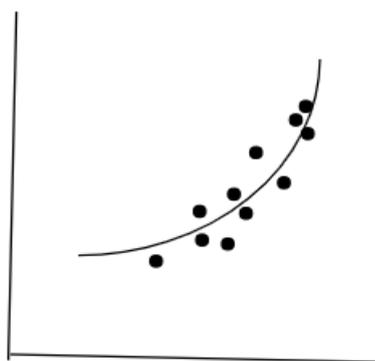
| Positive non-linear correlation | Negative non-linear correlation |
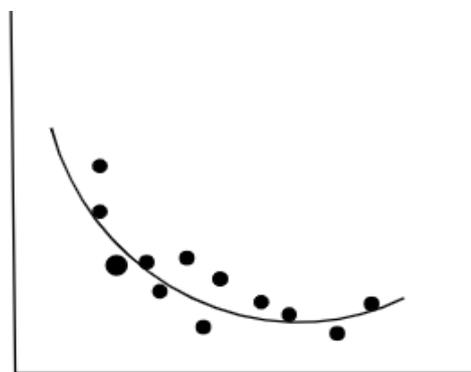
f. Linear and non-linear (curvilinear) correlation: The distinction between the linear and the non-linear correlation is based upon the ratio of change between the variables.

If the amount of change in one variable tends to bear constant ratio to the change in the other variable, then the correlation is said to be linear. For example,

X	10	20	30	40
Y	70	140	210	280

The correlation would be called non-linear or curvilinear if the amount of change in one variable does not bear a constant ratio to the amount of change in other variable. For example, if the amount of rainfall doubles, the production of wheat or rice etc. would not necessarily be doubled**.**

The techniques of analysis for measuring non-linear correlation are more complicated than those for the linear correlation. Therefore, we generally make an assumption that the relationship between the variables is of linear type.

g. Spurious or non-sense correlation: The variables that cannot concise ably be casually related is called spurious correlation or non-sense correlation. For example, there is a extremely high correlation between the series represented by the production of pig and the production of iron .Yet, no one have ever believed that this correlation has any meaning or that it indicates the existence of cause-effect relationship.

Limitations of Linear Correlation:

The formula

$$i)\ r_{xy} = \frac{\sum x_i y_i}{\sqrt{\sum x_i^2} \cdot \sqrt{\sum y_i^2}}$$

is applicable only when we have linear correlation between the variables. Though, the two variables may be strongly connected with non-linear relationship.

ii) The linear or simple correlation does not tell us to estimate the cause and effect relationship between the variables.

iii) Linear correlation coefficient does not help us in estimating the numerical values of the parameters i.e. regression coefficients.

Test of significance 'r' when the true population (ℓ) =0: If true population (ℓ) =0, the sampling distribution of 'r' (estimate of ℓ) is symmetrical.

t* = variable / SE (variable)= $r / \sqrt{(1-r^2)}/n-1$

Therefore, t* = $r(\sqrt{n-2}) / \sqrt{1-r^2}$

Then we compare the calculated value of 't' with the table value of 't' with (n-2) d.f. at 5% or 1% LOS.

Test of significance of "r" when the true population, is not equal to 0: it means the distribution is not normal but it is skewed. The higher value of the true population, more skewed the sampling distribution of 'r', then Fisher Test is applied.

Test of significance of rank correlation coefficient (r′) when true population, ℓ, =0: In this case the sampling distribution of r′ has a normal distribution. To test this statistics, Z-test is applied.

To conclude from the concept of correlation, we say that correlation only indicates the degree and direction of relationship between two variables. However, it does not apply to cause-effect relationship i.e. correlation does not tell us which variable is the cause and which one is the effect. For example, demand for a commodity and its price generally be found to be highly correlated. But, the question whether demand depends on price or vice-versa is not be answered by correlation theory.

Regression Analysis: Regression analyses describe the functional relationship between the variables and enable us to make estimate of one variable from another. For example, economic theory tells us that, other thing being equal, quantity demanded of a commodity depends on its price. It is possible to test this hypothesis and further to find out by how much on an average is

demand expected to change if the price change by certain percentage. This is done through regression analysis. It tells us the cause and effect relationship. The variable which is the cause is called the subject or the independent variable and the other variable is called as relative or dependent variable.

Thus, regression analysis attempts to establish the nature of relationship between the variables i.e. to study the functional relationship between the variable and thereby provide a mechanism for prediction or forecasting.

Regression: Regression is the measure of the average relationship between two or more variables in terms of the original units of the data.

Lines of Regression: Literary meaning of regression is 'stepping back towards average'. This concept of regression was first used in biometry. But, nowadays, regression word is used in statistics. For convenience if two variables are measured on the same individual then the corresponding scattered diagram will show that they are clustered around a curve what we called as regression line. It the curve is a straight line then that is known as regression line. There are two types of regression lines in case of bi-variate data:

i)   To predict the value of say 'y' variable for a given value of x-variable.

ii)   To predict the value of 'x' variable for a given value of y-variable.
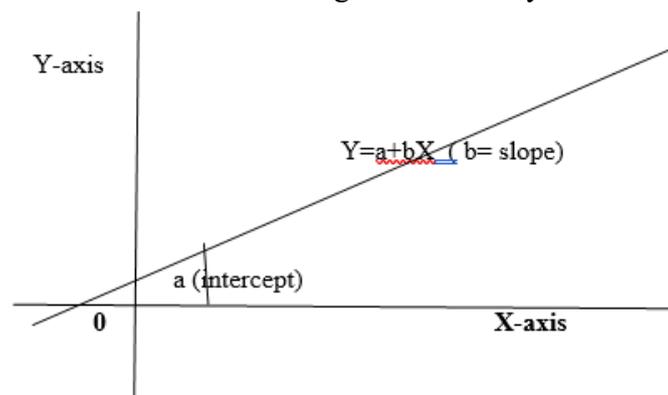
Properties of Regression line:

i)   Regression coefficient is affected by change of scale but not by the change of origin.

ii)   Means of observed and the estimated value from the regression line are the same. .

iii)   The magnitude of correlation coefficient between two variables denotes the proportion of variability in the observed value which is accounted for by the regression equation.

$Y = a + bX$

iv)   Correlation coefficient is the geometric means of the regression coefficient.

$$GM = (x_1.x_2)^{1/2}$$

$$r_{xy} = \frac{\sum x_i y_i}{\sqrt{\sum x_i^2} \cdot \sqrt{\sum y_i^2}}$$

v)   If one of the regression coefficient is <1, the other will be >1.

i.e. $b_{yx} < 1$ then $b_{xy} > 1$

vi) The arithmetic means (AM) of the regression coefficient is always greater than the value of the correlation coefficient (r), i.e. AM of two regression line is given by:

$(b_{yx} + b_{xy})/2 > r$

Also note that

- If two regression lines are perpendicular to each other, it means there is no correlation between the variables.
- If the regression lines moves from right to left, then, there is negative correlation.
- Linear correlation coefficient between two independent variables is zero.
- Correlation analysis does not provide numerical values for the coefficients of the functional relationship. i.e. slope and intercept cannot be worked out.

Equation: Statement of equality between the two quantities. For example, 5X =15 then, for X =3, there is equality**.**

Identity: If the equality is true for all values assigned to X. Then it is called identity. For example,

$(X^2 - 4) = (X-2)(X+2)$

Regression Equation: Algebraic expression of the regression line is the regression equation. For example:

Y = a + bX > this is regression line of Yon X.

X = a + bY > this is regression line of X on Y.

Model: It is the miniature of real world economic complexity.

Function: Functional relationship between dependent and independent variable.

Difference between Correlation and Regression:

i) Correlation coefficient is a measure of degree of co variability between and Y while, regression analysis is to study the nature of relationship between the variables so that we may able to predict the value of one variable on the basis of other.

ii) In correlation analysis, we cannot study the cause and effect relationship, while in regression analysis it is possible to study the cause and effect relationship.

iii) There may be a non-sense correlation between the two variables which is purely due to chance and has no practical relevance such as increase in income and increase in weight of a group of people. However, there is nothing like in regression analysis.

iv) Correlation coefficient is independent of change of scale and origin while, regression coefficients are independent of change of origin but not of scale.

Conclusion

To conclude from the concept of correlation and regression, we say that correlation only indicates the degree and direction of relationship between two variables. However, it does not apply to cause-effect relationship i.e. correlation does not tell us which variable is the cause and which one is the effect. For example, demand for a commodity and its price generally be found to be highly correlated. But, the question whether demand depends on price or vice-versa is not be answered by correlation theory. While regression analysis attempt to establish the nature of

relationship between the variables i.e. to study the functional relationship between the variable and thereby provide a mechanism for prediction or forecasting.

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AN INTRODUCTION TO DESCRIPTIVE STATISTICS

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Definition of Key Terms

- **Unit of Analysis**: Also referred to as cases. The most elementary part of what is being studied or observed. Example: Individuals, households, Countries, states, firms, industries, etc.

- **Variables:** A real valued function which takes any value. In other words, concepts, characteristics, or properties which can vary or change, from one unit of analysis to another. Please note that all variables must vary, if there is no variation among the different cases then it is not a variable. Some examples of variable include gender, social class, education, age, etc.

- **Dependent variable-DV:** If one variable depends upon or is a consequence of other variable, it is termed as dependent variable.

- **Independent Variable-IV:** A variable that is antecedent to the dependent variable is termed as independent variable. For instance, if we say height depends upon age, then height is dependent variable and age is independent variable. Another example is yield of wheat is dependent upon fertilizer consumption then,

$Y= f(X)$

In the above equation, Y is wheat yield in Kg/ha which is a dependent variable and X is the amount of fertilizer in Kg/ha which is a independent variable. Thus, from the above equation we say that yield of wheat is dependent upon fertilizer intake.

- **Random variable/ Variate:** A random variable is a real valued function which can be defined on the outcome of an experiment. In other words, when a variable takes certain value at certain probability. It is also known as stochastic variable, chance variable. For example, if we throw a coin or dye.

- **Continuous variable:** A variable which takes any value between two limits. For example-Height, weight, etc.

- **Discrete variable**: A variable which takes specified value. For example- no. of children in a family, no of grains in a cob whether in fraction or in whole number.

- **Extraneous variable:** The independent variables that are not related to the purpose of study, but may affect the dependent variable are termed as extraneous variable. E.g.

$Y= f(HYV, AREA, FERTILIZER)$ and also rainfall.

Here, rainfall is not included, so it may be extraneous variable.

A study must always be so designed that the effect on the dependent variable is attributed entirely to the independent variable(s) and not to some extraneous variable or variable(s).

Level of measuring variables:

(a) Nominal: Nominal scales are adopted for non-quantitative (containing no numerical implication) labeling of variables which are unique and different from one another.

Types of Nominal Scales:

Dichotomous/dummy: A nominal scale that has only two labels is called dichotomous. E.g. yes/no

Nominal with order: the labels on a nominal scale are arranged in an ascending or descending order. E.g. Excellent, Good, Average, Poor, Worst.

Nominal without order: Such nominal scale has no sequence. E.g. Black, White

(b) Ordinal: An ordinal variable has qualitative categories that are ordered in terms of degree or magnitude. E.g. A nominal variable includes class or degree obtained. The variable degree obtained may include the following categories: None, High school diploma, College/University degree, Masters, Advanced degree Ph.D. All of these categories are qualitative and are ordered in terms of the amount of education each individual has completed.

Another example-At Amazon .in every product has a customer review section where the buyers rate the listed products according to their buying experience, product features quality, usage, etc. The rating so provided are as follows: 5Star-Excellent; 4Star-Good; 3Star-Average; 2Star-Poor; 1-Star-Worst.

(c) Interval Scale: An interval scale is also called as cardinal scale which is the numerical labeling with the same difference among the consecutive measurements units. With the help of this scale, researcher can obtain a better comparison between the objects. E.g. A survey conducted by an automobile company to know the number of vehicles owned by the people living in a particular area who can be its prospective customers in future. In adopting the interval scaling technique for the purpose and provided the units as 1, 2, and 3,4,5,6 to select from. In this scale every unit has the same difference, i.e.1, whether it is between 2 and 3 or 4 and 5.

(d) Ratio Scale: One of the most superior measurement techniques is the ratio scale. Similar to an interval scale, a ratio scale is an abstract number system. It allows measurement at proper intervals, order, categorization and distance with an added property of originating from a fixed zero. Here, the comparisons can be made in terms of the acquired ratio.

Descriptive Statistics:

Descriptive statistics are often used to describe variables. Descriptive statistics are performed by analyzing one variable at a time (univariate analysis). All researchers perform these descriptive statistics before beginning any type of data analysis.

Frequency: A number of times a thing happens.

Frequency distribution: If a large number of data are summarized into different classes and the class frequency are also given. Then, this representation of classes along with class frequency is called frequency distribution or frequency tables.

Weight/ classes	40	50	60
16-18 years	10		
18-20 years		20	
20-22			5

Table shows that for 35 students (in total) 10 is the frequency of the students having weight 40 Kg and age 16-18 and so on. This is called frequency distribution or distribution table. 16 are the lower limit of the class and 18 is the upper limit of the class.

Open Class: When ever either upper or lower or some time both limits are not given, we call them as open class. E.g.

Classes	Frequency
0-18 years	10
18-20 years	20
20 and above	22

Class mid point: It is the middle point of the class and is calculated by:

(Upper limit+ lower limit)/2

Class interval or width of the class: Upper limit minus lower limit is called class interval.

Absolute Frequency: This tells you how many times a particular category in your variable occurs.

Relative Frequency: This tells you the percentage of each category/ value relative to the total number of cases.

Cumulative Frequency: This is simply a commutation of the relative frequency for each category/ value

For Example: Table provides an example of a frequency table for an ordinal variable (note it is ordinal because the categories are qualitative and ordered) named socioeconomic class. If there were numbers assigned to each category that were also ordered, we could treat this as an interval level variable.

Frequency Table: Socioeconomic Class

Socioeconomic Class	Frequency	Per cent	Cumulative Percent
Upper	50	7.14%	7.14%
Upper Middle	150	21.43%	28.57%
Middle	300	42.86%	71.43%
Lower Middle	150	21.43%	92.86%
Lower	50	7.14%	100%
Total	700	100%	

Cross tabulation: This is also referred to as grouped frequency table for two variables. A cross tabulation simply presents the absolute frequency broken down by categories of two or more variables. It is also possible to find percentages in these types of tables. For instance, using the example below, we can find the percentage of young people that listen to music.

Cross tabulation of music preference and age

Preference	Age		
	Young	Middle Age	Old
Music	14	10	3
News-Talk	4	15	11
Sports	7	9	5

There are four characteristics by which we can compare two or more than two distribution. These are:

1.   Central Tendency or central value or central class

2.   Dispersion

3.   Skewness

4.   Kurtosis

We will discuss each one by one below.

1.   Measures of Central Tendencies:

Central Tendency: Central tendency is the value of the variable which represents the distribution thoroughly. It may or may not be one of the values of the distribution. Central tendency must be measured in certain unit. E.g. Class Representative.

Measures of Central Tendency: These are three namely mean, median, and mode.

Mean: Mean is of different types:

i)   Arithmetic Mean(AM)

ii)   Geometric Mean (GM)

iii)   Harmonic Mean(HM)

iv)   Weighted Mean(WM)

v)   Pooled Mean(PM)

(i)   Arithmetic Mean (AM): It is calculated by

$$\bar{x} = \frac{X_1 + x_2 + x_3 \ldots \ldots + x_n}{N}$$

$$\text{Or} \quad \bar{x} = \frac{f_1 x_1 + f_2 x_2 + \ldots \ldots f_n x_n}{f_1 + f_2 + \ldots \ldots + f_n}$$

$$\text{Or} \quad \bar{x} = \frac{\sum_{I=1}^{n} f_i x_i}{N}$$

Advantage of Arithmetic Mean: Even one or two values are missing; even then we can calculate arithmetic mean.

Disadvantage of Arithmetic Mean: It gives more weight age to the extreme values.

(ii)   Geometric Mean (GM): GM of 'n' number is the nth root of the product. Suppose the numbers are $x_1, x_2, x_3.........,x_n$, then

GM= $(x_1.x_2..............x_n)^{1/n}$

Take log on both sides, we get:

Log GM= 1/n {log x_1+ log x_2+...............+ log x_n}

If x_1 is having frequency f_1

X_2 is having frequency f_2

$.x_n$ is having frequency f_n then,

$$GM= \left(\underline{x_1^{f1} \cdot x_2^{f2} ....x_n^{fn}} \right)^{1/\sum fi = N}$$
$$n$$

$$\text{Or Log GM} = 1/N \sum_{i=1} (f_i \log x_i)$$

For example, GM of 2, 4, 8 is $(2.4.8)^{1/3} = (64)^{1/3} = 4$

Merits of Geometric Mean:

a)   It is rigidly defined.

b)   It is based on all the observation of a series.

c)   It is capable of further algebraic treatment.

d)   GM is not much affected by the fluctuation of sampling.

Demerits of Geometric Mean:

a)   It is neither easy to calculate nor easy to understand.

b)   If any value in a series is zero, then we cannot calculate the Geometric Mean. E. g. GM= 2x4x0x8=0

c)   If one of the value or the item in a series is negative then also we cannot find the GM.

d)   Like arithmetic average, it may be a value which does not exist in a series.

e)   It gives more weight age to the smaller value.

(iii)   Harmonic Mean (HM): It is the reciprocals of AM's of the reciprocals. Suppose there are 'n' observation, then

$$\text{AM's of reciprocals} = \frac{1/x_1 + 1/x_2 + ... + 1/x_n}{N}$$

$$\text{Or } 1/H = \frac{1/x_1 + 1/x_2 + ... + 1/x_n}{N}$$

$$\text{Or } H = \frac{N}{1/x_1 + 1/x_2 + ... + 1/x_n}$$

Example: Find out the AM, GM, &HM of 2, 4, 8.

Solution: AM = (2+4+8)/3 =14/3 =4.66

GM = $(2.4.8)^{1/3}$ = $(64)^{1/3}$ = 4

HM = 1/H = (1/2+1/4+1/8)/3 = (4+2+1)/24 = 7/24

or H = 24/7 =3.42

It is clear from the above example that AM ≥ GM ≥ HM

When we should make use of Harmonic Mean?

Whenever we deals with quantum of time and rate, then we use HM. E.g. A cyclist cover 1st mile @ 3miles/hour and 2nd miles @ 4miles/hour, then

HM = 1/H = (1/3 +1/4)/2 = 7/24 = 3.42

HM gives more weight age to the smaller values.

Merits of Harmonic Mean (HM):

i)   It is rigidly defined.

ii)   It is based on all the observation of the series.

iii)   Capable of further algebraic treatment.

iv)   It is not much affected by the fluctuation of sampling.

v)   It gives more weight age to the smaller values.

vi)   It measures the relative change.

Demerits of Harmonic Mean:

i)   It is not readily understood nor can be calculated with ease.

ii)   It gives very high weight age to smaller value.

iii)   It is usually a value which does not exist in a series.

iv)   Generally it is not a good representative of statistical technique.

(iv)   Pooled Mean (PM): Pool up all the means and then take average. Suppose $n_1 = \bar{x}_1$, $n2 = \bar{x}$,……….. $n_n = \bar{x}_n$

$$\text{Therefore, PM} = \bar{x} = \frac{n_1 \bar{x}_1 + n_2 \bar{x}_2 + \ldots + n_n \bar{x}}{n_1 + n_2 + n_3 + \ldots\ldots\ldots + n_n}$$

$$\text{or PM} = \bar{x} = \frac{\sum_{i=1}^{n} n_i \bar{x}_i}{\sum_{i=1}^{n} n_i}$$

(v)   Weighted Mean (WM): Suppose weight w_1 is assign to x_1, weight w_2 is assign to x_2 and weight w_n is assign to x_n then, weighted mean is calculated by:

$$WM = \frac{w_1 x_1 + w_2 x_2 + \ldots\ldots\ldots + w_n x_n}{w_1 + w_2 + \ldots\ldots\ldots + w_n}$$

$$Or \quad WM = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}$$

Difference between mean and average: In means, we have different types of means like AM, GM, HM, PM, WM. While average gives only average mean.

Average: It is an attempt to find one single figure to describe the whole of figures. In other word, an average value is a single value within the range of the data that is used to represent all the values in the series. Since average is somewhat within the range of the data, it is also called a measure of central value/ tendency.

Characteristics of a good average:

a)   It should be rigidly defined.

b)   It should be based on all the observation of the series.

c)   It should be capable of further algebraic treatment.

d)   It should be easy to calculate and simple to flow.

e)   It should not be affected by the fluctuation of sampling.

Drawbacks of Arithmetic Average:

a)   It gives greater importance to higher items of a series and lesser importance to smaller items.

b)   It gives fallacious conclusion.

c)   Arithmetic average some time gives such results which appear almost absurd.

Mathematical Properties of Arithmetic Average:

i)   The sum of the deviation of the items from the mean is always zero.

ii)   The sum of the squared deviation of the items from the mean is less than the sum of the squared deviation of the items from any other value.

Cumulative Series: Cumulative series can be either "more than type" or "less than type" In more than type the frequencies are cumulative upwards so that the first class interval has the highest frequency and it goes on decline in the subsequent class. In less than type, the frequencies are cumulative downwards so that the first class has the lowest frequency and the subsequent class has the higher cumulative frequency. Hence we can say frequency above or below a particular point is the cumulative frequency.

Change of origin and change of scale: Whenever we are adding or subtracting the unit in any item or variable, then it is called change of origin and when we divide the unit in a particular item or variable then it is called change of scale.

Median: **Median is the value of the variables which divide the total frequencies into two equal half such that half of this lies above this value of variable and other half below this value of variable**. (Either in ascending or descending order). E. g.

X =1, 2, 4, 6, 7.

F = 1, 1, 1, 1, 1.

Hence 4 is the median value.

If x = 1, 2, 4, 6, 7, 8, and

f =1, 1, 1, 1, 1, 1 then take mean = (4+6)/2 = 5 Therefore, 5 is the median value.

If the date is given in distribution form then the median is calculated as:

$$M = L + \frac{(N/2 - C)}{f} h$$

Where, L = Lower limit of the median class,

N = Total frequency,

C = Cumulative frequency just above the median class,

f = Frequency of the median class,

h = Width of the median class.

Merits of Median:

i)   Even if the value of extreme is not known, median can be calculated if the number of item is known.

ii)   It can be easily calculated and understood without any difficulty.

iii)   It is rigidly defined.

iv)   It is not affected by the values of extreme items.

v)   It gives best results in a study of those phenomenon's which are incapable of direct quantitative measurement.

Drawbacks of Median:

i)   It is not suitable of further algebraic treatment.

ii)   It is more likely to be affected by the fluctuation of sampling then the average.

iii)   Arrangement of items in ascending order is somewhat difficult.

Mode: Mode is the value of the variable which occurs more frequently.

E.g. 1, 1, 2, 2, 2, 3, 4, 5. Here, 2 is the value of the mode.

In group distribution, mode can be found out by:

$$Mode = L + \frac{\blacktriangle_1}{\blacktriangle_1 + \blacktriangle_2} h$$

Where L = Lower limit of the model class;

$\blacktriangle_1$ = Difference in the frequency of the model class and the preceding class;

$\blacktriangle_2$ = Difference in the frequency of the model class and the following class;

h = width of the model class.

Model Class: It is that class in which mode lies.

Suppose by chance, if there are two equal frequency's i.e. 4&5 then, we use approximation method

Mean – Mode = 3 (Mean- Median).

Merits of Mode:

i)   It possesses the merits of simplicity.

ii)   It is commonly understood.

iii)   It cannot be a value which cannot found in a series.

iv)   It is affected by the values of extreme items.

v)   For the determination of mode, it is not necessary to know the values of all the items of series.

Drawbacks of Mode:

i)   Mode is ill-defined, indeterminate and indefinite.

ii)   Not based on all the observation of a series.

iii)   Mode is not capable of further mathematical treatment.

iv)   Mode may be unrepresentative in many cases.

v)   In many cases, it may be impossible to get a definite value of mode.

Note: Mode is the best measurement of normal data i.e. data normally distributed and median is the best measure of skewed distribution and arithmetic mean is affected mostly with extreme values. Standard deviation is most important measure of variation for any type of data.

2. Dispersion:

Suppose

| A | 10 | 15 | 75 | 1000 | Average-275 |
| B | 200 | 300 | 150 | 450 | Average-275 |

Here, average figure of A&B is equal i.e. 275. Here, the measure of central tendency fails and in this case we go for dispersion. Dispersion means spread or scattered of values around the central tendency is called dispersion. In the above example workers in factory 'A' are more spread than in factory 'B'. Dispersion is also measured in certain unit.

 Measures of Dispersion:

i)   Range;

ii)   Inter quartile range;

iii)   Inter decile range;

iv)   Quartile deviation/ semi inter quartile range;

v)   Standard deviation;

vi)   Mean deviation from mean;

vii)   Mean deviation from mode;

viii)   Mean deviation from median.

Why should we go for dispersion? Whenever Central tendency fails to resort two or more than two distribution, then we go for dispersion. For instance, let there are two factories 'A' &'B'

A	Rs.50	Rs.100	Rs.75	Rs.175	Average- Rs. 100
B	Rs. 10	Rs. 50	Rs.40	Rs. 300	Average- Rs. 100

From here we can draw the conclusion that although the average wages are the same. But different workers in these two factories possess different wages for their work.

i)   Range: Difference between higher limit and the lower limit in a class e.g. 300-10 = 290

Note: For calculating range, the values of the variables are taken into account and the frequencies are completely ignored.

Coefficient of range: The relative measure corresponding to range is called coefficient of range.

Coefficient of range = (L-S) / (L +S) where, L = Largest item and S = Smallest item

Coefficient: means a pure number that is independent of the unit of measurement.

Quartile: The value which divide the data into four equal parts. In other words, it is the value of the variable below which 25% of the frequency lies and is known as first quartile or lower quartile. (Q_1).

Second Quartile: it is the value of the variable below which 50% of the frequencies lies and is denoted by (Q_2).

Third Quartile: It is the value of the variable below which 75% of the frequencies lies and is denoted by (Q_3).

 F 0-----------25(Q_1) ------------50(Q_2)------------75(Q_3)--------100

Caution: We don't go for the value of the variable below which 100% of the frequency lies.

ii)   Inter quartile range: Difference between the third quartile and the first quartile i.e. Q_3-Q_1

Quartile deviation/ semi inter quartile range:

 $Q = (Q_3-Q_1)/2$

How to calculate quartile if the data is given in distribution forms?

 Quartile (Q_i) = L + { iN/4—C}.h /f

 i= 1,2,3

When i =1, it is first quartile;

When i =2, it is second quartile;

When i =3, it is third quartile.

L = lower limit of the class in which quartile lies;

N = Total frequency;

C = Cumulative frequency just above the quartile class;

h = Width of the quartile class;

F = Frequency of the quartile class.

The above formula is valid only when data are to be arranged in ascending order and the cumulative frequency is of "less than type".

In a series of individual observation and in a discrete series, the value of lower and upper quartile would be the value of $\{(N+1)/4\}^{th}$ and $3\{(N+1)/4\}^{th}$ item respectively.

Quartile Class: it is that class in which the desired quartile lies.

Decile: These are the values which divide a series into ten equal parts. In a series of individual observation and in a discrete series, the value of lower and upper decile would be the value of D_1 = value of $\{(N+1)/10\}$th and D_2 =value of $2\{(N+1)/10\}^{th}$ and D_9 = value of $9\{(N+1)/10\}^{th}$ item respectively.

Note: In a continuous series the value of quartile and decile is calculated by N/4 and N/10 respectively.

iii)   **Inter decile range:** it is the value of the variable below which ten % of the frequency lies and is represented by D.

Inter decile range: (D) = D_9 -- D_1

If the data is given in distribution forms, then

Di = L + { iN/10—C}.h /f

Where, i= 1,2,3------9;

L = lower limit of the decile class;

N = Total frequency;

F = Frequency of the decile class;

C = Cumulative frequency just above the decile class;

H = Width of the decile class.

iv)   **Mean deviation from mean:** Deviation from mean and then take the mean

$$MD \text{ from mean} = \frac{1}{N}\sum f_i \left| x_i - \bar{x} \right|$$

$$Where, N = \sum_{i=1}^{n} f_i$$

Here, deviation from mean = $(x_1 - \bar{x})$, $(x_2 - \bar{x})$,------------$(x_n - \bar{x})$,----- $(x_i - \bar{x})$

v)   **Mean deviation from mode:**

$$MD \text{ from mode} = \frac{1}{N}\sum f_i \left| (x_i - mode) \right|$$

vi)   **Mean deviation from median:**

$$MD \text{ from median} = \frac{1}{N}\sum f_i \left| (x_i - median) \right|$$

3. Skewness:

Departure from symmetry is known as skewness and when a distribution is not symmetrical (or is asymmetrical) it is called skewed distribution. It is of two types:

i) Positive skewness/positively skewed distribution: In a positively skewed distribution, the value of mean is maximum and that of mode is least- the median lies in between the two. In this case, excess tail is on the right hand side.
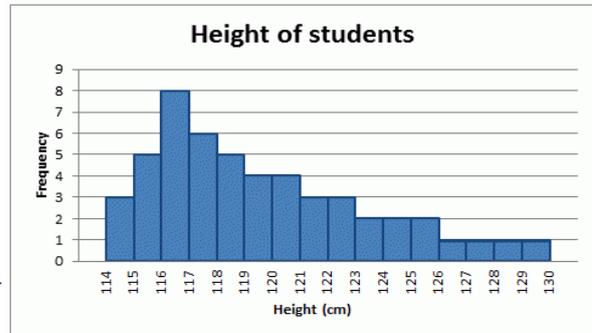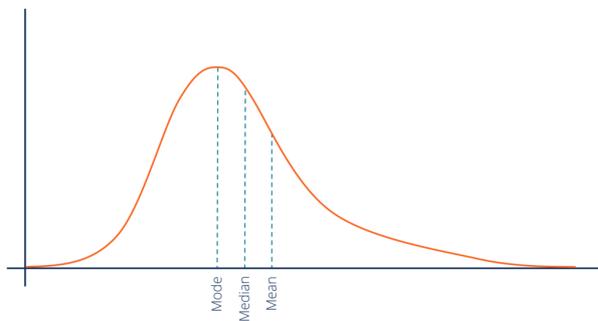
ii) Negative skewness/ negatively skewed distribution: In a negatively skewed distribution, the value of mode is maximum and that of mean least- the median lies in between the two. Here, the excess tail is on the left hand side.
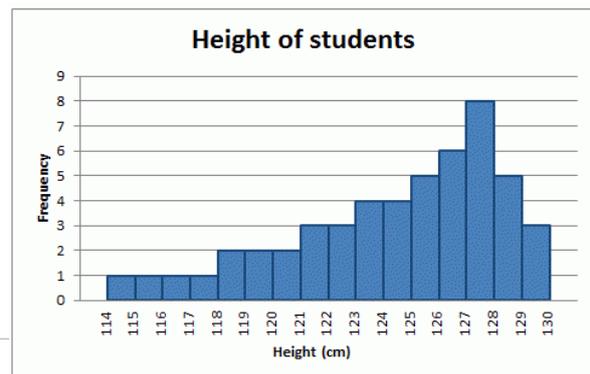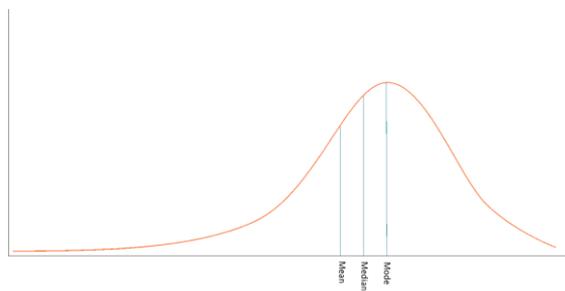
iii) Symmetrical and Asymmetrical Distribution: Two distribution may have the same mean and standard deviation but, may differ widely in their overall appearance as can be seen from below
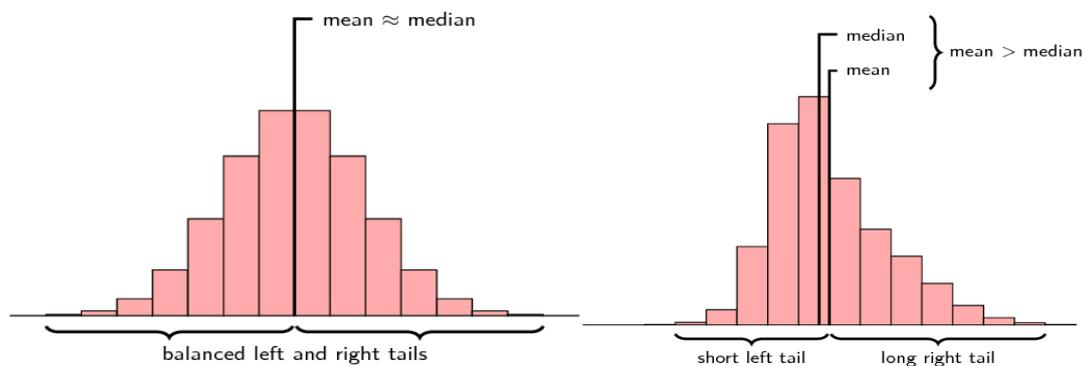
Symmetrical Distribution   **Asymmetrical distribution**

Measures of skewness help us to distinguish different types of distribution. Skewness refers to lack of symmetry.

Symmetrical Distribution:
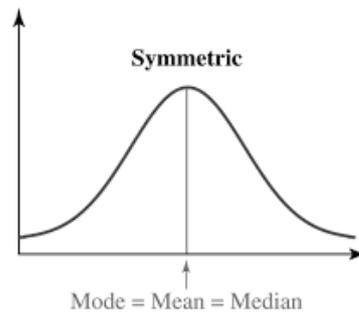
It is clear from the above diagram that in a symmetrical distribution, the value of mean, median and mode coincide. The spread of the frequencies is the same on both sides of the centre point of the curve.

Measures of Skewness: It is measured by coefficient of skewness or moment coefficient of skewness.

Skewness - Measures and Interpretation

Skewness is a key statistical measure that shows how data is spread out in a dataset. It tells us if the data points are skewed to the left (negative skew) or to the right (positive skew) in relation to the mean. It is important because it helps us to understand the shape of the data distribution which is important for accurate data analysis and helps in identifying outliers and finding the best statistical methods to use for analysis. In this article, we will see skewness, different types of skewness and its core concepts.

Types of Skewness

Skewness describes the direction and degree of asymmetry in a dataset's distribution. Various types are as follows:

1. Positive Skewness (Right Skew)

In a positively skewed distribution, the right tail is longer than the left which means most data points are on the left with a few large values pulling the distribution to the right.

Relationship:

Mean > Median > Mode

Examples: Income distribution, exam scores and stock market returns.

2. Negative Skewness (Left Skew)

In a negatively skewed distribution, the left tail is longer which means most data points are on the right with a few smaller values pulling the distribution to the left.

Relationship:

Mean < Median < Mode

Examples: Test scores on easy exams, age at retirement and gestational age at birth.

3. Zero Skewness (Symmetrical Distribution)

Zero skewness shows a perfectly symmetrical distribution where the mean, median and mode are equal. In a symmetrical distribution, the data points are evenly distributed around the central point.

Relationship:

Mean = Median = Mode

Example: A perfectly balanced dataset with equal frequencies of all values.

Tests of Skewness

There are several ways to find the skewness of a dataset which can help to find whether the data is positively skewed, negatively skewed or roughly symmetric. Below are some common methods used to measure skewness:

1. Visual Inspection

This is the simplest and quickest method for assessing skewness by creating a histogram or a density plot of the given data.

- If the plot has a long tail on the right, the data is positively skewed (right-skewed).
- If the plot has a long tail on the left, the data is negatively skewed (left-skewed).
- If the plot is roughly symmetric, the data has no skewness (zero skew).

2. Skewness Coefficient (Pearson's First Coefficient of Skewness)

This is a numerical measure of skewness based on the relationship between the mean and mode. It helps us to find if the data is skewed when the mean and mode are not equal.

Formula: Skewness=Mean−Mode *Skewness=Mean−Mode*

- Positive Skew: If the mean is greater than the mode, the skewness is positive.
- Negative Skew: If the mean is smaller than the mode, the skewness is negative.
- Zero Skew: If the mean is equal to the mode, the skewness is zero which indicates a symmetric distribution.

3. Skewness Based on Quartiles

This method checks the distances between the quartiles to find skewness. If the quartiles are not equidistant, it suggests skewness:

- The third quartile (Q3) minus the median (Me) should ideally be equal to the median (Me) minus the first quartile (Q1) in a symmetric distribution.
- If this condition is not met, it shows either a positive or negative skew which depends on which side is longer.

Interpretation of skewness:

- **Skewness = 0:** The distribution is symmetric means the mean, median and mode are equal.
- **Skewness > 0:** The distribution is positively skewed (right-skewed) with the tail on the right side longer than the left.
- **Skewness < 0:** The distribution is negatively skewed (left-skewed) with the tail on the left side longer than the right.

Difference between Dispersion and Skewness

While dispersion and skewness may seem similar but they measure different aspects of data distribution. Dispersion refers to the extent to which data points are spread out from the central

value (mean or median). Dispersion helps understand the variability of data while skewness helps to identify the shape and asymmetry of data.

4. Kurtosis

It refers to the relative flatness of the top of the curve as compared to symmetrical curve.

Another characteristic of a frequency distribution is Kurtosis.

Kurtosis refers to the flatness or the peakedness of a distribution.

A distribution can be Leptokurtic, Mesokurtic or Platykurtic.

Leptokurtic Distribution:

A distribution with a high peak. It is more peaked than the normal distribution.

Mesokurtic Distribution:

A distribution with a medium peak and resembles a bell shape. It is also called a normalcurve.

Platykurtic Distribution:

A distribution with low peak. It is flatter than the normal curve.
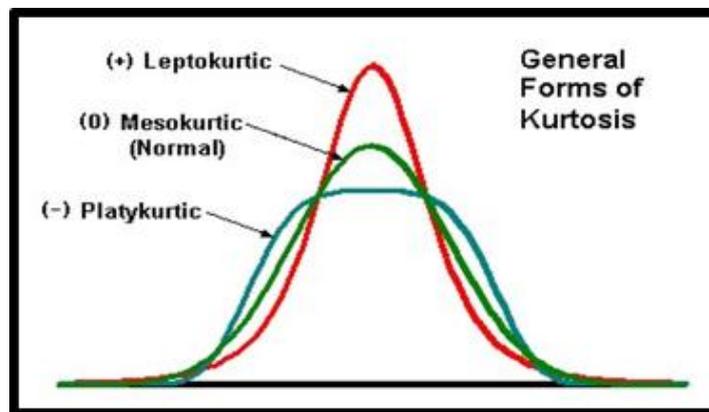
The standard value of kurtosis is taken as 3 and the curve with value of kurtosis less than 3 are called platikurtic curve and the curve with value of kurtosis more than 3 are called leptokurtic. In normal or mesokurtic curve, the value of kurtosis is 3. The bigger the value of kurtosis in a frequency distribution, greater its departure from normality.

Measures of Kurtosis: is known as the moment coefficient of kurtosis or coefficient of kurtosis. Kurtosis is equal to the fourth moment about the mean divided by square of the second moment about the mean.

Condition for symmetrical distribution: Coefficient of skewness is zero and coefficient of kurtosis is 3. In symmetrical distribution, the value of mean, median and mode coincide. The spread of frequency is same on both side of the center point of the curve.

Measures of Variability

Measures of variability are defined as the dispersion (or deviation) away from the mean for each variable. Measures of variability only exist for internal level variables. There are four measures of variability- range, standard deviation, variance, and coefficient of variation. We will discuss each one by one below:

a) **Range**: The range is found by taking the highest value of a variable minus the lowest value of that variable.

b) **Standard deviation**: The standard deviation exists for all interval variables. It is the average distance of each value away from the sample mean. The larger the standard deviations, the farther away the values are from the mean; the smaller the standard deviation, the closer the values are to the mean. Suppose you passed out a questionnaire asking randomly selecting individuals to rate the Prime Minister Modi's job performance on a scale from 1 to 10. And suppose you find that average these individual give the PM a rating of 5.8 and suppose this variable i.e. employment has a standard deviation of 1.2. This mean that on an average, each rating of the PM is approximately 1.2 points away from 5.8 (the sample mean).

Standard deviation is the square root of the mean of the squared deviation from arithmetic mean. It is also known as root mean squared deviation for the reason that it is the square root of the mean of the squared deviation from arithmetic mean introduced by Karl Pearson in 1823. A smaller value of SD means a high degree of uniformity of the observation as well as homogeneity of a series; a larger SD means just the opposite. It is extremely useful in judging the representativeness' of the mean.

c) **Variance:** it is nothing but the square of standard deviation i.e. variance = σ^2

$$\text{Where} \quad \sigma = \text{Standard deviation and} \quad \text{Variance} = \sigma^2 = \frac{\sum(x_i - \bar{x})^2}{N}$$

The variance cannot be interpreted as meaning anything other than the standard deviation squared.

d) **Coefficient of variation:** developed by Karl Pearson is the most commonly used measure of relative variation. It is used in such problem where we want to compare the variability of two or more than two series. It is unit less as it is the ratio.

CV = (Standard Deviation / mean) x100

It measures the spread i.e. percentage in variation. More the variation more will be the heterogeneous field; less the variation, more will be the homogeneous field. E.g. For Boys, CV=4.41 and for Girls, CV = 3.08

In this example CV is more for boys; hence height of boys shows greater variation. In field CV varies from 15-20%

Standard Error: SE is the standard deviation in the sampling distribution of desired statistics. Standard error is used only for sampling distribution. Standard error plays a larger role in testing for significance, and can drastically affect the output. For instance, large standard error will cause variables to be insignificant, which may indicate an incorrect use of a statistical method or analysis. The standard error (SE) of the mean measures the accuracy of a sample mean compared to the true population mean. It is calculated by dividing the sample standard deviation by the square root of the sample size.

Difference between standard error and standard deviation: Standard deviation is concerned with original values while Standard error is concerned with statistics computed from the sample of original values.

Difference between variance and standard deviation: Both the variance and SD are the measures of the variability in a population. These two measures are closely related as variance $=^2$. Variance is average squared deviation from the arithmetic mean and SD is the square root of the variance. The smaller the value of variance (σ^2) less the variability or greater the variability in a population.

Difference between mean deviation and standard deviation:

i) Algebraic signs are ignored while calculating the mean deviation whereas in the calculation of SD, signs are taken into account.

ii) MD can be computed from either mean or mode while, the SD is always computed from arithmetic mean.

Conclusion

Based on the introduction to descriptive statistics, the primary conclusion is that descriptive statistics are used to summarize, organize, and simplify large datasets into meaningful, interpretable, and manageable summaries without drawing conclusions beyond the specific data analyzed. Key conclusions and takeaways from the introduction include: they transform raw, complex data into easy-to-understand formats (tables, graphs, and numerical metrics); they describe data through three main categories: distribution (frequency), central tendency (mean, median, mode), and variability/dispersion (range, standard deviation, variance); a critical conclusion is that descriptive statistics only describe the collected sample or population data and cannot be used to make inferences, predictions, or generalizations about a larger population; and they serve as the first step in data analysis, allowing for the detection of outliers and errors, which helps prepare data for more complex inferential statistical techniques.

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ADVANCES AND INNOVATIONS IN
SOIL AND WATER CONSERVATION ENGINEERING

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1. Introduction

Soil and water are fundamental natural resources that support agricultural productivity, food security, ecological balance, and socioeconomic development. Healthy soil provides the physical, chemical, and biological foundation for plant growth, while water acts as the primary medium for nutrient transport, biological processes, and ecosystem functioning. However, rapid population growth, intensive agricultural practices, deforestation, urbanization, and climate change have placed unprecedented pressure on soil and water resources across the world. As a result, problems such as soil erosion, land degradation, declining soil fertility, groundwater depletion, surface water pollution, and increased vulnerability to floods and droughts have become widespread and severe. Soil and Water Conservation Engineering emerged as a scientific and engineering discipline to address these challenges through the planned management of land and water resources. Traditionally, conservation efforts relied on structural and agronomic measures such as contour farming, terracing, bunding, check dams, strip cropping, and rainwater harvesting. These practices have played a crucial role in reducing runoff, minimizing soil loss, and improving moisture availability in agricultural landscapes. However, changing rainfall patterns, increased rainfall intensity, prolonged dry spells, and expanding land use pressures have reduced the effectiveness of conventional methods when applied alone. This has created a strong need for innovation, integration, and modernization in soil and water conservation practices.

Contemporary innovations in Soil and Water Conservation Engineering represent a shift from isolated, experiencebased interventions toward datadriven, technologyenabled, and ecosystemoriented approaches. Advances in geospatial technologies such as Geographic Information Systems (GIS), Remote Sensing, and Digital Elevation Models (DEMs) have enabled accurate assessment of erosion risk, runoff behavior, and watershed characteristics at multiple spatial scales. These tools allow conservation structures to be designed and placed with greater precision, thereby improving their efficiency and longterm performance.

Water management techniques have changed concurrently with the incorporation of sensor technology, Internet of Things (IoT) platforms, and automated monitoring systems. Precision irrigation and adaptive water allocation are made possible by realtime measurements of soil moisture, rainfall, evapotranspiration, and streamflow. This greatly lowers water losses and increases crop water productivity. Additionally, the use of machine learning and artificial intelligence (AI) has created new opportunities for assessing the effects of climatic variability on

land and water resources, optimising conservation planning, and forecasting soil erosion. The increasing focus on bioengineering and naturebased solutions is another significant aspect of modern conservation engineering. The use of vegetation, organic amendments, biochar, geotextiles, and biodegradable materials strengthens soil structure, improves infiltration, and enhances resilience against erosion while maintaining ecological balance. These approaches align engineering interventions with natural processes, making conservation practices more sustainable and environmentally compatible.

Modern soil and water conservation engineering is no longer limited to improving agricultural productivity alone. It plays a critical role in climate change adaptation and mitigation, sustainable watershed management, groundwater recharge, and protection of downstream water quality. By linking conservation measures with integrated watershed management and sustainable landuse planning, contemporary innovations aim to maximize benefits across agricultural, environmental, and socioeconomic systems. Against this backdrop, this chapter presents a comprehensive overview of contemporary innovations in Soil and Water Conservation Engineering. It discusses recent technological advancements, modern design approaches, digital tools, bioengineering solutions, and realworld applications that enhance conservation effectiveness. The chapter also highlights current challenges and future directions, emphasizing the need for interdisciplinary research, capacity building, and inclusive implementation strategies to ensure longterm sustainability of soil and water resources.

2. Principles and Drivers of Innovation

2.1 Objectives of Soil and Water Conservation Engineering

The discipline aims to:

- Reduce soil erosion and sediment transport
- Improve soil moisture retention and fertility
- Optimize water use for agriculture
- Protect water quality across watersheds

2.2 Contemporary Drivers of Innovation

- Water scarcity due to climate variability
- Demand for higher resourceuse efficiency
- Development of digital sensing and automation technologies
- Integration of ecological and engineering approaches

3. Advances in Water Conservation Technologies

Water conservation is a cornerstone of modern soil and water engineering.

3.1 Precision Irrigation and IoT Systems

To reduce water wastage and enhance crop performance, modern irrigation systems make use of sensors, remote data transmission, and intelligent controls. Irrigation systems based on the Internet of Things (IoT) reduce operational water use and energy requirements by dynamically adjusting water distribution based on soil moisture levels. These systems have been designed

using hybrid agentbased and system dynamics techniques, showing optimised water irrigation and decreased operating time.

3.2 Automated and Efficient Irrigation Techniques

Techniques such as drip and automated irrigation significantly lower water use while maintaining or enhancing crop yields compared to conventional sprinkler or flood systems particularly important in regions with water scarcity.

3.3 HydrogelEnhanced Soil Water Retention

Hydrogel polymers improve soil's waterholding capacity, especially in sandy or coarse soils. These materials absorb and slowly release water, reducing irrigation frequency, lowering runoff, and enhancing soil stability.

3.4 Rainwater Harvesting and Managed Recharge

Rooftop collection systems and regulated aquifer recharge structures are examples of innovations in watershed design that raise groundwater levels and provide water during dry spells. For systemlevel resilience, this combines engineering and watershed management.

4. Innovations in Soil Erosion Control and Conservation

4.1 Structural Measures

Engineering structures like contour bunds, check dams, terraces, vegetated waterways, and spillways remain essential. Contemporary design approaches employ digital elevation models (DEMs) and GIS to optimize placement and performance, significantly reducing soil loss and increasing structural effectiveness.

4.2 Soft Engineering and Bioengineering Techniques

Soft engineering integrates biological and ecological principles:

- **Vegetative buffers and live staking** enhance soil cohesion
- **Rolled erosion control products (RECP)** protect surfaces while vegetation establishes
  These approaches harness plant systems to stabilize soil and reduce runoff.

4.3 Conservation Agriculture and InSitu Moisture Conservation

Conservation agriculture minimal tillage, mulching, cover cropping increases soil organic matter and enhances infiltration. Insitu moisture conservation practices like contour plowing, tied ridging, and basin listing enhance infiltration and minimize surface runoff.

4.4 Traditional Innovations with Modern Value

As part of larger conservation measures, indigenous techniques like zaï pitsimproved planting trenches that capture water and nutrients in arid landshave been redesigned, demonstrating how traditional knowledge influences modern engineering design.

5. Digital and DataDriven Innovations

5.1 Remote Sensing, GIS, and Spatial Analysis

Highresolution satellite data and Geographic Information Systems (GIS) enable largescale soil erosion mapping, watershed planning, and realtime monitoring of land cover changes. These tools allow engineers to quantify risk and prioritize interventions.

5.2 Sensors and RealTime Monitoring

Soil moisture sensors, weather stations, and automated data loggers provide continuous feedback for irrigation and conservation structures, promoting proactive management. Integration with decision support systems (DSS) facilitates scenario analysis and planning under changing environmental conditions.

5.3 Machine Learning and Predictive Modeling

Machine learning models, including transformerbased data fusion techniques, are improving soil and moisture prediction accuracy, enabling better scheduling of conservation actions and water application.

6. Case Studies of Innovation in Practice

6.1 Smart Irrigation in SemiArid Agriculture

IoTdriven irrigation systems in semiarid farms have shown reduced water use with maintained crop yields, demonstrating their utility in waterlimited environments.

6.2 Hydrogel Implementation in Sandy Soils

Hydrogel applications in arid and semiarid zones have improved soil moisture retention, reduced stress during dry spells, and minimized irrigation demand, providing a scalable solution in challenging climates.

6.3 GISOptimized Erosion Structures

Watershed programs using DEMs and GIS to design contour banks and check dams have recorded significant reductions in sediment yield and improved agricultural sustainability.

7. Challenges and Limitations

Despite advances, several challenges remain:

- **Economic Constraints:** High initial costs limit technology adoption, particularly for smallholder farmers.
- **Technical Barriers:** Data connectivity and infrastructure gaps impede realtime monitoring systems.
- **Knowledge and Training:** Effective operation of digital tools requires specialized skills.

These challenges emphasize the need for supportive policies, capacity building, and scalable technologies for broad adoption.

8. Future Directions and Emerging Trends

8.1 Integrated DigitalEco Engineering

Blending ecological restoration with digital monitoring and AI promises multifunctional landscapes that conserve soil and water while supporting biodiversity.

8.2 AIDriven Decision Support

AI algorithms will increasingly predict erosion risk and optimize water allocation amidst climatic variability.

8.3 Nanotechnology and Smart Materials

Nanosensors and advanced materials may enhance soil health monitoring and targeted water delivery in realtime.

Conclusion

Modern advances in soil and water conservation engineering are revolutionising conventional methods by providing effective, longlasting, and technologically advanced solutions to water scarcity and soil degradation. Agricultural landscapes become more resilient when structural engineering is combined with digital analytics, biological systems, and local knowledge. Future directions depend on inclusive policy frameworks, interdisciplinary research, and fair access to technology.

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ENDOPHYTIC MICROBES AND THEIR APPLICATION IN PEST MANAGEMENT: POTENTIAL AND CHALLENGES

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Abstract

Numerous microbiotas invade living plants in the natural world. Depending on the species, host plants have varying degree of microbial invasion. The relationship between the micro - organisms and its host can range from mutualistic symbiosis to latent pathogenesis. The microbes could be latent pathogens, endophytes or may be epiphytes. Insect pest causes about 18 – 26 percent losses globally, to battle this losses, high use of chemical pesticides were being used, which is devastating the environment with major concerns. Pesticide usage in the crops causing several problems, use of several synthetic pesticides can cause air, soil, and water pollution, contaminating the human food chain and other living beings. These challenges *i.e.,* growing environmental and human safety concerns, have driven the need for integrated management approaches. Among the non-chemical control options, biological control in general and in particular address the need for sustainable solutions to pest suppression. One underexplored, but promising, alternative approach is also gaining attention: the use of beneficial endophytes as biological control agents for crop protection (Grabka *et al.,* 2022). Endophytes represent an eco-friendly alternative. These refers to the fungi living inside the host plant. it is derived from two Greek words, Endon" meaning within and "phyton" meaning plant. The first record of endophyte in plant protection, was in elm tree against beetle, *Physocnemum brevilineum* which is a vector of Dutch elm disease. These endophytes can colonize naturally, or can be inoculated artificially into the host plant. These provide indirect and direct defense in plants against insect herbivores. Use of antagonistic endophytes as biocontrol agents is drawing special attention as an attractive option for management of some plant diseases, resulting in minimal impact to the environment (Silva *et al.,* 2019). Therefore, utilisation of microbial strains has emerged as a sustainable, eco-friendly and non-toxic approach.

Keywords: Endophytes, Herbivore Insects, Indirect Defense, Pest Management.

Introduction

In order to feed the rapid growing population, which is estimated to reach about 9.7 billion by 2050, there is a constant pressure to increase the yield of crops to feed the population. This can be achieved either by increasing the cultivable land or by enhancing the productivity. Since there is a limited potential to increase the cultivable land area, major focus is laid on increasing productivity. Diverse abiotic and biotic challenges render the crop productivity. Insect pest are the major biotic challenge that decrease the productivity and quality of the crops. They cause approximately 18 to 26 percent economic losses each year. Also, over rely on chemical insecticides, led to pesticide resistance, resurgence and outbreak of secondary pests and negative effects on non – targeted organisms. So, a need for non-chemical approach is evolving. Among these non-chemical options, biological control in general and in particular address the need for sustainable solutions to suppress pest population. One underexplored, but promising, alternative approach among the biocontrol measures is gaining attention *ie.,* the use of beneficial endophytes as biological control agents for crop protection (Grabka *et al.,* 2022). Use of antagonistic endophytes as biocontrol agents is drawing special attention as an attractive option for management of some plant diseases, resulting in minimal impact to the environment (Silva *et al.,* 2019). Therefore, utilisation of microbial strains has emerged as a sustainable, eco-friendly, and non-toxic approach.

Anton De Bary was the first person to use the term " endophyte" for the fungi living inside the plant tissue. Darnelin is the first one who initiated the study of biology of endophytes in 1904 in a field weed (Tan *et al.,* 2001). The hyper diversity of fungal strains, estimated that more than 1 million different strains. (Fouda *et al.,* 2015). Intensive study of rhynie chert revealed that fossil record of endophytic association with land plants was discovered in *Nothia aphylla* more than 400 million years ago. In addition, 1981 to 1985 is a historical period for endophytic - mediated plant protection against herbivore insects. (Rodriguez *et al.,* 2009). Use of endophytes in plant protection was found in elm trees for the first time (Webber, 1981). A natural biological control agent, endophytic fungus, *Phomopsis oblonga* which was found to colonize naturally in the inner bark of elm trees, prevented the breeding of scolytid elm bark beetle, *Physocnemum brevilineum* (vector) which transmit the dutch elm disease (Webber, 1981). This was due to active secondary metabolites and mycotoxins that included (nor sesquiterpene γ-lactone, the tegmic esters of two novel 5,6-dihydro-5-hydroxy-2-pyrones, nectriapyrone) were responsible for anti insecticide properties. Similarly, Gaynor and Hunt (1983) noticed that, decrease in the attack frequency of the Argentine stem weevil, (*Listronotus bonariensis*), in several ryegrass *sps.* due to high infection of fungi. These endophytes are common microbiota, living at least a part of their lives inside plants (inter-cellular or intra cellular). Asymptomatic fungal endosymbionts of plants called as endophytes. These colonize internal plant tissues (healthy leaves, stems, twigs, bark, fruit, roots, flower and seeds) without causing pathogenicity. These can be isolated from different plant tissues.

Isolation and identification of Endophytes

Endophytes can be isolated very easily on any microbial growth, on any nutrient media. but, plant tissues inhabitat epiphytes and endophytes combinedly, it is very crucial to remove epiphytic microbial communities, if present in the plant samples. So, to wash out epiphytic microbes, sample tissue should be surface sterilized with disinfectant (Sodium hypochlorite (NaOCl), 70% ethanol and hydrogen peroxide (H_2O_2). Care has to be taken, such that higher dose of disinfectant and high exposure time may cause mutagenesis. To check the efficacy of sterilization, selected leaf sample tissue is kept on suitable media plate, if no growth is observed after incubation period, sterilization is considered as adequate. Pour plate and spread plate method is most commonly used methods for employing isolation of endophytic microbiota. Isolation can be done by two techniques: Cultivation-based techniques, uses the recovery and testing of isolates, whereas cultivation-independent techniques screen for variations in the total endophytic communities (Menpara and Chanda, 2013). Recent studies have confirmed that the occurrence of endophytes by different cultivation-independent assays and by fluorescence in situ hybridization-confocal laser scanning microscopy studies (Berg *et al.,* 2014). After isolation and following proper incubation protocols, pure isolates will be identified from mixed population either by morphological observation or by molecular identification. **(**Kashyap *et al.,* 2023). Recent approaches like metagenomic have also been extensively used to access the diverse community of endophytes.

Endophyte Establishment and Colonization

These Endophytes colonizes all the parts of plants in localized position or spreads to all the parts of host plant without harming their hosts. Transmission can be either by vertical or horizontal. Vertical transmission enables the transfer of fungi between host mother plant and its offspring whereas horizontal transmission transmits endophytic fungi through wounds roots, flowers and lenticels (White *et al.,* 2019).

Host Plant - Endophyte Interaction

These microbes share a complex relationship with host plants either directly or indirectly modulating the development,growth and protecting host plant from pathogen invasion and insect attack. Multiple type of relation exists between host plant and microbe which may be neutral, positive (beneficial) and negative (harmful). Different factors together influence the successful colonization of microbes that includes host plant type, plant tissue, biotic and abiotic stress. (Khan *et al.,* 2023). Process involved in plant root colonization by endophytes includes Attraction, recognition, colonization.

Release of molecular exudates as stimulus from the roots elicit a chemotactic response by the endophytes present in the soil. Recognition is a very complex phase where, receptors in the plants recognize microbial molecules that trigger different pathways typically, MAMPs (Microbe-Associated Molecular Patterns) and plant PRRs (Pattern Recognition Receptors). Finally, colonization of endophytes, in the plants influences the phytohormone levels and

increases ROS enzymes. Different hypothesis were formulated to study the interaction between host plant and microbe.

Balanced Antagonism Hypothesis: This was given by B. Schulz and S. Boyle. The hypothesis says that, if fungal virulence (endophyte virulence factors) and plant defense (plant immune molecules) are balanced, the association between endophytes and their host plants will maintain a balanced antagonism i.e., asymptomatic. The balanced antagonism between the host and the endophyte is maintained by avoiding activation of the host defenses and activating resistance against toxic metabolites of the host. When fungal virulence and plant Defense are at equilibrium, the fungal colonization would apparently be asymptomatic and avirulent (Kusari *et al.,* 2012). If the fungal virulence factors can act against plant defense mechanisms, a plant-pathogen relationship would lead to plant disease. (Suryanarayanan *et al.,* 2016).

Multiple Balanced Antagonism: Inside the plant (*in planta)* an endophytic microbe must deal with variety of micro-organisms *ie.,* with bacteria and other fungi as well as host defense. So, in order to grow asymptomatically in their respective hosts, endophytes must maintain balance with multiple living biota inside the plant.

Mainly two mechanisms helps or maintain asymptomatic relationship.

- Firstly, endophytic microbes produce a Metabolites that counteract those produced by the host plants and by modulating the host's intrinsic defense response and altering phytohormone concentrations. secondly, by facilitating the detoxification of constitutive defense metabolites within plants and by secreting lytic enzymes. Otherwise, there would be chance of switching lifestyle of microbe from endophyte to pathogen.

- Ex: Switching life-styles of endophytic and pathogenic strains of *Colletotrichum magna* is suggested by disrupting single genetic loci or closely linked genes that induce anthracnose in cucurbit. switching life-styles of *Colletotrichum* might possible because of excessive humidity or poor nutrient supply that alter host's susceptibility in natural conditions plants (Rai and Agarkar 2016).

Endophytes Interaction in Insect World

Endophytes are universal, they form association with a diverse range of organisms in the plant kingdom and provide indirect defense for plants against herbivores.

Various other benefits are also provided by endophytic microbiota to host plants.

➢ Metabolites and induced systemic resistance enhance the plants defense mechanisms against pests. Volatile compounds emitted from the host plant, recruit natural enemies of insect pests, indirectly defending the plant by reducing pest fitness and survival. Also, the colonization of endophytes improves the availability of essential nutrients to the plants. (Panwar *et al.,* 2024). Consequently, through the interaction, plant produces phenols, terpenes, flavonoids and many other volatile compounds as their secondary metabolites to induce resistance against insect herbivores. Endophytes releases toxins to induce plant host defense mechanism, thereby facilitating plant to counter attack against herbivorous insects. Through fungal endophytic colonization in the plant tissues elicits defense mechanism which is directly impacting herbivores

and plant pathogens. Plant defense responses involves the release of volatile organic compounds, which function as an indirect defense mechanism by attracting the natural enemies of herbivores. (Parveen *et al.,* 2024).

Types of Endophytes

Various microbes belonging to different groups have been identified as endophytes *viz.,* archaea, bacteria, and fungi (Yadav *et al.,* 2019) and other microbes like actinomycetes. Among bacteria., proteobacteria, Firmicutes, Actinobacteria were isolated as endophytes.

➢ **Endophytic bacteria: Gram-negative, Gram-positive bacteria**

Ex: Enterobacter, Bacillus, Pseudomonas, Micro bacterium and *Burkholderia.*

Xie *et al.,* 2020 tested the biocontrol ability of a Gram-positive, endospore-forming bacterium (*Bacillus amyloliquefaciens* - ZJU1 strain) frequently isolated from healthy mulberry plants by screening for foliar endophytes showing antagonism against pathogens *Botrytis cinerea*. So, when an endophyte free plant was inoculated with ZJU1 strain, there was a significant decrease in the leaf necrosis and mortality also, disease resistance gene expression was also very high. ZJU1 also showed significantly reduce in the survival rate of pest (General herbivore *Spodoptera litura*) below 50% saying, *amyloliquefaciens* ZJU1 is promising for the development of successful strategies for biocontrol applications.

Endophytic fungi were mostly reported from phylum Ascomycota and Basidiomycota were, Ascomycota was the most dominant.

1) *M. Robertsii* endophyte - destruxin A (Secondary metabolite of fungi) Increased mortality rates of up to 100% of adults- West Indian fruit fly, *Anastrepha obliqua* (Macquart). (Rios-Moreno *et al.,* 2016).

2) *Trichoderma asperellum* PC211 strain from the stem of rice seedlings could infect nymphs and adults of BPH. *Trichoderma* acts directly as an entomopathogen through parasitism mechanism and the production of insecticidal secondary metabolites, antifeedant compounds and repellent metabolites (Zhou *et al.,* 2018)

3) *M. robertsii* triggered jasmonic acid (JA) biosynthesis pathway as host plant response Lipoxygenase 1 (lox1)., 12-oxo-phytodienoate reductase 7 (opr7) in maize. *M. robertsii* - inoculated seed were up-regulated compared to control plants, suppressing the growth *of Agrotis ipsilon*. (Ahmad *et al.,*2020)

Actinomycetes: *Streptomyces sps.*

Ex: Insecticidal activity of endophytic actinomycetes from *Azadiracta indica* against *Myzus persicae.*

Transgenic Endophytes: Trangenically modified endophyte genomes could be really a useful strategy and an alternative genetic manipulation of the host plant. Genes introduced into endophytic microbes could confer new characteristics, which may be useful in bio-control of plant pathogens, growth promotion of host plants, and/or production of medicines for humans or animals.

Ex: Endophytic bacterium *Clavibacter xyli subsp. cynodontis*, which colonizes the xylem of several plant species, was transgenically modified to express the *Bacillus thuringiensis* gene encoding endotoxin for control of insects. (White *et al.,* 2019).

Biocontrol activity of endophyte may differ in vitro and in vivo laboratory conditions, they might be unable to confirm any activity under field trials. Therefore, it is recommended to evaluate biocontrol activity initially in vitro and in vivo laboratory conditions, followed by field trials to check the adaptability of biocontrol agents in the biotic and abiotic environment. So, to evaluate biocontrol activity of endophytes, a best approach is to identify the field problems, continuous in vivo and in vitro experiments for endophyte antagonistic activity against pathogen and plant disease development provide a solution to the disease or pest problems.

Commercialization of Biocontrol Agents

Major issue of a biocontrol agent is its success or failure as a commercial product (Vurukonda *et al.,* 2018). Commercialization of bio-control products should undergo multi -step processes, including

- Isolation of micro-organisms from the natural ecosystem
- Evaluation of bio-agent both in vitro and under glass house conditions
- Testing of the best isolate under field conditions
- Mass production, formulation
- Delivery, compatibility
- Registration and release (Junaid *et al.,* 2013).
- Some government organizations (agencies) are responsible to confirm biosafety of biocontrol agents and biopesticides (Tranier *et al.,* 2014).
- A commercial product should be complied with farmer's requirements such as repeated positive results, reasonable price, easy handling and prolong product shelf-life (Vurukonda *et al.,* 2018).

Potential:

Endophytes are eco-friendly, Microbials are traditionally seen as an alternative or back up treatment when arthropod natural enemies are unavailable or insufficiently effective.

❖ **Endophytes produce Anti -insect toxin secondary metabolites**

Ex:1) Rugulosin anti insect toxin produced by the endophyte *Phialocephala scopiformis* reduced the growth and development of *C. fumiferana.* These endophytes -horizontally transmitted. (Sumarah and Miller, 2009)

2) Anti-insect potential, *Nigrospora sp.* isolated from *Tinospora cordifolia* on the survival and development of *Spodoptera litura* (Lepidoptera: Noctuidae), a polyphagous pest, was affected when fed on artificial diet amended with different concentrations of ethyl acetate extract of *Nigrospora sp* conferring resistance to host plants against insect herbivores mediated by fungal alkaloids. Insect suffered significantly higher mortality and showed prolonged development period; adverse effects were also observed on adult emergence, longevity and reproductive

potential of *S. litura* on amended diet as compared to unamended diet. Insecticidal properties of *Nigrospora sp.* be used for imparting resistance in plants against insects. (Thakur *et al.,* 2012).

- Inoculating seedlings with toxigenic endophyte strains has been demonstrated to be effective in providing the tree with tolerance to herbivorous insect.

- Usage of endophytic microbes in tissue culture techniques. Ex: *B. bassiana* in tissue culture of banana. Mycosis rates in *B. bassiana*-treated plants were 23.5–88.9% when compared to control. Presence of the fungus inside treated plants led to a reduction in larval damage of up to >50%. Endophytic *B. bassiana* accumulated mycotoxins (Ghosh *et al.,* 2020).

- Recombinated endophytic microbes offering resistance to insect herbivore. Ex: Endophytic bacterium Strain WH2 was genetically engineered to express anti-pest *Pinellia ternata* agglutinin (PTA). The PTA gene (pta) was cloned into plasmid pP43NMK and transformed to strain WH2 for expression caused decrease in the survival and fecundity of WBPH fed on rice seedlings inoculated with WH2::pta.(Qi *et al.,* 2013)

- Consortia of beneficial microorganisms are used in plants as inoculants; they confer better results. Acts simultaneously as biocontrol agents and as agents to improve plant growth and yields, they are multifunctional.

- The development of a bioformulation possessing a mixture of bioagents could be a viable option for the management of major pests and diseases in crop plants.

- Ex*: B. bassiana* has potential as a dual-purpose microbial control organism against both insect pests and plant pathogens. A bioformulation containing a mixture of *Beauveria bassiana* (B2) and *Bacillus subtilis* (EPC8) was tested against *Fusarium* wilt and fruit borer in tomato under glasshouse and field conditions. (Prabhukarthikeyan *et al.,* 2014).

- Induced Systemic Resistance (ISR) – Endophytes like *Pseudomonas* and *Bacillus* species can trigger plant Défense pathways, making plants more resistant to pests.

- Production of Bioactive Compounds – Some endophytic bacteria and fungi synthesize insecticidal, antifungal, or antimicrobial compounds that directly suppress pests.

- Disruption of Pest Microbiomes – Endophytes can alter the gut microbiome of herbivorous pests, reducing their ability to digest plant material or detoxify plant defenses.

- Biopesticide Potential – Endophytic fungi like *Beauveria bassiana* and *Metarhizium anisopliae* are already used as biocontrol agents against insect pests.

- Volatile Organic Compound (VOC) Emission – Endophytes can release VOCs that repel pests or attract natural predators.

- Enhancing Plant Growth – By improving plant health and nutrient uptake, endophytes indirectly strengthen plants against pest attacks.

- Disrupting Insect Development – Some endophytes produce hormones or toxins that interfere with insect growth and reproduction.

- Higher number of pollen grain production: Ex: Melon plants sprayed with *B. bassiana* conidial suspensions were endophytically colonised throughout the entire plant growth cycle and reached the floral tissues. In addition, the endophytically-colonized plants produced a significantly higher number of pollen grains, and flowered earlier than control plants. changes in the emitted blend of volatiles were observed in the endophytically-colonised plants, which emitted more of the pollinator attractants D-limonene and benzene acetaldehyde than control plants (Gonzalez *et al.,* 2023).

- Reduce the virulence of insect vector for virus transmission: Ex: effects of fungal endophyte infection of meadow ryegrass (*Lolium pratense*) on the frequency of the barley yellow dwarf virus (BYDV). The virus is transferred by aphids, which may be deterred by endophyte-origin alkaloids within the plant. The number of aphids and the percentage of BYDV infections were lower in endophyte-infected plants compared to endophyte-free plants, indicating that endophyte infection may protect meadow ryegrass from BYDV infections. (Lehtonen *et al.,* 2006)

Challenges

- Herbivores have evolved to detoxify the defensive Secondary metabolites. Ex: Fall armyworm (*Spodoptera frugiperda*) converts maize endophytes into its own probiotics to detoxify benzoxazinoids (Bxs), a group of defensive metabolites in maize.

- Endophytes can affect the complex multitrophic interactions involving plants, insect pests, and natural enemies. While the use of endophytic fungi as biocontrol agents holds great promise, it is crucial to consider the potential negative impacts on natural enemies.

Examples:

i. Presence of the fungal endophyte *Acremonium coenophialum* (Gams) had a negative effect on the growth and survival of two parasitoids, *Euplectrus comstockii* (Howard) and *Euplectrus plathypenae* (Howard).

ii. **2)**The endophyte-inoculated plants in the diet of fall armyworm larvae led to a reduction in the pupal mass of the parasitoids.

iii. **3)**The parasitoid *Bracon hebetor*, when parasitizing larvae of *Spodoptera litura* Fabricius feeding on cauliflower inoculated by *Aspergillus spp.,* experienced prolonged development time of the larvae and reduced parasitism rates by the adults (Kaur *et al.,* 2015).

iv. Omnivorous predatory bug *M. pygmaeus* on tomato plants previously inoculated with a non-pathogenic isolate of *F. oxysporum*, Surprisingly, this endophyte still enhanced pest control by deterring the predator from feeding on the plant, thereby increasing its feeding activity on the prey. (Eschweiler *et al.,* 2019).

These results suggest that changes in food web structure influenced by fungal endophytes can impact the success of natural enemies in controlling herbivore populations. (Panwar *et al.,* 2024)

- Great challenge for considering endophytic fungi as a strategy in plant protection is to manage their reproducible introduction into crops, and to predict the outcome.

- Effectiveness of these endophytes as biocontrol agents require phytosanitary tool needs to be proven in the field to stimulate growers to adopt it in view of gaining clear economic benefits.

- Need for proper understanding metabolic pathways and signaling functions involved in multipartite interactions

- Need for effective screening for important and essential metabolites that could be deployed directly in the field to circumvent known environmental challenges.

- Complete genomes of these endophytic microorganisms (i.e., the plant endobiome) is need to know more about the molecular basis for these multilevel interactions which requires skills and cumbersome.

- Most of the secondary metabolite genes in fungi are generally silent in culture and are activated while being co-cultured with other microbes.

- Continued research on endophyte–insect–plant–environment interactions are critical to advancing our knowledge of these fungi as a sustainable pest management tactic.

- some natural enemies also feed on the plants harbouring endophytic fungi and could attack herbivorous insects that may be negative effects to NEs due to fungal endophytes.

- urgent need to improve communication between the public and researchers for efficient usage of biocontrol methods.

- loss of viability and reduced effectiveness of the product against pathogen or pest during storage.

- On the other hand, some potential biocontrol agents might be compatible with particular plants under a limited range of environmental conditions.

- A lack of understanding of usage of biocontrol methods, may end up with reduced confidence for usage and demand in the product. Therefore, a full understanding of the practical use of endophytes as biocontrol agents in agriculture is essential.

Future Scope

- Time to salvage the ecosystem is now, potential use of endophytic bacteria and fungi to improve agricultural productivity is a sustainable alternative.

- The use of advanced biotechnological tools (omics) to investigate both the community and functionalities of endophytic microorganisms is recommended. Advanced 'omic' technologies offers the ability to search for genes on a global scale that are found to be induced or repressed during colonization of plant tissues.

- Exploring the synergistic integration of endophytic fungi with other sustainable pest management tactics, such as cultural practices, host plant resistance, and natural enemies, can lead to more comprehensive and robust integrated pest management approaches.

- An area in need of detail study, this raises the issue of whether inoculation of agronomically important plants with fungal entomopathogens might create a problem by producing metabolites that could potentially enter the food chain.

- Endophytic organisms encompassing synergetic consortia of both bacterial and fungal endophytes should be developed and supported in their role as bio formulated inoculants for use in agriculture, to sustain ecological balance.

- Use of newer biotechnological tools to study the Endo microbiome in terms of genomics, proteomics, and transcriptomic functional traits.

- Understanding the complexity of ecological interactions between different types of biological control agents is itself a subject that requires further research.

- Endophytic microorganisms could increase the various ways in which microbials can interact with arthropod natural enemies, and these interactions can be both positive and negative for pest control. A better understanding of these interactions offers new opportunities to optimize and further develop biological pest control. (Gonzalez *et al.,* 2016).

- Determining how to combine both microbial and arthropod natural enemies with available technologies.

- Present endophytic microbial biocontrol agent selection process should involve testing in the field, in the "real-world" cultivation environment to determine if the selected isolates maintain their capacity as useful agricultural products.

- In terms of biological control, studies need to focus on unveiling direct and indirect effects of the application of microbial bio logical control agents and microbial communities within insects (symbionts) and plants (endophytes) on arthropod natural enemies.

- There is a need for an extensive bioprospecting study of endophytic microorganisms from diverse ecological niches.

- Still, there are big gaps regarding the lifestyle and the working of these microbes. Research shows that only about 1–2% of known species of plants have been studied for endophytic associations and most of these are from land plants, whereas aquatic plants (lakes, ocean, etc.) are completely unexplored.

- Complex interactions between hosts and endophytes, which can include switch lifestyle candidate endophytes should be studied in planta under different conditions, including abiotic stress.

- The future of agriculture will involve the increasing consideration and integration of the plant microbiome in pest and disease management.

- Research is required before microbiome engineering shows predictable and consistent benefits that will lead to its widespread adoption.

- The application of multi-strain bacterial consortium over single inoculation could be an effective approach for reducing the harmful impact of stress on plant growth. (Suman *et al.,* 2016)

- Deliberate need in increase of study regarding endophytes in different insects orders. Till now more research conducted in lepidopteran insects, focus needed to shift on other insect orders too.

- Only a few plants have ever been completely studied relative to their endophytic biology. Consequently, the opportunity to find new and beneficial endophytic microorganisms among the diversity of plants in different ecosystems is considerable.
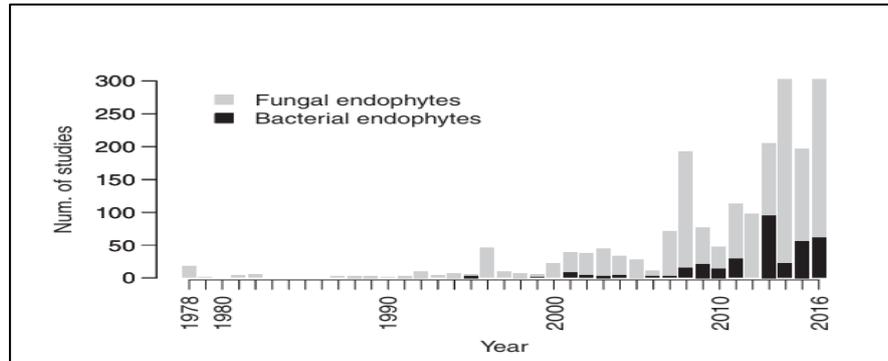
The number of studies characterizing endophyte biodiversity (Bacteria and fungi) published each year since the late 1970s (Harrison *et al.,* 2020)

- Our palette is vast and includes entomology, mycology (including fungal metabolites), and botany (plant physiology, anatomy, morphology, pathology, chemistry). We can understand these complex interactions when we collaborate with scientists in other disciplines who can help us understand the whole system. I.e., multidisciplinary approach (Vega *et al.,* 2018)

- As we strive to achieve global food security and a sustainable environment, the integration of endophytic fungi into integrated pest management programs holds great promise. (Panwar *et al.,* 2024)

- Need for continuous in vitro and in vivo experiments to derive efficient products that have a broad range of applications with varied crops.

Conclusions

- The agriculture sector must guarantee healthy food with sustainable production using environmentally friendly methods.

- Endophytic microbes hold immense potential as biological control agents against insect pests. These endophytes can also enhance plant growth and resistance against pathogens, providing a holistic approach to crop protection

- By combining endophytes with other IPM strategies and leveraging interdisciplinary research, endophytic microbes can become a cornerstone of sustainable agriculture, reducing dependency on chemical inputs while promoting environmental health.

- During the last two decades endophytes have been targeted as valuable sources of new bioactive compounds and secondary metabolites.

- These endophytic microbes have great potential in tissue culture, as dual biological agent and their insecticidal active compounds, secondary metabolites can be used as anti-insect toxins for anti- herbivore.

- Apart from their potential, they pose challenges where adverse effect shown in natural enemies, advantage to herbivore, reproducibility at field level. There is a gap in research study in lifestyle, use of biotechnology tools, synergism of microbial consortia.

- Several challenges must be addressed to fully harness their potential. Advances in biotechnology, genomics, and microbial formulation techniques offer promising avenues to overcome these challenges.

- However, the successful commercialization of endophytic entomopathogenic fungi-based biocontrol agents requires further field-level investigations. It showed be highly reproducible at field level showing economic benefits to growers for its successful commercialization.

- The future of agriculture involves increasing consideration and integration of the plant microbiome in pest and disease management.

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CLIMATE-RESILIENT FARMING: A PATHWAY TO SECURE AGRICULTURE IN A CHANGING CLIMATE

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Abstract

Climate-resilient farming has emerged as one of the most important approaches for securing global agriculture against the rising uncertainties of climate change. Over the past two decades, farmers around the world have witnessed unpredictable rainfall, prolonged droughts, sudden floods, shifting temperature patterns, and the outbreak of new pests and diseases. These changes have severely affected crop yields, soil health, and livelihood security. Climate-resilient farming provides a scientific yet practical framework for adapting to these changes while ensuring long-term sustainability. It integrates traditional knowledge with modern innovation to create farm systems that are robust, flexible, and efficient. Through methods such as climate-smart cropping, soil regeneration, agroforestry, integrated farming systems, crop diversification, precision agriculture, and efficient water management, farmers can protect their fields against climate stress while improving productivity.

At its core, climate-resilient farming is not just a set of techniques but a mindset that encourages farmers to anticipate risk, adapt practices, and build resilience across their crops, livestock, and natural resources. It strengthens community institutions, enhances farmer skills, and promotes inclusive decision-making to ensure that even small and marginal farmers can adopt sustainable solutions. With global warming becoming more severe each year, climate-resilient farming stands as a powerful strategy that harmonizes environmental health with economic security. This article presents a comprehensive understanding of climate-resilient farming, its major components, practical applications, farmer-centered approaches, and future pathways. It emphasizes how resilient agriculture can protect both food security and farmer livelihoods, making it an essential pillar of sustainable rural development.

Keywords: Climate-Resilient Farming, Strengthening Agriculture, Uncertain Future.

Introduction

Climate change is reshaping the very foundation of agriculture. The farming community especially small and marginal farmers faces unprecedented challenges as weather patterns become erratic. Fields that once depended on predictable monsoon cycles now confront drought

one year and severe flooding the next. Crop diseases spread faster, new pests attack standing crops, and soil loses its fertility due to extreme heat and intensive chemical use. In this backdrop, the concept of climate-resilient farming offers hope, direction, and a comprehensive adaptation pathway.

Climate-resilient farming is not merely a response to climate threats; it is a holistic approach that builds long-term strength into the agricultural system. It is the art and science of managing farms in a way that reduces vulnerability while increasing the capacity to withstand, recover, and thrive despite changing climate conditions. This approach helps farmers adopt flexible cropping systems, preserve soil and water, diversify income sources, and integrate modern tools like weather-based advisories and digital monitoring.

Understanding the Changing Climate in Agriculture

Farmers across the world feel climate change more directly than anyone else. Rising temperatures lead to faster evaporation of water from soil and plants. Heatwaves damage sensitive crops like wheat, mustard, and vegetables. Unexpected rains during harvest season spoil grains kept for drying. Unseasonal storms flatten crops, and heavy rains erode fertile soil. These changes create a cycle of loss, repeating across seasons and causing financial stress.

Climate-resilient farming acknowledges these realities and encourages farmers to create farm systems that do not collapse when weather shocks occur. It recognizes that no single solution can work everywhere. Instead, resilience must be built across soil, seeds, water, crops, livestock, and community knowledge.

Principles of Climate-Resilient Farming

Climate-resilient farming rests on a few core principles that guide all strategies and interventions. It promotes adaptability, sustainability, resource-efficiency, and ecological harmony. The first principle is diversification, which reduces dependency on a single crop and spreads risk across multiple sources of income. The second principle is soil conservation, which improves the farm's natural ability to retain water and nutrients. The third principle is water efficiency, which ensures that farmers make the most of every drop in both dry and wet seasons. Another principle is integrating traditional wisdom with modern science to create practical, cost-effective solutions. Finally, climate-resilient farming places the farmer at the center, recognizing that local knowledge, community cooperation, and training are essential for long-term resilience.

Climate-Smart Cropping Systems

Climate-resilient farming begins with choosing crops that can tolerate local climate stress. Heat-tolerant wheat, flood-tolerant rice, drought-resistant millets, and pest-resistant varieties help farmers manage extreme conditions. Along with improved varieties, farmers adopt staggered sowing, mixed cropping, and crop rotation to reduce risk. Staggered sowing spreads crop maturity across different weeks, ensuring that sudden rain or heat does not destroy the entire field. Mixed cropping, such as blending legumes with cereals, protects soil fertility and reduces pest attacks. Crop rotation breaks disease cycles and rejuvenates soil. These systems make farms stronger, more productive, and less vulnerable to climate shocks.

Soil Health as the Foundation of Resilience

Healthy soil is the heart of climate resilience. Soil rich in organic matter holds moisture during drought and drains excess water during heavy rainfall. Climate-resilient farming encourages farmers to adopt practices like composting, mulching, green manuring, and minimum tillage. These techniques nourish the soil, reduce chemical dependency, and support microbial life. Over time, improved soil structure increases yield stability even when climate conditions become unfavourable. Soil testing helps farmers apply only the nutrients required, reducing input costs and preventing environmental harm. When farmers protect soil, they protect their future.

Water Management for Climate Stress

As water becomes increasingly scarce or irregular, climate-resilient farming prioritizes efficient water use. Techniques like drip irrigation, sprinkler systems, farm ponds, check dams, and contour bunding help farmers conserve water and manage rainfall. In dryland regions, farmers adopt in-situ moisture conservation by using crop residues to cover the soil and prevent evaporation. In flood-prone areas, raised-bed farming protects crops from waterlogging. Rainwater harvesting structures ensure that excess rainfall becomes an asset instead of a source of destruction. Water security is fundamental to agricultural resilience, and these methods ensure that farms remain productive even during droughts or excessive rains.

Agroforestry and Biodiversity Enhancement

Agroforestry integrating trees with crops and livestock is a powerful climate-resilient strategy. Trees regulate temperature, reduce soil erosion, improve water efficiency, and provide additional income from fruits, fodder, or timber. They create a microclimate around the field, protecting crops from heat and heavy winds. Climate-resilient farming also promotes biodiversity in fields. Flowering plants attract pollinators, legumes enrich soil nitrogen, and diverse crops minimize pest outbreaks. Biodiversity makes farms more stable and productive in the long run.

Integrated Farming Systems

An integrated farming system combines crops, livestock, fisheries, poultry, and agroforestry into one sustainable unit. This system recycles waste, reduces input costs, and provides multiple income streams. For example, cow dung becomes manure, crop residues feed livestock, and pond water irrigates fields. Integrated systems absorb climate stress better because they do not depend on a single crop for income. When one component is affected by climate, others offer support. These systems are especially beneficial for smallholders who face frequent climatic uncertainties.

Digital Tools and Climate Advisory Services

Technology plays a major role in building climate resilience. Weather-based advisories inform farmers about upcoming rainfall, temperature changes, or pest outbreaks so they can prepare in advance. Mobile apps guide sowing dates, fertilizer schedules, and irrigation timing. Drones monitor crop health and detect stress early. Satellite imagery helps predict drought patterns and soil moisture. Combined with local extension services, digital tools empower farmers to make

informed decisions. They help reduce loss and improve efficiency in a highly unpredictable climate.

Farmer-Led Innovation and Traditional Knowledge

Climate-resilient farming respects local practices that have supported communities for generations. Traditional drought-proof crops, community seed banks, indigenous livestock breeds, natural pest remedies, and water-harvesting wisdom form an important foundation. When combined with scientific research, these practices become more effective and reliable. Farmer-led innovation encourages farmers to experiment with new methods and share their learning with others. Climate resilience grows stronger when farmers trust the system and actively participate in shaping it.

Risk Management and Income Diversification

Insurance, credit access, and market linkages form an essential part of climate resilience. Crop insurance protects farmers from income loss during extreme weather. Access to affordable credit prevents distress sales of land or livestock. Market linkages ensure better prices for resilient crops like millets, pulses, and oilseeds. Income diversification such as beekeeping, mushroom cultivation, dairy farming, or value-added processing provides financial cushions. A resilient farm is not only environmentally strong but economically secure as well.

Climate-Resilient Infrastructure at Village Level

Village-level infrastructure such as solar pumps, community irrigation systems, storage facilities, custom-hiring centers, and rural processing units enables farmers to withstand climate stress. Storage reduces post-harvest losses caused by unexpected weather. Custom-hiring centers make modern machinery affordable. Climate-resilient villages support farmers through collective action, ensuring that individual households do not bear the burden alone.

Challenges in Adopting Climate-Resilient Farming

Despite its benefits, climate-resilient farming faces several barriers. Many farmers, especially smallholders, lack the capital to invest in new technologies. Limited awareness, risk aversion, and poor extension services restrict adoption. In dry or remote areas, water scarcity remains a major obstacle. Market systems often do not reward resilient crops fairly. Policy-level gaps, fragmented advisory services, and limited research outreach also slow down progress. Building resilience requires coordinated efforts across scientists, extension agents, policymakers, and communities.

Future Pathways for Climate-Resilient Agriculture

The future of climate-resilient farming lies in scaling innovations and making them accessible to every farmer. Climate-proof seeds, micro-irrigation, solar-based energy solutions, digital crop monitoring, and regenerative agriculture will shape tomorrow's farm landscape. Strengthening farmer training, decentralizing seed production, improving market linkages, and promoting climate-smart villages are essential steps. Climate resilience must become a national and global priority, supported by long-term policies and farmer-centric programs.

Summary

Climate-resilient farming is an essential approach for protecting agriculture from the growing impacts of climate change. As farmers face frequent droughts, floods, heatwaves, and unpredictable weather, building resilience across the farming system becomes critical. Climate-resilient farming integrates modern science with traditional wisdom to create flexible, sustainable, and productive farm practices. It involves climate-smart crop varieties, crop diversification, mixed and staggered cropping, and soil health management through composting, mulching, and reduced chemical use. Water conservation techniques such as drip irrigation, rainwater harvesting, and raised-bed farming help farmers manage both scarcity and excess rainfall. Agroforestry enhances biodiversity while protecting fields from temperature fluctuations, and integrated farming systems provide multiple income sources that reduce risk.

Digital tools such as weather advisories, satellite monitoring, and mobile-based guidance empower farmers with timely information. Traditional knowledge, community seed banks, and farmer-led innovations support local adaptation. Risk management through insurance, credit, and market support strengthens economic resilience. Village-level infrastructure, collective action, and training programs further enhance farmers' ability to cope with climate uncertainty.

The approach also acknowledges challenges such as financial limitations, poor awareness, weak extension services, and market constraints. Overcoming these barriers requires coordinated action from government agencies, research institutions, markets, and farming communities. The future of climate-resilient farming lies in accessible technology, climate-proof villages, and strong farmer-centric policies. Overall, climate-resilient farming offers a meaningful pathway to safeguard food security, environmental health, and farmer livelihoods in an era of increasing climate stress.

Conclusion

Climate-resilient farming is no longer just an option; it is a necessity for the survival of agriculture in the 21st century. As climate change intensifies, farmers cannot rely on traditional practices alone to protect their crops, soil, or income. They need agricultural systems that bend without breaking, recover quickly from shocks, and remain productive under varying climatic conditions. Climate-resilient farming provides precisely this stability by combining scientific techniques, ecological balance, and farmer-centered innovation.

This approach strengthens the entire farm ecosystem soil, water, crops, livestock, and community institutions so that farming remains viable even when climate behaves unpredictably. It reduces vulnerability, enhances productivity, and ensures long-term sustainability. Most importantly, it restores confidence among farmers who often feel powerless in the face of recurring climate risks.

To truly secure the future of agriculture, climate resilience must become embedded in policies, extension services, research priorities, and market systems. Every farmer small or large should have access to the knowledge, tools, and support needed to adopt resilient practices. When climate-resilient farming becomes mainstream, agriculture will not only survive climate change

but thrive despite it. It stands as a powerful pathway toward ecological health, food security, and dignified rural livelihoods.

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VERTICAL FARMING: AGRICULTURE OF THE FUTURE

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Abstract

Vertical farming has emerged as a promising innovation to address the growing challenges of conventional agriculture, including land scarcity, climate change, water limitations, and rapid urbanization. This technology involves cultivating crops in vertically stacked layers under controlled environmental conditions using advanced systems such as hydroponics, aeroponics, aquaponics, artificial lighting, and automated climate control. By decoupling food production from natural climatic variability, vertical farming enables year-round cultivation with enhanced productivity and resource efficiency.

However, the technology faces several challenges, including high initial investment costs, energy dependence, technical complexity, and limited feasibility for staple crops. Sustainability outcomes largely depend on integrating renewable energy and cost-effective technologies. The chapter concludes that vertical farming should be viewed as a complementary system to conventional agriculture rather than a complete replacement. With continued technological advancements, policy support, and sustainable energy integration, vertical farming has the potential to play a significant role in future food production systems and urban agriculture, contributing to global food security and environmental sustainability.

Keywords: Controlled Environment Agriculture (CEA), Hydroponics, Aeroponics, Urban Agriculture.

1. Introduction

Agriculture has always evolved in response to human needs, population growth, climate variability, and technological progress. From the domestication of crops to mechanization, from the Green Revolution to precision agriculture, each phase of agricultural development has aimed to increase productivity while managing limited natural resources.

In the twenty first century, agriculture faces unprecedented challenges: shrinking arable land, rapid urbanization, climate change, water scarcity, soil degradation, and the growing demand for fresh, safe, and nutritious food. These pressures have compelled scientists, policymakers, and entrepreneurs to rethink conventional farming systems.

Vertical farming has emerged as one of the most promising responses to these challenges. By growing crops in vertically stacked layers under controlled environments, vertical farming represents a fundamental shift from land dependent agriculture to technology driven food

production. It offers the possibility of producing high yields in small spaces, closer to consumers, and independent of seasonal and climatic uncertainties. This chapter explores vertical farming as the agriculture of the future, examining its principles, technologies, benefits, limitations, and its potential role in building sustainable food systems.

2. Concept and Evolution of Vertical Farming

Vertical farming refers to the cultivation of crops in vertically arranged layers, often integrated into buildings, warehouses, or shipping containers. Unlike traditional farming, which relies heavily on soil and open fields, vertical farming commonly uses soilless cultivation techniques such as hydroponics, aeroponics, and aquaponics. Environmental factors such as light, temperature, humidity, and nutrients are precisely controlled to optimize plant growth.

The idea of growing plants in controlled environments is not new. Greenhouses have been used for centuries to extend growing seasons. However, the concept of stacking crop production vertically gained momentum in the early 2000s with advances in LED lighting, automation, and sensor technologies. As cities expanded and farmland around urban centres declined, vertical farming gained attention as a way to produce food within city limits.

Over time, vertical farming has evolved from experimental projects to commercial enterprises. Today, vertical farms operate in many parts of the world, supplying leafy greens, herbs, and specialty crops to urban markets. While still a developing sector, its rapid growth reflects a broader transformation in how food can be produced in the future.

3. Key Technologies Used in Vertical Farming

3.1 Controlled Environment Agriculture (CEA)

At the heart of vertical farming lies controlled environment agriculture. CEA allows farmers to regulate all critical growth factors, including temperature, carbon dioxide concentration, humidity, light intensity, and nutrient supply. By removing environmental variability, crops can grow faster, healthier, and with greater uniformity.

3.2 Lighting Systems

Artificial lighting, particularly LED technology, plays a central role in vertical farming. LEDs can be tailored to emit specific wavelengths of light that maximize photosynthesis and influence plant morphology. Compared to traditional lighting, LEDs are energy-efficient, long-lasting, and generate less heat, making them suitable for stacked growing systems.

3.3 Soilless Cultivation Techniques

- Hydroponics involves growing plants in nutrient-rich water solutions without soil. It is widely used in vertical farming due to its efficiency and simplicity.
- Aeroponics delivers nutrients in the form of mist directly to plant roots, using very little water and enabling rapid growth.
- Aquaponics combines hydroponics with fish farming, where fish waste provides nutrients for plants, and plants help purify the water.

3.4 Automation and Artificial Intelligence

Automation reduces labour requirements and improves precision. Sensors continuously monitor plant health and environmental conditions, while artificial intelligence analyses data to optimize growth parameters. Automated systems can adjust lighting, irrigation, and nutrient delivery in real time, increasing efficiency and consistency.

4. Advantages of Vertical Farming

4.1 Efficient Land Use

One of the most significant advantages of vertical farming is its ability to produce large quantities of food in minimal space. By stacking crops vertically, productivity per unit area increases manifold compared to conventional farming. This is particularly valuable in densely populated urban areas where land is scarce and expensive.

4.2 Water Conservation

Vertical farming uses significantly less water than traditional agriculture. Closed loop irrigation systems recycle water, minimizing losses due to evaporation and runoff. In a world facing increasing water scarcity, this efficiency is a major advantage.

4.3 Climate Independence

Traditional agriculture is highly vulnerable to climate variability, extreme weather events, pests, and diseases. Vertical farming operates indoors under controlled conditions, reducing dependence on weather and enabling year-round production. This stability enhances food security and reduces crop failure risks.

4.4 Reduced Chemical Use

Because vertical farms are enclosed environments, pest pressure is lower, and the need for chemical pesticides and herbicides is greatly reduced or eliminated. This leads to cleaner produce and lower environmental contamination.

4.5 Proximity to Consumers

Urban vertical farms shorten supply chains by producing food closer to consumers. This reduces transportation costs, fuel consumption, and postharvest losses while providing fresher produce with longer shelf life.

5. Environmental and Sustainability Implications

Vertical farming aligns closely with the principles of sustainable agriculture. By minimizing land conversion, it helps preserve natural ecosystems and biodiversity. Reduced water use and elimination of agricultural runoff lower pressure on freshwater resources. Additionally, by enabling local food production, vertical farming can reduce greenhouse gas emissions associated with long-distance transportation.

However, sustainability outcomes depend largely on energy sources. Vertical farms require substantial electricity for lighting, climate control, and automation. If powered by fossil fuels, the environmental benefits may be diminished. Integrating renewable energy sources such as solar, wind, or energy-efficient building designs is essential to enhance sustainability.

6. Economic and Social Dimensions

6.1 Economic Viability

The economic feasibility of vertical farming depends on crop selection, scale, technology costs, and market access. High-value, fast-growing crops such as leafy greens and herbs are currently the most profitable. While initial investment costs are high, operational efficiencies and technological improvements are gradually reducing production costs.

6.2 Employment and Skill Development

Vertical farming creates new employment opportunities that differ from traditional agriculture. Jobs often require technical skills related to engineering, data analysis, plant science, and system management. This shift can attract younger generations to agriculture and promote innovation driven rural and urban employment.

6.3 Food Security and Nutrition

By enabling consistent and localized food production, vertical farming can strengthen food security, particularly in urban areas and regions with limited arable land. Fresh, pesticide free produce contributes to improved nutrition and public health.

7. Limitations and Challenges

- Despite its potential, vertical farming faces several challenges:
- High Initial Costs: Infrastructure, technology, and energy requirements make entry expensive.
- Energy Dependence: Artificial lighting and climate control consume large amounts of electricity.
- Crop Limitations: Staple crops such as cereals and pulses are currently not economically viable in vertical systems.
- Technical Complexity: System failures, power outages, or management errors can lead to rapid crop losses.
- Addressing these challenges requires continued research, policy support, and integration of renewable energy and cost-effective technologies.

8. Role of Vertical Farming in Future Agriculture

Vertical farming is not a replacement for conventional agriculture but a complementary system. While traditional farming will continue to supply staple crops, vertical farming can specialize in high-value, perishable produce and urban food supply. Together, these systems can form a resilient and diversified agricultural landscape.

In the future, vertical farms may be integrated into smart cities, residential buildings, and commercial complexes. Advances in biotechnology, automation, and renewable energy will further enhance productivity and sustainability. As global populations grow and environmental constraints intensify, vertical farming offers a viable pathway toward feeding cities sustainably.

Conclusion

Vertical farming represents a transformative approach to food production, addressing many of the limitations of conventional agriculture in an increasingly urbanized and resource-constrained world. By combining technology, innovation, and sustainability principles, it enables efficient, reliable, and environmentally responsible food production. While challenges remain, ongoing advancements and supportive policies can unlock its full potential.

As agriculture moves toward a future shaped by climate uncertainty and population growth, vertical farming stands as a symbol of human ingenuity and adaptability. It reflects a broader shift toward smarter, cleaner, and more resilient food systems, reinforcing its place as a key component of the agriculture of the future.

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DISEASES OF PINEAPPLE AND THEIR MANAGEMENT

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Introduction

Pineapple (*Ananas comosus*) is a tropical fruit shrub bearing an edible fruit and is the most economically important member of the family Bromeliaceae. It is indigenous to South America, it has been cultivated for centuries and spread widely after its introduction to Europe in the 17th century, where it became a symbol of luxury (Bartholomew *et al.,* 2012). The plant grows as a small shrub, with individual flowers fusing to form a multiple fruit, and is propagated through offsets or side shoots (Stahl *et al.,* 2012). The name *Ananas* originates from the Tupi-Guarani word *nanas*, while "pineapple" reflects its resemblance to a pine cone. Archaeological evidence indicates its use in South America as early as 1200–800 BC (Ming *et al.,* 2015). Christopher Columbus encountered pineapple in 1493, and the Portuguese introduced it to India by the mid-16th century. In India, pineapple is cultivated mainly in Assam, Meghalaya, Tripura, West Bengal, Kerala, and Karnataka. Major varieties include Kew, Giant Kew, Queen, Mauritius, Jaldhup, and Lakhat. India ranks fifth globally, contributing about 8.2% of world production.

Pineapple (*Ananas comosus* L.) is susceptible to a wide range of fungal, bacterial, viral, and nematode diseases from the planting stage through fruit development and post-harvest handling. These diseases are of major economic importance due to their adverse effects on fruit yield, quality, availability of healthy planting material and storage. Pathogenic microorganisms can infect different plant parts such as roots, stems, leaves, and fruits. Among the most economically significant diseases are heart rot, fruit collapse, butt rot, black rot, fruitlet core rot, internal black rot, stem-end rot, fusariosis, yeasty rot, mealybug wilt of pineapple associated virus (PMWaV), and leaf spot diseases (Sapak *et al.,* 2021). These diseases can result in severe yield losses; like bacterial heart rot and fruit collapse have been reported to reduce pineapple productivity by up to 40% (Young *et al.,* 2022). Similarly, Sether and Hu (2002) documented that mealybug wilt associated with PMWaV can lead to a 30-55% reduction in fruit yield, depending on the plant's age at the time of infection. Other pineapple diseases may also cause substantial economic losses if not effectively managed through appropriate disease prevention and management strategies.

Fungal Diseases: Various fungal diseases which infected the pineapple are Phytophthora heart/ top rot (*Phytophthora cinnamomic*; *Phytophthora nicotianae*), Phytophthora root rot (*Phytophthora cinnamomi*), Base/ Butt Rot (*Thielaviopsis paradoxa/ Ceratocystis paradoxa*),

Black Rot (*Thielaviopsis paradoxa/ Ceratocystis paradoxa*), Fruit-Let Core Rot/ Green Eye disease (*Fusarium ananatum, F. guttiforme, F. subglutinans and Penicillium funiculosum*), Fusariosis (*Fusarium guttiforme, F. concentricum, F. fujikuroi, F. incarnatum, F. oxysporum, F. polyphialidicum, F. proliferatum, F. temperatum and F. verticillioides*), Interfruitlet Corking (*Penicillium funiculosum*), Leathery Pocket (*Penicillium funiculosum*), White Leaf Spot (*Chalara paradoxa*), Fruit Rot Yeasty disease (Hanse niaspora valbyensis, *Saccharomyces* spp. and *Candida* spp.), Stem End Rot and Internal Black Spot (*Neoscytalidium dimidiatum*), Leaf Spot (*Exserohilum rostratum, Curvularia clavate*), and Pineapple anthracnose (*Colletotrichum ananas/ C. gloeosprioides/ C. fructicola*).

- **Bacterial Diseases:** Different kind of bacterial pathogens attacked the pineapple and causes different type of bacterial diseases such as Marbling (*Pantoea ananatis* and *Acetobacter* sp.), Pink Disease (*Pantoea citrea, Gluconobacter oxydans* or *Acetobacter aceti*), Bacterial heart rot and fruit collapse (*Dickeya zeae*), Bacterial soft rot (*Enterobacter cloaca*).
- **Viral Diseases:** Pineapple infected by various viral diseases Mealybug Wilt Disease (ampelo virus), Yellow Spot (Capsicum chlorosis virus (Tospoviruses)).
- **Post Harvest Disease:** Postharvest diseases of pineapple such as black rot, fruitlet core rot, pink disease, and yeasty fermentation cause significant losses by reducing fruit quality during storage and marketing. These diseases mainly arise from fungal and bacterial infections entering through wounds or handling injuries after harvest.
- **Physiological Disorders:** Other miscellaneous diseases and disorder which are caused due to the adverse environmental conditions are Multiple Crowns, Fruit and Crown Fasciation, Collar of Slips, Dry Fruit and Bottle Neck, Sun-Scald, Internal Browning (Black heart).
- **Parasitic Nematodes:** Several species of parasitic nematodes *Meloidogyne javanica, Meloidogyne incognita, Pratylenchus brachyurus* and *Rotylenchulus reniformis* which attack the pineapple.

I. Fungal Diseases of Pineapple

Although pineapple is susceptible to a wide range of fungal diseases, this chapter confines its discussion to those diseases that are of major economic importance and pose serious constraints to production and postharvest quality.

1. Phytophthora Heart Rot or Top Rot

Phytophthora heart rot is a destructive disease of pineapple caused by the soilborne pathogens *Phytophthora cinnamomi* and *Phytophthora nicotianae*. Favoured by warm and moist conditions, the disease is prevalent in tropical and subtropical regions and can result in severe yield losses and deterioration of fruit quality, leading to significant economic damage.

Disease occurrence and distribution: Phytophthora heart rot is most prevalent in regions with high rainfall, poor drainage, and warm, humid conditions that favour the survival and spread of

Phytophthora spp. The disease is widely reported in major pineapple-producing areas of Asia, Africa, Central and South America, and the Pacific, where it poses a serious constraint to commercial production. In India, its occurrence is frequent in the warm and humid eastern regions. *Phytophthora nicotianae* has been identified as the principal causal pathogen responsible for severe losses in countries such as China (Shen *et al.,* 2013), Ecuador (Ratti *et al.,* 2018), Cuba (Rodriguez *et al.,* 2002), Uganda (Oculi *et al.,* 2020), and Mexico (Espinosa-Rodríguez *et al.,* 2015), whereas *P. cinnamomi* is the predominant pathogen reported in Australia, particularly affecting the MD2 variety (Anderson *et al.,* 2011).

Diagnostic Symptoms: Initial symptoms appear as water-soaked lesions on the leaves, which gradually enlarge, coalesce, and later dry up. The heart leaves of infected plants turn yellow to light coppery brown, followed by wilting and inward rolling of leaf margins. As the disease advances, the heart leaves collapse, turn brown, and die. Infected young leaves are easily pulled out, revealing water-soaked, rotten basal tissues with a foul odour caused by secondary microbial invasion.

The growing point of the stem becomes yellowish-brown, with a distinct dark line separating healthy and diseased tissues. Rotting fruits may also emit an offensive smell, and severe infections often result in plant stunting and reduced yield due to associated root rot. Pineapple plants of all growth stages may be affected; however, 3–4-month-old crown plantings are most susceptible. Fruiting plants and suckers on ratoon crops can also develop symptoms under favourable conditions (Ratti *et al.,* 2018).

Disease Cycle

The disease is caused by the oomycetous pathogens *Phytophthora cinnamomi* and *Phytophthora nicotianae*, which survive in soil and infected plant debris primarily as chlamydospores for several years. These survival structures germinate either directly, producing infective hyphae, or indirectly by forming sporangia that release motile zoospores capable of infecting roots, stems, and young leaf tissues (Oculi *et al.,* 2020).

Phytophthora spp. are soilborne pathogens and require free water for sporangial formation and zoospore release; therefore, infection and disease development are greatly enhanced under high soil moisture and poor drainage. The disease spreads rapidly in warm, humid environments, particularly in waterlogged soils, leading to extensive tissue decay and severe losses in pineapple production (Espinosa-Rodríguez *et al.,* 2015).

Disease Management

Cultural methods

- **Cultural and drainage management:** Cultural practices are essential for managing Phytophthora heart rot, with adequate soil drainage being the most critical factor. Cultivation on well-drained soils, planting on raised beds (minimum 20 cm height), construction of surface and subsurface drainage systems, maintaining the water table at least 60 cm below the soil surface, avoiding excessively deep planting, and preventing soil entry into the plant heart during planting significantly reduce disease incidence.

- **Soil pH management:** Proper soil pH regulation is important since *P. cinnamomi* becomes more active at pH levels above 4.0. Liming materials should therefore be used cautiously, while sulfur application may be considered as a supplementary measure to lower soil pH when it exceeds 5.5.

- **Good agricultural practices (GAP):** Adoption of integrated agronomic practices enhances pineapple productivity and fruit quality. These include proper soil preparation, appropriate planting systems and spacing, use of healthy planting materials, balanced fertilization, efficient irrigation management, and integrated weed, pest, and disease management strategies (Aristoteles *et al.,* 2011; Baiswar *et al.,* 2021; Rohrbach & Johnson, 2003).

- **Sanitation and field hygiene:** Destruction of infected plants and crop residues reduces pathogen inoculum and prevents the persistence of resistant structures such as chlamydospores and sclerotia in soil. Use of sanitized tools, careful handling to minimize fruit injuries, suitable irrigation practices, and effective nutrient management help reduce plant stress and susceptibility to field and postharvest diseases (Ventura *et al.,* 2009; Soler *et al.,* 2018).

- **Crop management and production practices:** Crop rotation with non-host crops and effective weed management disrupts disease cycles and reduce pathogen reservoirs. Artificial floral induction is recommended to synchronize flowering and harvesting, thereby improving fruit uniformity and marketability.

Chemical methods

- Systemic fungicides applied at recommended rates and intervals reduce Phytophthora heart rot severity, and planting material should be treated with registered fungicides before planting to minimize primary infection.

- Soil drenching or foliar spraying after planting protects plants, and fungicides should be applied immediately after early symptom appearance for effective control.

- Severely infected plants should be removed and destroyed, while surrounding plants should be soil-drenched with hexaconazole (0.4%) to prevent disease spread.

- Pineapple leaf spot can be controlled by spraying zineb, mancozeb, or ziram at 0.2% concentration.

2. Phytophthora Root Rot

Phytophthora root rot of pineapple is a serious soil-borne disease caused primarily by the water molds *Phytophthora cinnamomi* and *P. nicotianae* var. *parasitica*. The disease is most prevalent in high-rainfall regions and in fields with poor drainage, were prolonged soil moisture favours pathogen activity. Severe losses commonly occur during extended wet periods, particularly when rains persist into cooler months. Even moderately well-drained soils can become conducive under prolonged wet weather. The disease can eliminate the ratoon crop, significantly reducing plantation longevity. Rough-leaf pineapple varieties and some low-acid hybrids are more susceptible than Smooth Cayenne.

Diagnostic Symptoms

Above-ground symptoms are often non-specific and resemble damage caused by nematodes, mealybug wilt, or oxygen-deficient soils. Initial symptoms include stunting, reduced vigor, and low yield. Leaves gradually change from healthy green to shades of yellow and red, with leaf tips and margins becoming necrotic. Affected plants can be easily pulled from the soil due to extensive root decay. Internally, leaf bases appear white with water-soaked, grey-brown transverse lesions that slowly progress from the base toward the tip. Infected fruits remain small, ripen prematurely, emit a foul odor due to tissue rot, and become unmarketable. If infection is detected early, plants may recover; however, when roots are destroyed back to the stem, regeneration often fails.

Disease Cycle

The pathogens persist in soil, plant debris and infect pineapple roots under favorable moisture conditions. Infection is promoted by excessive soil moisture, poor aeration, and inadequate drainage. Once roots are infected, the pathogen spreads upward, leading to crown and leaf base rot. Disease severity increases during prolonged wet periods, especially in poorly drained fields. Soil factors also influence pathogen activity: *P. cinnamomi* becomes more aggressive as soil pH rises above 4.0, while *P. nicotianae* is more active in soils with higher nutrient status. Spread within plantations is facilitated by surface runoff, irrigation water, contaminated planting material, and movement of infested soil.

Disease Management

Cultural Methods

- Cultural management reduces Phytophthora root rot incidence, with well-drained soils and careful site selection being essential.
- Raised beds (minimum 20 cm), surface and internal drainage channels, runoff interception, and underground drainage systems help prevent waterlogging.
- Use only disease-free planting material and maintain proper planting depth to avoid soil entering the plant heart.
- Soil pH should be carefully managed, as *Phytophthora cinnamomi* is more active at higher pH; liming should be used cautiously, and sulfur may be applied when pH exceeds 5.5 as part of integrated management.

Chemical Methods

- Chemical control involves the use of systemic fungicides to suppress disease development.
- Planting material should be treated with registered fungicides before planting to reduce initial inoculum.
- Post-planting drenching or spraying with recommended systemic fungicides at proper rates and intervals reduces disease severity.
- Fungicides are most effective when applied at early symptom stages, as severely infected plants respond poorly to treatment.

3. Base or Butt Rot

Base or Butt rot of pineapple are caused by *Thielaviopsis paradoxa* (de Seynes) Hohn (anamorph), an Ascomycetes fungus that also possesses a sexual (teleomorph) stage known as *Ceratocystis paradoxa* (Dade) C. Moreau. The pathogen produces infective conidia (macrospores and microspores), mycelium, and thick-walled chlamydospores (aleurioconidia), which serve as resting spores in soil and plant debris (Swaroop Kumar, 2007; Abdullah *et al.,* 2009). The teleomorph stage is rarely observed in nature and is considered less virulent, infecting plants mainly under stress conditions (Alvarez *et al.,* 2012). *T. paradoxa* is a facultative parasite, surviving saprophytically on dead tissues and acting primarily as a wound parasite on healthy plants (Reyes, 1999). Butt rot primarily affects pineapple planting material such as crowns, slips, and suckers before or immediately after planting (Joy and Sindhu, 2012). The disease is favoured by warm, humid, and wet conditions and is particularly severe when planting material is harvested during showery weather and stored in heaps (Nurnadirah *et al.,* 2018). Black rot, caused by the same pathogen, is a major postharvest disease, with symptoms developing mainly during storage and transit (Snowdon, 2010; Adikaram and Abayasekara, 2012). In Malaysia, Morris, Sarawak, and MD2 pineapple cultivars are reported to be highly susceptible to black rot (Thalip *et al.,* 2015; Singh *et al.,* 2018).

Diagnostic Symptoms

Butt rot symptoms are confined to the basal tissues of crowns, slips, and suckers. Infected tissues become soft, stringy, and develop grey to black discoloration, often leaving cavities at the base of the stem (Rohrbach and Johnson, 2003; Joy and Sindhu, 2012). Severely affected plants fail to establish, wilt rapidly, and exhibit stunted growth. Unlike Phytophthora heart rot, young leaves remain firmly attached even as basal tissues decay. Infected plants can easily break off at ground level.

Disease Cycle

Thielaviopsis paradoxa survives in soil and decaying pineapple residues as chlamydospores and mycelium (Abdullah *et al.,* 2009). Infection occurs mainly through fresh wounds created during detachment of planting material, harvesting, or mechanical injury (Elliott, 2009). Under high humidity, the pathogen produces conidia that are disseminated by wind, water, soil movement, insects, and rodents. While the anamorph stage dominates during the growing season, the teleomorph stage (*C. paradoxa*) is rarely encountered and infects plants under stress conditions such as overwintering (Alvarez *et al.,* 2012). Disease development is rapid under warm and wet conditions (Nurnadirah *et al.,* 2018).

Disease Management

Cultural Methods

- Careful handling of planting material minimizes wounds during separation from the parent plant or fruit (Joy and Sindhu, 2012).
- Planting tools and equipment should be properly sanitized to prevent contamination.

- Planting materials should be cured by exposing the butt end to sunlight in a single layer during storage to reduce disease incidence.
- Improving soil drainage and avoiding planting during wet weather reduce disease risk (Joy and Sindhu, 2012).
- Mechanical injuries during harvesting should be minimized, and damaged or sunburned fruits should be discarded to control black rot (Snowdon, 2010).

Chemical Methods

- Fungicidal treatment of planting material effectively controls butt rot; triadimenol and propiconazole are used in Australia, while dipping or spraying with 1% Bordeaux mixture or 0.25% copper oxychloride is recommended in India (Joy and Sindhu, 2012).
- Untreated planting material with high inoculum levels can lead to up to 100% disease incidence (Rohrbach and Johnson, 2003; Sipes and Wang, 2017).
- For black rot control, broken peduncles should be dipped in approved fungicides before storage at 9°C (Rohrbach and Johnson, 2003).
- Benzoic acid and benomyl are commonly used in Malaysia, while acetic acid dips (4–5%) and hot water treatment at 54°C for 3 minutes are also effective (Eng, 2009; Wijeratnam *et al.,* 2006).

Integrated Disease Management (IDM) Strategies

- Integrated management combining cultural sanitation, careful handling of planting materials, fungicide application, and improved drainage provides effective disease control.
- Biological control agents such as *Pseudomonas* spp., *Bacillus* spp., *Chromobacterium* spp., *Serratia* spp., *Pichia guilliermondii*, and *Trichoderma asperellum* show strong antagonistic activity against *T. paradoxa* and offer potential for sustainable management (Nurnadirah *et al.,* 2018).

4. Black Rot

Black rot of pineapple fruit is caused by the fungal pathogen *Thielaviopsis paradoxa* (De Seynes) Höhn., syn. *Chalara paradoxa*, which is also responsible for butt rot of pineapple. The fungus is soil- and debris-borne and is well adapted to survive on infected plant residues and decaying organic matter. It produces two types of asexual spores: hyaline, cylindrical endoconidia and thick-walled, dark brown chlamydospores. These chlamydospores enable the pathogen to survive under adverse environmental conditions and serve as an important source of primary inoculum. The pathogen grows rapidly under warm and humid conditions and readily colonizes wounded or stressed plant tissues, particularly during postharvest handling.

Diagnostic Symptoms

Black rot is a postharvest disease that begins with circular, water-soaked lesions developing on damaged peduncles, wounds, or the fruit surface. These lesions rapidly enlarge and extend into the flesh, causing the tissue to become soft, watery, and eventually disintegrated with

characteristic blackened patches. Under favourable conditions, visible symptoms may appear within 3-4 days after harvest, leading to rapid loss of fruit quality (Joy & Sindhu, 2012; Swaroop Kumar, 2007; Wijesinghe *et al.,* 2010). Fruits showing translucency are more vulnerable to infection due to increased susceptibility to mechanical injury and juice leakage (Reyes *et al.,* 2004).

Disease Cycle

The disease cycle begins when *T. paradoxa* gains entry into the fruit, most commonly through a broken peduncle during or after harvesting (Joy & Sindhu, 2012; Swaroop Kumar, 2007). The pathogen may also infect through wounds and natural openings on the fruit surface. Pineapple fruits affected by translucency are more susceptible to black rot, as translucent tissues are easily injured and facilitate pathogen invasion (Reyes *et al.,* 2004). Leakage of juice from damaged fruits or broken peduncles further enhances fungal growth and colonization. After penetration, the fungus rapidly invades fruit tissues, leading to extensive decay during storage, transport, and marketing.

Disease Management

Cultural methods

- Preventive cultural practices during harvesting and postharvest handling are essential for black rot management.
- Careful harvesting should avoid peduncle breakage and mechanical injuries that facilitate pathogen entry, and damaged or translucent fruits should be excluded from storage and marketing (Reyes *et al.,* 2004).
- Proper sanitation of tools, containers, and storage facilities reduces fungal inoculum.
- Rapid cooling, minimizing juice leakage, and avoiding warm, humid storage conditions reduce disease development, with susceptible varieties such as Morris, Sarawak, and MD2 requiring special postharvest care (Singh *et al.,* 2018).

Biological methods

- Biological control using antagonistic microorganisms and natural biocontrol agents can suppress pathogen growth and reduce postharvest decay.
- Eco-friendly biological strategies complement cultural practices and help reduce reliance on chemical treatments.

Chemical methods

- Chemical management includes the use of registered postharvest fungicides where permitted to reduce fungal infection.
- Fungicide treatments should follow recommended guidelines to prolong storage life and improve disease control.

Integrated disease management (IDM) Strategies

- Integrated disease management combines careful harvesting, sanitation, proper storage conditions, biological control, and judicious fungicide use.

- This holistic approach effectively suppresses black rot, particularly in susceptible pineapple cultivars.

5. Fruit-Let Core Rot/ Green Eye disease

Fruitlet core rot (FCR), also known as green eye disease, is an internal fruit disease of pineapple caused by several fungal pathogens. The main causal agents include *Fusarium guttiforme* and *Penicillium funiculosum* (currently renamed *Talaromyces funiculosus*) (Barral *et al.,* 2020). Other associated *Fusarium* species reported include *F. ananatum*, *F. subglutinans*, *F. proliferatum*, *F. sacchari*, and *F. verticillioides* (Vignassa *et al.,* 2021). Molecular studies identified *Fusarium ananatum* as a distinct pathogen responsible for FCR, different from *F. guttiforme*, which causes fusariosis (Stępien *et al.,* 2013). The disease has historically been attributed to *P. funiculosum*, particularly in Malaysia (Lim, 1985).

Diagnostic Symptoms

FCR is primarily an internal fruit disorder. Smooth Cayenne fruits generally show no external symptoms, whereas rough-leaf (Mauritius) cultivars may display uncoloured fruitlets known as "green eye." Severely affected fruitlets become brown to black, sunken, and dry while remaining firm in texture (Gu *et al.,* 2015). Internally, browning begins beneath the floral cavity and may extend to the fruit core, typically remaining confined to individual fruitlets (Barral *et al.,* 2020). The browning results from oxidation of phenolic compounds into quinones mediated by enzymes such as polyphenol oxidase and laccase (Avallone *et al.,* 2003). Increased accumulation of soluble and cell wall-bound phenolic acids occurs following symptom development (Barral *et al.,* 2020).

Disease Cycle

Penicillium funiculosum infects developing fruit between flower initiation and open-flower stages, with infection favored by cool temperatures (16-20°C) during the five weeks following flower initiation (Lim, 1980). The fungus can build up in leaf hairs damaged by mites, facilitating infection. Similar cool conditions also favor infection approximately 10–15 weeks after flower induction. *Fusarium guttiforme* typically enters the fruit through open flowers or injury sites, and infection risk increases when flowers develop and fruits mature under warm conditions. Physical injuries caused by sunburn or insect pests can enhance disease incidence (Ibrahim *et al.,* 2017).

Disease Management

Cultural methods

- Cultural practices help reduce fruitlet core rot incidence by minimizing mechanical injuries during crop growth and handling.
- Effective management of mites and insect pests is essential, as injuries facilitate pathogen entry.
- Protecting fruits from environmental stress such as sunburn using foam nets or protective coverings reduces disease development, especially in susceptible varieties.

Biological methods

- Plant-derived products such as eucalyptus oil and extracts from *Acalypha wilkensiana* and *Syzygium aromaticum* show antifungal activity against causal pathogens and offer eco-friendly disease management options (Adewuyi-Samuel *et al.,* 2019).

Chemical methods

- Fungicides have limited effectiveness against fruitlet core rot due to internal infection, but targeted application into terminal leaf openings during inflorescence emergence can reduce infection.
- Fungicide combinations applied at flower induction stage significantly reduce disease severity (Petty *et al.,* 2005).

Integrated Disease Management (IDM) Strategies

- Integrated disease management combines cultural practices, effective pest control, targeted fungicide application at critical stages, and biological or plant-based products.
- Adoption of multiple approaches helps minimize infection risk and improve overall disease suppression.

6. Fusariosis

Fusariosis is a major fungal disease of pineapple primarily caused by *Fusarium guttiforme*, although several other *Fusarium* species are also associated with the disease. These include *F. ananatum*, *F. fujikuroi*, *F. concentricum*, *F. incarnatum*, *F. oxysporum*, *F. polyphialidicum*, *F. proliferatum*, *F. temperatum*, *F. verticillioides*, *F. semitectum*, and *F. chlamydosporum* (Ibrahim *et al.,* 2016). The disease can cause significant yield losses and reported around 30-40% in Brazil (Carnielli-Queiroz *et al.,* 2019). The pathogen survives in infected planting materials and crop residues and produces resistant structures such as chlamydospores that persist in soil (Ventura *et al.,* 1993).

Diagnostic symptoms

Fusariosis affects all parts of the pineapple plant but is most conspicuous on fruits. Diagnostic symptoms include lesions and brown discolouration of fruitlets, sunken or rotten fruit skin, gum exudation, stem rosetting and curvature due to girdling, dry rot of leaves, chlorosis, increased leaf number per spiral, and natural cracking of fruits (Ibrahim *et al.,* 2016; Sapak *et al.,* 2021). Rough-leaf cultivars are generally more susceptible than smooth-leaf varieties.

Disease Cycle

Infection occurs mainly through wounds caused by insects, particularly the pineapple fruit caterpillar (*Thecla basilides*), or through infected planting materials. The pathogen spreads via contaminated propagules and plant debris. The sporadic nature of the disease and its association with insect injury make epidemics irregular but potentially severe (Ventura *et al.,* 1993).

Disease Management

Cultural methods

Destruction of infected crop residues reduces survival structures such as chlamydospores in soil. Use of disease-free planting material, sanitation practices, and selection or development of resistant varieties are important preventive strategies.

Biological methods

Biological control agents including antagonistic yeasts and *Trichoderma* spp. have shown potential in suppressing the pathogen. Plant-derived products such as thyme essential oil have also demonstrated antifungal activity (Korres *et al.,* 2011).

Chemical methods

Chemical fungicides remain widely used in commercial pineapple production. Treatments of planting materials with fungicides such as benomyl or captafol, as well as combinations including azoxystrobin, cyproconazole, carboxin, thiram, tebuconazole, and methyl thiophanate, have been evaluated for disease control. Fungicide and insecticide applications at flower induction and shortly after forcing may reduce disease incidence.

Integrated Disease Management Strategies

An integrated approach combining resistant varieties, sanitation, destruction of infected residues, hot water treatment of planting materials (54°C for 90 minutes), insect vector management, biological agents, and judicious fungicide use is recommended for effective management of fusariosis.

7. Interfruitlet Corking

Interfruitlet corking disease is primarily associated with the fungus *Penicillium funiculosum* (syn. *Talaromyces funiculosus*). The pathogen infects developing fruits, often in association with damage caused by mites, particularly through removal of trichomes (fruit hairs), which facilitates fungal colonization. The disease is sporadic in occurrence and is influenced by environmental and physiological factors such as season, plant size, and sun exposure.

Diagnostic Symptoms

Early symptoms include shiny patches on the fruit shell where trichomes have been removed by mite feeding. As the disease progresses, corky or suberized tissue develops externally between fruitlets, typically affecting patches of eyes rather than the entire fruit. Fine transverse cracks may appear on sepals and bracts, and in severe cases, corkiness restricts fruitlet development leading to malformation of one side of the fruit. Fissures commonly occur on the upper portion of fruits and on sun-exposed sides, particularly during the later stages of fruit ripening (Rabie *et al.,* 1997).

Disease Cycle

Infection occurs primarily during early fruit development, often following damage caused by mites or environmental stress. The disease is most commonly observed in fruits initiated in early autumn and may be confused with boron deficiency due to similar symptoms. Sun exposure, smaller plant size, moisture conditions, and seasonal factors influence disease development and severity.

Disease Management

Cultural methods

- Control of mite populations to prevent trichome damage reduces infection risk.
- Proper crop nutrition and avoidance of plant stress help minimize symptom development.

- Managing plant canopy to reduce excessive sun exposure and maintaining optimal moisture conditions decreases fissures and corking.

Biological methods

- Biological approaches using natural enemies of mites and antagonistic microorganisms may help reduce pathogen establishment, though research is limited.

Chemical methods

- Fungicides generally have limited effectiveness, but targeted application into terminal leaf openings during inflorescence emergence may reduce disease incidence.

Integrated disease management (IDM) Strategies

- Integrated management includes mite control, cultural practices to reduce environmental stress, accurate diagnosis to distinguish from nutrient deficiencies, and judicious fungicide use for effective control of interfruitlet corking (Rabie *et al.,* 1997).

8. Leathery Pocket

Leathery pocket disease is caused by the fungus *Penicillium funiculosum* (syn. *Talaromyces funiculosus*). The pathogen infects developing pineapple fruits, particularly during early reproductive stages, and is associated with mite-damaged leaf hairs that facilitate fungal colonization.

Diagnostic Symptoms

Fruits generally show no external symptoms. Internally, affected fruitlets develop corky, leathery tissue on the walls, resulting in brown discoloration and a firm, leathery texture.

Disease Cycle

The disease occurs sporadically and infection takes place during fruit development between flower initiation and open-flower stages. Cool temperatures (16–20°C), especially during the fifth week after flower initiation and at flower induction, favor infection. The fungus builds up in leaf hairs damaged by mites, which act as predisposing factors for disease development.

Disease Management

Cultural methods

- Reducing mite infestation and minimizing plant stress during flowering help limit disease occurrence.

- Proper crop monitoring during susceptible growth stages is important due to the sporadic nature of the disease.

Biological methods

- Biological control targeting mites or fungal pathogens may support disease management, though specific strategies remain limited.

Chemical methods

- Chemical control is generally impractical and uneconomic due to sporadic disease occurrence.

- Miticide applications at flower induction and about three weeks after forcing can reduce disease incidence.

Integrated disease management (IDM) Strategies

- Integrated management should focus on mite control, monitoring environmental conditions favouring infection, and maintaining good crop health to reduce disease risk.

9. Water Blister

Water blister disease is caused by the fungus *Chalara paradoxa*, which is also responsible for butt (base) rot and white leaf spot in pineapple. It is a major postharvest disease affecting fruits intended for the fresh market. The pathogen primarily infects through wounds and thrives under warm, humid conditions.

Diagnostic Symptoms

Symptoms usually develop three to four days after harvest. The disease causes soft, watery rot of the fruit flesh, making the overlying skin glassy, water-soaked, and brittle. Advanced infection results in disintegration of the skin, flesh, and core, leading to leakage through the shell. In severe cases, only the fibrous fruit shell remains, which collapses easily under pressure.

Disease Cycle

The disease rarely occurs in the field unless fruits are over-ripe or injured. Infection mainly occurs through bruises, growth cracks, and especially broken fruit stalks. Warm and wet conditions favor disease development, with higher incidence during summer harvest periods. Marketing fruits with crowns attached can reduce infection by limiting pathogen entry points.

Disease Management

Cultural methods

- Careful handling during harvesting and postharvest operations prevents bruising and mechanical injury.
- Sunburnt or damaged fruits with cracks should be rejected, and packing areas must be kept sanitary by removing pineapple refuse and rejected fruits.
- Keeping crowns attached during marketing helps reduce infection risk.

Biological methods

- Biological management options are limited, but maintaining hygienic conditions helps reduce pathogen load and disease spread.

Chemical methods

- Dip the fruit base in recommended fungicides within five hours after harvest, especially during warm and wet weather.
- Regular disinfection of packing sheds is recommended to reduce fungal inoculum.

Integrated disease management (IDM) Strategies

- Integrated management includes careful harvesting, sanitation, rapid postharvest cooling (around 9°C), fungicide treatments, and proper storage conditions for effective control of water blister disease.

10. Leaf Spot Disease

Leaf spot disease in pineapple is generally considered of minor importance unless severe infection affects the entire plant. Multiple fungal pathogens have been associated with the disease, including *Exserohilum rostratum* (Luo *et al.,* 2012), *Curvularia clavata* (Zhong *et al.,* 2016), *Chalara paradoxa* (Joy & Sindhu, 2012), *Fusarium* spp. (Ibrahim *et al.,* 2017), and *Neoscytalidium dimidiatum* (Sapak *et al.,* 2021).

Diagnostic Symptoms: Symptom expression varies among pathogens: *E. rostratum* produces greyish- to yellowish-white lesions that may coalesce and extensively damage leaf tissue; *C. clavata* causes water-soaked, chlorotic to necrotic irregular lesions, mainly along leaf margins and veins; and *Fusarium* spp. induce small necrotic spots that develop into brown to dark-brown lesions. Infection by *N. dimidiatum* begins as small brown spots that rapidly elongate, forming cream or whitish lesions with brown margins, sometimes bearing dark mycelium and spores. White leaf spot caused by *Chalara paradoxa* is associated with wound infection and is also linked to water blister and butt rot in pineapple. Initial symptoms appear as small brown spots on leaves, typically at sites where leaf margins are damaged by rubbing during strong winds. Under wet conditions, lesions elongate rapidly and may exceed 20 cm, extending toward the leaf tip. During dry weather, affected tissues become cream-coloured or nearly white with a papery appearance, while lesion margins often remain brown.

Disease Cycle

The pathogen infects through wounds and is most active under warm and wet environmental conditions. Disease occurrence is common between March and May, particularly during periods of prolonged rainfall.

Disease Management

Cultural methods

- Minimizing mechanical injury to leaves and reducing plant stress helps limit infection.
- Management is generally unnecessary due to the minor economic importance of the disease.

Biological methods

- Specific biological control measures are rarely used due to the low economic impact of the disease.

Chemical methods

- Chemical control is generally not recommended because the disease has little economic significance.

Integrated disease management (IDM) Strategies

- Routine monitoring and maintaining overall plant health are sufficient, and active intervention is generally unnecessary.

11. Fruit Rot Yeasty Disease

Yeasty rot of pineapple is caused by several yeast species, mainly *Hanseniaspora valbyensis*, *Saccharomyces* spp., and *Candida* spp. (Rohrbach & Johnson, 2003; Korres *et al.,* 2011). These yeasts are ubiquitous in nature and commonly occur on fruit surfaces, in soil, and in the

surrounding environment. They are unicellular fungi that reproduce primarily by budding and possess strong fermentative ability, allowing them to rapidly metabolize sugars present in pineapple juice. In Malaysia and some other regions, *Candida* sp. has been reported as a predominant causal organism (Sapak *et al.,* 2021; Joy & Sindhu, 2012). The pathogens are opportunistic and mainly infect through wounds or cracks in the fruit.

Diagnostic Symptoms

The disease is characterized by bubbling exudation of gas and juice from cracks or injuries on the fruit surface, resulting from fermentation and carbon dioxide production. The external rind becomes olive green to brown and leathery as the disease progresses. Internally, the pulp turns bright yellow, soft, and spongy, with the formation of large gas cavities. Advanced infection leads to collapse of internal tissues, leaving only the shell and spongy remnants of the fruit (Joy & Sindhu, 2012).

Disease Cycle

Infection typically occurs through mechanical injuries, insect damage, frost injury, or physiological cracking between fruitlets. Rapid environmental changes, especially shifts from cool dry conditions to warm wet weather during spring, promote fruit cracking and facilitate yeast entry. Once inside, yeasts ferment sugars, producing alcohol and carbon dioxide, which leads to tissue breakdown and characteristic gas formation. The disease may develop both pre-harvest and post-harvest, particularly in overripe fruits. Yeasts spread through contaminated surfaces, insects, handling practices, and exposure of wounded tissues to the environment.

Disease Management

Cultural methods

- Cultural practices are the main strategy for managing yeasty rot, including avoiding mechanical injury during field operations and harvesting.
- Protect developing fruits in frost-prone areas with paper bags to reduce cracking, and control insect pests that cause fruit injury.
- Harvest early and exclude fruits with inter-fruitlet cracking or physical damage from the fresh-fruit market to reduce spread and losses.
- Maintain proper field sanitation and ensure careful handling during transport and storage to prevent infection (Joy & Sidhu, 2012; Sapak *et al.,* 2021).

Chemical methods

- Chemical control options are limited as yeasty rot pathogens are opportunistic yeasts entering through wounds.
- Preventive postharvest sanitation and approved fungicidal washes or disinfectants can reduce surface microbial load and delay disease development.
- Management mainly emphasizes preventive measures rather than curative chemical treatments.

Biological methods

- Biological control information is limited; antagonistic microorganisms may compete with pathogenic yeasts on fruit surfaces and reduce colonization.
- Maintaining a balanced microbial environment on fruit surfaces may help suppress disease development, though specific commercial agents are not widely reported.

Integrated Disease Management (IDM) Strategies

- Integrated management combines cultural and preventive strategies such as minimizing fruit injuries, protecting fruits from frost damage, managing insect pests, harvesting at proper maturity, and maintaining strict hygiene during harvesting, storage, and transport.
- Early removal of cracked or damaged fruits from production and marketing channels reduces disease incidence and economic losses (Rohrbach & Johnson, 2003).

12. Stem End Rot and Internal Black Spot

Neoscytalidium dimidiatum is a fungal pathogen reported to cause several diseases in economically important crops and was identified as the causal agent of stem-end rot and internal black spot disease in MD2 pineapple (Kuruppu *et al.,* 2021; Sapak *et al.,* 2021). The pathogen is capable of infecting fruit tissues internally without causing visible external damage in early stages.

Diagnostic Symptoms

Stem-end rot is characterized by brown to dark discoloration and rotting near the stem-end region, often accompanied by blackened skin. Internal black spot disease presents as brown to black lesions in the flesh tissues, usually beneath the floral cavity and typically confined to individual fruitlets. External symptoms may be absent, making early diagnosis difficult (Kuruppu *et al.,* 2021).

Disease Cycle

The pathogen enters the fruit during early developmental stages through nectary ducts. Infection progresses internally as the fruit develops, causing localized browning and tissue degradation. Symptoms become more apparent as fruit maturity advances, particularly under favorable environmental conditions (Sapak *et al.,* 2021).

Disease Management

Cultural methods

Use healthy planting material, maintain field sanitation, avoid fruit injury, and ensure proper handling during harvesting and postharvest operations to reduce infection.

Chemical methods

Limited information is available; preventive fungicide applications and postharvest sanitation treatments may help reduce pathogen load.

Biological methods

Specific biological control measures are not well documented; however, antagonistic microorganisms may offer potential disease suppression.

Integrated Disease Management (IDM) Strategies

Adopt integrated practices including monitoring fruit development stages, minimizing wounds, maintaining orchard hygiene, and proper postharvest handling to limit disease incidence and spread (Kuruppu *et al.,* 2021; Sapak *et al.,* 2021).

13. Pineapple Anthracnose

Pineapple anthracnose is caused by *Colletotrichum ananas/ C. gloeosprioides/ C. fructicola. Colletotrichum gloeosporioides* Penz., identified through morphological characterization of isolates obtained from infected leaves collected in Hainan province. The pathogen exhibits optimal mycelial growth at 25-30°C and spore germination at 28-30°C, with an optimum pH range of 6.0–8.0. Complete darkness favors mycelial growth, while alternating light and dark conditions enhance spore germination. Preferred carbon sources for growth include glucose, D-fructose, and maltose, whereas yeast extract, peptone, and beef extract support both mycelial development and spore germination.

Diagnostic Symptoms

Anthracnose symptoms typically include necrotic lesions on pineapple leaves or fruit tissues, which may enlarge under favourable environmental conditions. The pathogen produces characteristic black dot like fungal structures that aid in morphological identification.

Disease Cycle

The pathogen survives on infected plant debris, latent infections, and alternative host tissues, serving as primary sources of inoculum. Under warm and humid conditions, *Colletotrichum spp.* produces abundant conidia that are dispersed by rain splash, wind, insects, and mechanical contact. High relative humidity (>90%) and the presence of free water are critical for spore germination, appressorium formation, and host penetration. Environmental factors such as optimal temperature, nutrient availability, and light conditions influence pathogen growth, infection efficiency, and disease progression. The pathogen often establishes quiescent infections in immature tissues, which remain latent until favorable conditions or host ripening trigger symptom development and secondary spread.

Disease Management

Cultural methods

Use disease-free planting material, maintain field sanitation, remove infected plant debris, and reduce leaf wetness through proper spacing and aeration.

Chemical methods

Preventive fungicide applications may be used under favorable environmental conditions for disease development.

Biological methods

Potential biological control may involve antagonistic microorganisms that suppress pathogen growth, although specific agents require further evaluation.

Integrated Disease Management (IDM) Strategies

Combine cultural practices, environmental monitoring, and timely protective treatments to reduce disease incidence and limit spread.

II. Bacterial Diseases of Pineapple

1. Marbling

Marbling disease is caused by bacterial pathogens, mainly *Pantoea ananatis* and *Acetobacter* spp. The disease occurs sporadically and is generally considered a minor problem, although it may become serious in lowland tropical regions where fruit mature under warm and humid conditions.

Diagnostic Symptoms

Infected fruits typically show no external symptoms, making field diagnosis difficult. Internally, affected tissues exhibit red-brown discoloration with a granular appearance and woody consistency. Diseased fruits are often characterized by low acid and sugar content.

Disease Cycle

Infection occurs during flowering when bacteria enter through open flowers or natural growth cracks on the fruit surface. Warm and wet environmental conditions favor disease development and symptom expression during fruit maturation.

Disease Management

Cultural methods

- Selection of moderately resistant cultivars such as 'Smooth Cayenne' helps reduce disease incidence.
- Maintaining good field hygiene and minimizing fruit injuries can limit infection.

Chemical methods

Specific chemical control measures are not well established due to the internal nature and sporadic occurrence of the disease.

Biological methods

Biological control options are currently limited and not widely reported.

Integrated Disease Management (IDM) Strategies

Monitoring fruit quality and rejecting infected fruits during processing is the most practical management approach, along with cultivar resistance and proper field management practices.

2. Pink Disease

Pink disease is caused by bacteria including *Pantoea citrea*, *Gluconobacter oxydans*, and *Acetobacter aceti*. The disease occurs sporadically, mainly under cool and wet environmental conditions.

Diagnostic Symptoms

External symptoms are usually absent, even in fully ripe fruits. Internally, infected tissues may appear water-soaked or light pink with an aromatic odour. During heat sterilization (canning), infected tissues darken from pink to dark brown. Infection may be limited to individual fruitlets or, in severe cases, affect the entire fruit cylinder.

Disease Cycle

Infection occurs through open flowers, particularly under cool weather conditions. Disease incidence increases following dry periods before flowering combined with rainfall during flowering. Bacteria are likely spread by nectar-feeding insects and mites from infected or decaying fruits.

Disease Management

Cultural methods

Use relatively resistant cultivars such as 'Smooth Cayenne' and maintain orchard sanitation by removing infected or decaying fruits.

Chemical methods

Chemical control is generally not required due to the sporadic nature of the disease.

Biological methods

❖ Specific biological control measures are not widely reported.

Integrated Disease Management (IDM) Strategies

Monitoring and good field hygiene are usually sufficient, as disease incidence remains low and high temperatures naturally suppress the pathogen.

3. Bacterial Heart Rot and Fruit Collapse

Bacterial heart rot (BHR) and fruit collapse (ghost disease) are primarily caused by *Dickeya zeae* (syn. *Erwinia chrysanthemi*), a soft-rot bacterium with a broad host range and strong tissue-macerating ability (Rohrbach & Johnson, 2003; Sapak *et al.,* 2021). The pathogen produces enzymes that degrade plant tissues, leading to soft rot symptoms in vegetative parts (BHR) and fruit tissues (fruit collapse). Similar heart rot symptoms may also be caused by *Phytophthora* spp., particularly *P. nicotianae* and *P. cinnamomi.*

Diagnostic Symptoms

BHR symptoms begin as water-soaked lesions at the white basal tissues of young leaves in the central whorl, progressing to olive-green or brown discoloration. Infected leaves become soft, foul-smelling, and easily detached. Fruit collapse symptoms appear on mature fruits 2–3 weeks before ripening and include exudation of juice and release of rotten-smelling gas bubbles, sometimes producing an audible hissing sound. The fruit shell turns olive green, and internal examination reveals rotted cavities within skeletal fibres (Kaneshiro *et al.,* 2008; Young *et al.,* 2022).

Disease Cycle

The pathogen enters through natural openings, wounds, or open flowers and multiplies rapidly within host tissues. Spread occurs via contaminated tools, infected plant debris, wind-driven rain, and insect vectors such as ants, beetles, mites, and flies. Warm and humid conditions favor infection and disease progression. Fruit collapse develops when bacteria invade developing fruits, often originating from nearby infected plants or collapsed fruits (Rohrbach & Johnson, 2003).

Disease Management

Cultural methods

- Use disease-free planting material, maintain field sanitation, promptly remove and destroy infected plants and fruits, and disinfect tools.
- Ensure proper irrigation, balanced nutrition, and minimize plant stress to reduce disease susceptibility.

Chemical methods

Chemical control is limited for bacterial infections; regulated pesticide use may help manage associated pathogens, but reliance on chemicals alone is ineffective.

Biological methods

- Potential biological agents such as *Bacillus* spp., *Pseudomonas fluorescens*, and *Trichoderma* spp. may help suppress pathogen development.
- These biological agents are most effective when used as part of integrated management strategies.

Integrated Disease Management (IDM) Strategies

- Combine sanitation, use of resistant cultivars, crop rotation, vector management, and monitoring of environmental conditions.
- Integrated approaches focusing on prevention and early removal of infected material are essential to reduce disease spread and economic losses.

4. Soft Rot

Soft rot of pineapple fruit is caused by the bacterium *Enterobacter cloacae*, identified through morphological, biochemical, cultural characteristics, and PCR assays. The disease has been reported to occur sporadically, particularly following heavy rainfall and flooding events, causing significant economic losses in pineapple-growing regions such as Kerala.

Diagnostic Symptoms

Symptoms include fruit deformation, water blister formation during immature stages, internal tissue decay, and soft rot in mature fruits. Severely infected fruits exhibit extensive tissue maceration and deterioration.

Disease Cycle

Disease outbreaks are associated with excessive moisture conditions such as heavy rainfall and flooding, which favor bacterial proliferation and spread. Infection likely occurs through wounds or natural openings, with rapid progression under humid conditions.

Disease Management

Cultural methods

- Avoid waterlogging through proper drainage.
- Maintain field sanitation.
- Remove infected fruits promptly to prevent disease spread.

Chemical methods

Antibiotic formulations containing 90% streptomycin sulphate and 10% tetracycline hydrochloride at 100 ppm have been reported to effectively inhibit the growth of *E. cloacae*.

Biological methods

Specific biological control measures are not well documented.

Integrated Disease Management (IDM) Strategies

Adopt integrated strategies including improved drainage, monitoring during heavy rainfall, sanitation practices, and targeted chemical treatments where necessary to minimize disease incidence.

III. Viral Diseases of Pineapple

1. Mealybug Wilt Disease

Pineapple mealybug wilt disease (PMW) is caused by ampeloviruses collectively known as pineapple mealybug wilt-associated viruses (PMWaVs), including PMWaV-1, PMWaV-2, PMWaV-3, and related strains (Sether & Hu, 2001; Dey *et al.,* 2018). The viruses are transmitted by mealybugs, mainly *Dysmicoccus brevipes* and *D. neobrevipes*, with ants such as *Pheidole megacephala* facilitating vector movement and protection. The disease occurs worldwide and significantly affects pineapple productivity.

Diagnostic Symptoms

Early symptoms include reddening of leaves midway along the plant, followed by pink discoloration, loss of leaf rigidity, downward rolling of leaf margins, and tip dieback. Root collapse and plant wilting may occur. Two symptom types are recognized: slow wilt (developing after prolonged feeding) and quick wilt (appearing rapidly after heavy infestation). Affected plants may produce smaller or malformed fruits, and symptoms are often more evident during cooler seasons when plant vigour is reduced.

Disease Cycle

The disease is introduced through infected planting material and spread by mealybugs during feeding. Mealybugs are dispersed by ants, wind, and farm activities. Ant–mealybug mutualism enhances disease spread, as ants protect mealybugs in exchange for honeydew. Disease incidence is closely associated with vector population density, plant age, and duration of feeding. Young plants develop symptoms within 2–3 months, whereas older plants may take up to 12 months.

Disease Management

Cultural methods

- Use wilt-free planting material and remove and destroy infected plants.
- Maintain weed-free field boundaries and avoid using heavily infected fields (>10% incidence) for propagation.
- Implement crop sanitation and fallow periods to reduce disease reservoirs.

Chemical methods

- Insecticides such as malathion, diazinon, or other recommended products can be used to manage mealybug and ant populations.
- Efficacy may be limited due to insect hiding sites.

Biological methods

- Natural enemies of mealybugs, including predators and parasitoids (e.g., *Lobodiplosis pseudococci*, *Nephus bilucernarius*, *Anagyrus ananatis*), can help control populations.
- Their effectiveness is reduced when ant populations are high.

Integrated Disease Management (IDM) Strategies

Effective management relies on integrated approaches combining vector control (mealybugs and ants), use of clean planting material, field sanitation, biological control, and regular monitoring to prevent severe outbreaks.

2. Yellow Spot

The disease is caused by *Capsicum chlorosis virus* (CaCV), belonging to the genus *Orthotospovirus* (Tospoviruses). These viruses infect a wide range of host plants including weeds and cultivated crops, which serve as reservoirs for infection. The virus primarily infects young pineapple crowns during early development stages.

Diagnostic Symptoms

Initial symptoms appear as small (2-5 mm), round, yellow chlorotic spots on the upper surface of young leaves. These spots gradually coalesce to form elongated yellow streaks along the leaf tissue, which later turn brown and necrotic. Infection of the central leaves causes distortion and bending of the plant. In severe cases, infection is lethal, leading to plant death. Fruit infections may occur through open blossoms, resulting in large blackened cavities on the fruit surface.

Disease Cycle

The virus is transmitted by thrips, which act as biological vectors. Infection occurs mainly during early plant growth or while crowns remain attached to developing fruit. Thrips acquire the virus from infected host plants, including weeds, and transmit it during feeding. Because infected plants usually die before propagation, vegetative transmission through planting material is minimal. The presence of alternative hosts in surrounding vegetation increases disease incidence.

Disease Management

Cultural methods

- Maintain strict weed control to eliminate alternate hosts.
- Avoid disturbing heavily infested weedy areas near young plantings or developing fruit to prevent thrips movement into pineapple fields.
- Use healthy planting material and maintain proper field sanitation.

Chemical methods

Apply recommended insecticides to control thrips populations, when necessary, especially before disturbing infected vegetation or adjacent fields.

Biological methods

Encourage natural enemies of thrips, such as predatory mites and beneficial insects, to reduce vector populations as part of ecological management.

Integrated Disease Management (IDM) Strategies

Adopt an integrated approach combining weed management, vector monitoring and control, use of clean planting material, and field sanitation to reduce virus spread and minimize disease incidence.

IV. Post Harvest Disease of Pineapple

Postharvest losses in pineapple are primarily caused by phytopathogenic fungi and bacteria, with infections typically occurring through wounds, insect damage, and injuries incurred during harvesting, transportation, handling, and packaging. Major postharvest diseases include black rot caused by *Thielaviopsis paradoxa*, fruitlet core rot (a disease complex with multifactorial etiology), yeasty fermentation associated with *Saccharomyces* spp. and *Candida* spp., and pink disease caused by *Tatumella citrea*. In addition to pathogenic infections, several physiological disorders also contribute significantly to fruit deterioration and economic losses. Among these, fruitlet core rot remains poorly understood due to its complex etiology, necessitating further investigation. Moreover, the presence of mycotoxigenic species such as *Fusarium proliferatum*, *F. ananatum*, and *F. oxysporum* poses serious food safety concerns, as mycotoxin-contaminated fruits may be harmful to human health. Effective management of postharvest diseases relies on minimizing fruit injuries during harvesting and postharvest handling, harvesting at optimal maturity, application of permitted fungicides, use of biological control agents, proper sanitation practices, wax coating, and maintenance of appropriate storage temperatures. Recent studies also highlight the potential of biotechnological approaches aimed at suppressing pathogen growth or reducing expression of susceptibility-related genes, particularly for managing pink disease. Although biological control strategies are environmentally friendly, large-scale production and application remain challenging (Baiswar *et al.,* 2021).

V. Pineapple Disorders

Pineapple is prone to several physiological disorders that can affect fruit quality and marketability. Among the most common are multiple crown formation, fruit and crown fasciation, collar of slips, dry and bottle neck, and sun-scald. These disorders are typically influenced by environmental conditions, cultural practices, and plant physiology rather than pathogens.

1. Multiple Crowns

Diagnostic Symptoms: Fruit typically develops more than one crown instead of the usual single crown. This results in a flat and broad fruit top, rendering the fruit unsuitable for canning. Affected fruits are corky in texture and have a bland flavor. The condition is considered heritable and is primarily observed in the Cayenne group, such as the Kew variety.

Management Strategies

- Avoid ratooning of the crop.

2. Fruit and Crown Fasciation

Diagnostic Symptoms: Fascinated fruits are severely deformed and often completely unusable. Proliferation may be so extreme that the fruit becomes flattened, twisted, and develops multiple

crowns. This disorder is associated with high plant vigor, which can delay flowering. Environmental and nutritional factors such as high soil fertility, warm temperatures, and calcium or zinc deficiencies may favor the development of fasciation.

Management Strategies

- Avoid excessive nitrogen fertilization to prevent overly vigorous growth.
- Maintain balanced soil fertility, ensuring adequate calcium and zinc levels.
- Monitor environmental conditions and avoid planting in areas prone to excessive heat stress.
- Balanced application of calcium and zinc can help in management of fasciation.

3. Collar of Slips

Diagnostic Symptoms: This disorder is marked by numerous slips growing from the stem around the base of the fruit or directly from the fruit itself. Excessive slip growth results in small, tapering fruits with knobs at the base. The condition is favored by high nitrogen fertilization, high rainfall, and relatively low temperatures.

Management Strategies

Apply a balanced dose of nitrogen as per recommended guidelines to avoid excessive vegetative growth.

Dry Fruit and Bottle Neck

Diagnostic Symptoms: Dry and bottle neck fruit types are closely related and may originate from the same parent. In the dry fruit type, the fruit is small, flowers are absent, and fruitlets fail to develop. In the bottle neck type, the lower fruitlets develop normally while the upper fruitlets fail to develop, giving the fruit a similar appearance to dry fruits. Both types produce suckers freely.

Management Strategies

- Select healthy planting material from normal, well-developed fruits.
- Avoid using plants showing these fruit types for propagation.
- Maintain balanced nutrition and proper crop management to reduce occurrence.
- Use of resistant variety is suggested.

4. Sun-Scald

Diagnostic Symptoms: Sun-scald occurs when a plant sags or topples over, exposing one side of the fruit to direct sunlight. The exposed surface cells are damaged, leading to browning or blackening of the fruit surface, and fissures may develop between fruitlets. Affected fruits decay rapidly and become prone to pest infestation.

Management Strategies

- Remove and carefully dispose of affected fruits immediately to prevent contamination of healthy crops.
- Plant at higher density to reduce sun exposure and the intensity of sun-scald.
- Bind leaves around fruits in areas with lush growth to provide natural shade.

- Cover sun-exposed fruit surfaces with dry straw, grass, or other locally available materials.
- Use banana leaves to cover fruits during April and May to protect them from excessive sunlight.

5. Internal Browning (Black heart)

Diagnostic Symptoms: Internal browning is a common physiological disorder, particularly in Smooth Cayenne types with low ascorbic acid content. It is exacerbated by exposure to cool nights followed by hot days before harvest, exogenous gibberellic acid (GA) application, and storage below 7°C. Initial symptoms include small, translucent, greyish spots at the fruit base near the centre. In severe cases, these areas gradually darken, and the interior flesh turns firm brown to black.

Management Strategies

- Avoid excessive GA application and ensure careful regulation of preharvest treatments.
- Minimize temperature fluctuations before harvest and avoid storing fruits below 7°C.
- Harvest fruits at appropriate maturity stages and handle gently to prevent stress-induced browning.

V. Diseases Associated with Parasitic Nematodes

Several plant-parasitic nematodes are associated with pineapple cultivation and contribute significantly to yield reduction and decline in plant vigor. The most important species include root-knot nematodes (*Meloidogyne javanica*, *Meloidogyne incognita*), root lesion nematode (*Pratylenchus brachyurus*), and reniform nematode (*Rotylenchulus reniformis*) (Guerout, 1975; Rabie, 2017). These nematodes have been reported from pineapple-growing regions worldwide including Costa Rica (Araya, 2019), Peru (Vera *et al.,* 2017), France (Soler *et al.,* 2021), Africa (Coyne *et al.,* 2018), Nigeria (Daramola *et al.,* 2013), India and Malaysia (Masdek *et al.,* 2007).

1. Root-knot Nematodes (*Meloidogyne spp.*)

Root-knot nematodes invade roots near the tips as second-stage juveniles. Feeding induces enlargement of plant cells resulting in gall formation. Mature females lay up to 2000 eggs on the root surface, and new generations develop rapidly under favorable conditions, completing cycles within approximately 25-30 days.

Diagnostic Features

- Distinct terminal swellings or galls on roots.
- Excessive root branching.
- Stunted root systems.
- Secondary invasion of galls by fungi leading to blackening or rot (Back *et al.,* 2002).

Plant Symptoms

- Stunting, yellowing, and dieback of plants.
- Reduced nutrient and water uptake.
- Increased susceptibility to stress.

Root-knot nematodes are considered the most damaging nematodes affecting pineapple and significantly reduce yields, particularly in ratoon crops.

2. Root Lesion Nematode (*Pratylenchus brachyurus*)

Root lesion nematodes are migratory endoparasites that live primarily within root tissues. Both juveniles and adults penetrate roots, feeding on cells and disrupting physiological processes. Their life cycle includes egg, three juvenile stages, and adult, typically completed within 29–45 days under warm conditions.

Diagnostic Features

- Black or necrotic lesions on root surfaces.
- Lesions may extend around the entire root.
- Loss of secondary roots and poorly developed root systems (Sipes *et al.,* 2005; Masdek *et al.,* 2007).

Plant Symptoms

- Reduced vigor and nutrient uptake
- Above-ground symptoms resembling nutrient deficiency
- Often masked by damage caused by root-knot nematodes

3. Reniform Nematode (*Rotylenchulus reniformis*)

Reniform nematodes are well adapted to warm, dry environments and possess a wide host range including rotational crops such as cowpea and watermelon. Unlike root-knot nematodes, juveniles can survive extended periods in fallow soil without feeding.

Diagnostic Features

- Reduced number of lateral and feeder roots
- Elongation of remaining roots allowing continued anchorage

Plant Symptoms

- Gradual decline in plant vigor
- Reduced nutrient uptake and productivity

Other nematode species such as *Paratylenchus* spp. have been reported in commercial pineapple farms, particularly in peat soils where they may contribute to yield decline (Masdek *et al.,* 2007). Low populations of *Aphelenchoides* spp. have also been observed.

Management Strategies

Cultural methods

- Maintain weed-free or host-free fallow periods (minimum six months recommended).
- Use non-host crops during long fallows.
- Remove infected plant residues and severely affected plants.
- Proper land preparation to expose soil to drying conditions and reduce nematode populations.
- Conduct pre-plant soil sampling to assess nematode levels.

Chemical methods

- Application of registered nematicides before planting when high populations are detected.
- Soil application of Carbosulfan 6G at 17 kg/ha has shown effectiveness.
- Some traditional chemicals such as methyl bromide and aldicarb have been withdrawn due to environmental concerns (Kim *et al.,* 2018; Xiang *et al.,* 2018).

Biological methods

- Use of biological control agents such as *Trichoderma* spp. and *Purpureocillium lilacinum*.
- Application of plant extracts, essential oils, organic acids, and bioactive natural products (Kiriga *et al.,* 2018; Forghani and Hajihassani, 2020; Soler *et al.,* 2021).

Integrated Disease Management (IDM) Strategies

- Combine cultural practices, biological agents, and selective chemical applications.
- Employ soil solarization, steaming, ozonated water, and silicon-based amendments as emerging strategies (Kokalis-Burelle *et al.,* 2016; Veronico *et al.,* 2017; Roldi *et al.,* 2017).

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SUSTAINABLE HORTICULTURAL NURSERY PRACTICES: PRODUCTION OF QUALITY PLANTING MATERIAL UNDER PROTECTED CONDITIONS

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1. Foundations of Sustainable Nursery Systems under Protected Conditions

Sustainable horticultural nursery management is the scientific and systematic production of genetically true-to-type, healthy, and vigorous planting material while minimizing environmental impact and optimizing resource use. For perennial horticultural crops in India, the long-term productivity of orchards is directly influenced by the quality of nursery stock. Poor-quality seedlings or grafts often result in uneven growth, delayed bearing, increased pest susceptibility, and reduced orchard lifespan. As Hartmann *et al.* (2018) emphasized, the physiological status and genetic integrity of propagules at planting determine subsequent crop performance more profoundly than many later agronomic interventions.

Protected nursery production refers to propagation and raising of plants within controlled or semi-controlled environments such as shade houses, insect-proof net houses, polyhouses, mist chambers, and climate-regulated greenhouses. These systems enable manipulation of temperature, humidity, light, and irrigation, thereby improving propagation success and ensuring uniformity. In Indian agro-climatic conditions characterized by temperature extremes, erratic rainfall, and increasing pest pressures, protected nurseries provide resilience and year-round production capability.

Sustainability in nursery systems integrates ecological, economic, and social dimensions. Ecologically, it involves efficient water and nutrient use, reduction of chemical pesticides, recycling of organic waste, and prevention of pathogen spread. Economically, it ensures profitability through high survival rates, premium-quality planting material, and reduced losses. Socially, it supports rural livelihoods, skill development, and availability of certified planting material to small and marginal farmers.

One of the most critical components of sustainable nursery systems is the establishment of authenticated mother blocks. FAO (2010) highlighted that nursery sustainability begins with selection and maintenance of elite, disease-free mother plants that serve as scion or seed sources. Regular indexing, sanitation, and monitoring of mother stock reduce systemic disease transmission, particularly viral infections in fruit crops.

Protected nursery systems also contribute to phytosanitary security. Soil-borne pathogens such as Pythium, Phytophthora, and Rhizoctonia are major constraints in open-field nurseries. By using sterilized growing media and raised platforms within protected structures, pathogen incidence is drastically reduced. According to FAO (2014), adoption of hygienic propagation systems significantly lowers the need for chemical control measures during early plant growth stages.

Another important principle is traceability. Each batch of planting material must be linked to a documented source, propagation date, and treatment record. Documentation not only ensures quality assurance but also supports certification processes. Modern nursery enterprises increasingly integrate digital record systems for monitoring plant batches, mother plant history, and phytosanitary treatments.

Resource-use efficiency is central to sustainability. Drip irrigation and micro-sprinkler systems reduce water consumption compared with conventional flooding. Nutrient application through fertigation ensures precise delivery and minimizes leaching losses. FAO (2017) reported that efficient irrigation scheduling in protected systems can reduce water use by 40–60% without compromising plant growth.

Energy-efficient design further enhances sustainability. Naturally ventilated polyhouses reduce energy dependence compared to fully climate-controlled structures. Solar-powered pumps and rainwater harvesting systems reduce operational costs and carbon footprint.

In the Indian context, sustainable nursery systems are increasingly aligned with national horticulture development programs promoting certified planting material. High-density orcharding in mango, guava, citrus, and pomegranate requires uniform grafts with well-developed root systems. Protected nurseries provide the structural and environmental stability necessary for such precision propagation.

Therefore, sustainable nursery foundations depend upon authenticated mother stock, hygienic infrastructure, controlled environments, efficient resource management, and systematic documentation. These elements collectively ensure that planting material supplied to farmers is genetically pure, physiologically robust, and environmentally safe.

2. Infrastructure, Growing Media, and Environmental Regulation

The infrastructure of a sustainable protected nursery determines its operational efficiency, plant health status, and economic viability. In India's diverse climatic zones, nursery structures must be adapted to local temperature regimes, humidity patterns, and rainfall distribution. The design and material selection of protected structures directly influence internal microclimate and plant growth.

Shade houses constructed with ultraviolet-stabilized shade nets regulate light intensity and reduce heat stress. Insect-proof net houses prevent entry of aphids, whiteflies, and thrips, thereby limiting viral transmission. Naturally ventilated polyhouses made of polyethylene film enable temperature moderation while allowing passive airflow. According to FAO (2013), simple low-cost protected structures are particularly suitable for small-scale nurseries in tropical regions.

Environmental regulation within protected nurseries revolves around temperature, humidity, light, and air circulation. Optimal temperature for most tropical fruit nursery plants ranges between 20°C and 30°C. Excessive temperatures cause desiccation and graft failure, while low temperatures delay root development. Mist chambers are widely used for vegetative propagation because they maintain relative humidity above 80%, reducing transpiration stress during root

initiation. Hartmann *et al.* (2018) described mist propagation as a reliable technique for achieving high rooting percentages in softwood and semi-hardwood cuttings.

Light management is equally critical. Shade nets with 35–50% shading are typically used for hardening young plants, whereas higher shading levels may be required for delicate tissue-cultured plantlets. Uniform light distribution ensures balanced photosynthesis and sturdy seedling growth. Poor light management often leads to etiolation and weak stems.

Growing media selection is fundamental for sustainable nursery production. Traditional soil-based media pose risks of pathogen contamination and variability in texture and fertility. Therefore, soilless substrates such as cocopeat, perlite, vermiculite, composted bark, and sand mixtures are widely adopted. These substrates provide adequate aeration, drainage, and root penetration. FAO (2014) emphasized that soilless media reduce soil-borne disease incidence and improve uniformity of growth.

Media sterilization is essential to eliminate pathogens and weed seeds. Steam sterilization and solarization are environmentally safe techniques compared to chemical fumigation. Solarization, involving covering moist media with transparent polyethylene under sunlight, effectively reduces pathogen load in tropical climates.

Water quality management is another determinant of sustainability. Irrigation water should be tested for salinity, pH, and presence of contaminants. High salinity adversely affects seedling vigor and root growth. Drip irrigation and micro-sprinkler systems ensure uniform water distribution and prevent waterlogging. Over-irrigation not only wastes water but also predisposes seedlings to root rot diseases.

Nutrient management under protected conditions relies on balanced fertilization. Controlled-release fertilizers and water-soluble nutrient formulations are commonly used. Excess nitrogen promotes succulent growth that is susceptible to pests and diseases. Integrated use of organic amendments such as vermicompost extracts and biofertilizers enhances microbial activity and nutrient availability. FAO (2017) reported improved root development in seedlings treated with beneficial microbial inoculants.

Hardening yards constitute an essential component of nursery infrastructure. After propagation or tissue culture acclimatization, plants must gradually adapt to external conditions. Controlled reduction in humidity and increased light exposure strengthens plant tissues and improve field survival.

Waste management practices contribute significantly to sustainability. Reuse of plastic trays after proper disinfection, recycling of organic residues through composting, and rainwater harvesting reduce environmental impact. Efficient layout planning with designated propagation zones, storage areas, and sanitation stations further enhances biosecurity.

Thus, infrastructure planning and environmental regulation in protected nurseries must integrate climatic adaptation, resource efficiency, hygiene, and waste minimization. A scientifically designed nursery environment ensures uniform growth, high survival rates, and environmentally responsible production of planting material.

3. Propagation Methods and Genetic Integrity

Propagation is the core function of horticultural nurseries, and sustainability depends upon both technical precision and genetic fidelity. In India, propagation systems must accommodate diverse fruit crops, ornamental plants, and vegetable seedlings while ensuring uniformity and disease-free status.

Seed propagation is primarily used for rootstock production and hybrid vegetable seedlings. Seeds must originate from certified sources to maintain varietal purity. Pre-sowing treatments such as priming and bio-inoculation enhance germination and early vigor. Plug tray systems filled with sterilized media provide uniform spacing and minimize transplant shock. According to Hartmann *et al.* (2018), containerized seedlings exhibit superior root architecture compared with bare-root seedlings.

Vegetative propagation ensures clonal uniformity and true-to-type characteristics. Grafting and budding are widely practiced in mango, citrus, guava, and sapota. Success depends upon compatibility between rootstock and scion, precise cambial alignment, and maintenance of adequate humidity. Protected structures prevent desiccation and contamination during graft union formation.

Cutting propagation under mist chambers is common for many ornamental and fruit species. Application of auxins such as indole-3-butyric acid enhances adventitious root formation. Controlled humidity and temperature significantly improve rooting percentages. Hartmann *et al.* (2018) documented that mist-regulated environments reduce transpiration stress, thereby increasing propagation efficiency.

Layering techniques, including air layering, are used in crops like litchi and guava. In protected nurseries, wrapping materials and rooting media remain moist and uncontaminated, improving root initiation and survival.

Micropropagation has emerged as a powerful tool for mass multiplication of elite genotypes and disease-free plants. Tissue culture laboratories produce large numbers of plantlets within limited space and time. FAO (2010) recognized micropropagation as a strategic technology for rapid dissemination of improved cultivars. However, acclimatization is critical. Tissue-cultured plantlets must be gradually hardened under shade-net conditions before field transfer.

Genetic integrity requires maintenance of registered mother blocks. Mother plants must be inspected regularly for off-types and disease symptoms. Roguing of infected plants prevents spread of systemic pathogens. Documentation of scion collection dates, propagation batches, and treatment records ensures traceability.

Certification systems often mandate periodic testing for viruses and bacterial pathogens. In citrus and other vegetatively propagated crops, pathogen indexing ensures long-term orchard health. FAO (2014) stressed that certified propagation material significantly reduces disease spread across regions.

Hardening and grading represent the final steps before marketing. Uniform height, stem diameter, root development, and leaf health are indicators of quality. Grading ensures that only

vigorous plants reach farmers, thereby protecting nursery credibility and enhancing field establishment success. Sustainable propagation thus integrates scientific techniques, hygienic handling, certified mother stock, and systematic documentation. Genetic fidelity and plant health are inseparable from the long-term sustainability of horticultural production systems.

4. Integrated Plant Health and Nutrient Management

Plant health management in protected nurseries must emphasize prevention rather than curative chemical control. Young seedlings and grafts are highly vulnerable to pathogens, insects, and nutrient disorders. Sustainable systems rely on integrated approaches combining hygiene, biological control, and balanced nutrition.

Damping-off caused by Pythium and Rhizoctonia species is a common nursery disease. Sterilized media, raised benches, and proper drainage reduce infection. Application of biological control agents such as Trichoderma species suppresses pathogenic fungi. FAO (2013) advocated integrated disease management strategies emphasizing sanitation and biological control.

Insect pests including aphids, whiteflies, thrips, and mites cause direct feeding damage and transmit viruses. Insect-proof net houses act as physical barriers, minimizing entry. Sticky traps assist in monitoring pest populations. Biological control agents and neem-based botanical pesticides are preferred in sustainable systems to reduce chemical residues.

Nutrient management is closely linked with plant health. Deficiencies of nitrogen, phosphorus, potassium, calcium, and micronutrients impair growth and increase susceptibility to stress. Controlled fertigation provides precise nutrient delivery. FAO (2017) highlighted that balanced fertilization improves root vigor and stress tolerance.

Over-fertilization, especially nitrogen excess, results in succulent growth attractive to pests. Therefore, nutrient solutions must be carefully calibrated according to crop stage. Periodic leaf and media testing guide nutrient adjustments.

Water management also influences plant health. Over-irrigation creates anaerobic conditions favoring root pathogens. Scheduling irrigation based on evapotranspiration and substrate moisture monitoring enhances efficiency and disease prevention.

Sanitation protocols are fundamental. Tools must be disinfected regularly. Workers should follow hygiene practices to avoid cross-contamination. Diseased plants must be removed promptly to prevent spread.

Certification standards often require compliance with phytosanitary regulations. FAO (2014) noted that adherence to quarantine and inspection protocols reduces transboundary pest movement.

An integrated plant health system reduces chemical dependency, preserves beneficial organisms, and enhances environmental sustainability. For Indian nurseries serving expanding horticultural sectors, integrated management safeguards productivity and farmer confidence.

5. Quality Assurance, Certification, and Future Perspectives in India

Quality assurance underpins sustainable nursery enterprises. Planting material must be genetically authentic, physiologically robust, and free from pests and diseases. In India's

expanding horticulture sector, certified planting material is essential for high-density orchards and export-oriented production.

Quality parameters include true-to-type characteristics, well-developed root systems, appropriate stem girth, uniform growth, and absence of visible defects. Hartmann *et al.* (2018) emphasized that vigorous root systems ensure rapid field establishment and improved nutrient uptake.

Certification systems involve registration of mother blocks, regular inspection, and documentation. FAO (2010) stressed the importance of formal seed and planting material certification frameworks to maintain quality standards. Documentation of propagation batches, treatments, and sales ensures traceability.

Economic sustainability requires cost-effective production and market access. Protected nurseries achieve higher survival rates and premium pricing. Diversification into ornamental plants and vegetable seedlings broadens income streams.

Climate change poses new challenges including temperature extremes and emerging pests. Protected nurseries provide adaptive capacity through environmental control and rapid multiplication of resilient cultivars. FAO (2017) recognized protected cultivation as a climate-smart strategy for horticulture.

Technological innovations such as sensor-based irrigation, automation, and digital inventory management enhance efficiency. Renewable energy integration reduces operational costs and environmental impact.

Capacity building and skill development among nursery workers are equally important. Training in grafting techniques, sanitation, and record-keeping improves quality consistency.

In the Indian context, alignment with national horticulture missions and export standards strengthens nursery enterprises. Adoption of globally recognized best practices ensures competitiveness and sustainability.

Sustainable horticultural nursery practices under protected conditions therefore represent a strategic pathway for enhancing productivity, ensuring plant health, and supporting climate-resilient horticulture in India.

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REVIEWING THE ROLE OF LIGHT SPECTRUM IN GROWTH AND REGULATION OF *AZOLLA*: IMPLICATIONS FOR SUSTAINABLE AGRICULTURE

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Abstract

Azolla, an aquatic fern and possess symbiotic relation with *Anabaena azollae*, in leaf pore cavity, which fixes the atmospheric nitrogen for fern and therefore has gained worldwide attention as a sustainable bioresource for agriculture. Apart its well-known function in biological nitrogen fixation, current studies highlights the significant influence of light quality on *Azolla's* growth, metabolism, secondary metabolite production and physiological regulation. Light spectrum is not only served as source of photon for photosynthesis but also regulate the plant morphology, pigment composition, and symbiotic efficiency. Expose of different wavelength of light like red, blue, and green have been shown to differentially affect frond proliferation, chlorophyll synthesis, protein accumulation, metabolite production, symbiotic association and antioxidant activity of plant. According to most of the studies reported on photobiology, concluded that plants grown under blue light result in increase in metabolite production with often show compact morphology. However, the red light stimulates faster biomass production compared to other light due to increase in efficient photosynthesis. Light can also affect on symbiotic association, balanced spectra can optimize both growth rate and nitrogen fixation capacity, making spectral management a promising strategy for controlled *Azolla* cultivation. Comprehending how the spectral composition shows the regulatory role in climate-resilient and resource-efficient agricultural systems, where indoor farming, vertical systems, and low-input technologies are expanding. Manipulating light environments using energy-efficient LEDs offers opportunities to enhance *Azolla* biomass yield, nutrient content, and biofertilizer potential without increasing chemical inputs. Linked with photobiology this chapter includes the physiological, biochemical, and molecular responses of *Azolla*, along with their implications for sustainable rice cultivation, organic farming, and integrated nutrient management. The chapter highlights how spectral optimization can enhance *Azolla*-based systems as environmentally friendly instruments for enhancing soil fertility, decreasing reliance on synthetic fertilizers, and promoting resilient agricultural practices in the face of climate change to agro ecological applications.

Introduction

Azolla is a small free- floating aquatic plant also known as mosquito fern, fairy moss, and magic fern widely distributed in a tropical, subtropical, and temperate ecosystems. It naturally occurs

between temperature range 15 and 35 °C in stagnant water bodies like drains, canals, ponds particularly in marshy terrain (Lumpkin & Plucknett, 1980). *Azolla genus* is free- floating fern and its name is obtained from Greek word, azo (to dry) and oolla (to kill) which signify that they cannot survive in the barren condition. The genus is a free floating saprophyte with imbricate leaves alternately placed on a stem with several branches and pendulous roots, leaves have two lobes submerged dorsal lobe and a floating (Pereira *et al.,* 2011). *Azolla* typically grows to a maximum size of 1.5 cm, but some species can grow to a height of 15 cm and have an array of shades, notably green to dark red, and enveloped with minute hairs. The plant's microscopic hairs give the leaf's top surface its velvety look and prevent water from adhering it, however water is essential component for growth and reproduction, they cannot survive without water (Carrapiço, 2010) The genus *Azolla* was established under the family *salvinales* by Lamarck in 1783 Earlier, it was widely assumed that plant belonged to the *salviniaceae* family, (Lumpkin & Plucknett, 1980). According to (Zimmerman *et al.,* 1989) *azolla* should not be placed in the same family as the genus *salvania*, and there are majorly five species reported namely *azolla filiculoides*, *azolla rubra, azolla mexicana, azolla caroliniana* and *azolla microphylla.*

Several environmental factors that affect the growth is aminlt the temperature influencing the growth rates of free-floating macrophytes (Sabetraftar & Damme, 2013) the ideal temperature for growth is typically between 18 and 28 °C, albeit this depends on specific species that are involved in growth and nitrogen fixation. The ideal relative humidity for plant growth is between 85 and 90%. A relative humidity of less than 60% causes *azolla* to dry out and delicate (Chakrabarti, 2009). *Azolla* is heterosporous in nature and consist of female and male spores in different sizes and carries sporangia on the lower surface of leaves and carries parenchymatous covering that surrounds sporangia on the lower surface of leaves (Nagalingum *et al.,* 2006). The *Azolla* sporophyte is made up of a multibranched rhizome that produces adventitious roots that hang down to absorb nutrients from water source (Chandra Roy, et al 2016). The rhizome produces tiny leaves, about 1 mm long, with a cup-shaped dorsal lobe that is aerial and contains chlorophyll, and a ventral lobe that is colorless and partially buried to provide the buoyancy (Lumpkin & Plucknett, 1980). Fern exhibits symbiotic relationships with endophytic blue-green algae named *Azolla-anabaena* in the plant's leaf cavities, facilitating a positive environment for the cyanobacteria as well as supplying the plant with nitrogen and source of energy in furthermore, these algae are crucial for the plant's nitrogen fixation and serve as commercial biofertilizer all across world. *Azolla* has diverse roles in biofuel, bioremediation, medicine, human food, agriculture, and biogas production and commonly known as "a green gold mine (Chandra Roy et al 2016).

Reproduction in *Azolla*

Fern can reproduce by both method sexual or vegetative mode of reproduction (Lumpkin & Plucknett, 1980). Asexual reproduction is more commonly observed in species while sexual reproduction occurs when environmental condition is not favorable. *Azolla* is heterosporous, with diploid sporophytes that produce two forms of spore called sporocarps, respectively

microsporocarps and mega sporocarps, which might be of the same kind or mixed at each ventral site (Nagalingum *et al.,* 2006). Small microsporocarps with a diameter of about 2 mm produce 8–130 microsporangia, each has 32–64 spores grouped into 3–10 maculae. Comparatively megasporocarps have diameter roughly 0.5 mm, produces a single megasporangium, which contains a single megaspore, which is significantly larger than a microspore, small colony of *Anabaena azollae* filaments containing akinetes is found in each megaspore. The cyanobacterium is passed down to water fern's offspring by sexual reproduction, when the female megaspore contains anabaena filaments harboring akinetes spores of cyanobacterium shown in (Fig.2). (Becking, 1987).
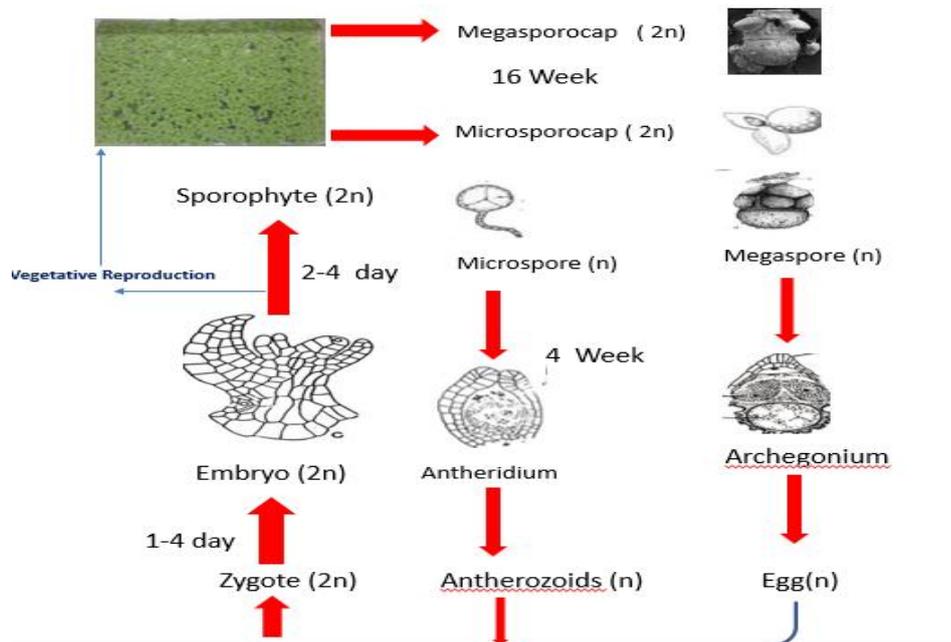
Figure 1: Spore formation stage in Azolla species

Light Emitting Diode for Plant Growth

Light is an essential element for the development and growth of plants. Plants are motile and special such that they receive signals from lighting and integrate this to promote their growth, reproduction, and function (Hogewoning *et al.,* 2010). Light spectrum like play significant impact on photomorphogenesis, photoperiodicity and phototropism. The wavelength of light ranges from 400 to 700 nm is important for mechanism of photosynthesis considered as photosynthetically active radiation. Earlier research for production of invitro plants under horticulture condition depends on use high intensity discharge and fluorescent lamps as artificial lighting but due to unstable wavelength, high heat production, high electricity consumption, and low output efficiency, nowadays the use of HID lamps is restricted, which raises the cost of production per plant (Monostori *et al.,* 2018). Therefore, LEDs used as potential alternative light source for invitro production and development of plant. Although the green technologies in crop production have been used since years ago as protected tool for increase biomass and stimulate targeted metabolites production (Bantis *et al.,* 2016). There is significant focus on using LEDs as a method toward horticultural studies (Folta & Carvalho, 2015). Manmade LEDs are employed

for improving nutrition quality and crop yield, a novel and exciting weapon for horticulture production especially in seasons with less light illumination, such winter and late autumn (Paradiso & Proietti, 2022a). The wavelength ranges of the LEDs include red (620-700 nm), blue (400-490 nm), UV (280-380 nm), (490-520 nm), green (520-570 nm), yellow (570-590 nm), orange (590-620 nm), and far-red (620-620 nm) (700–800 nm).

Light can affect growth individually or in conjunction. In contrast, the impacts of blue and red lighting on crop growth are well recognized. Blue light's mostly study on stomata opening, plant height, and chlorophyll biogenesis but red and far-red light combined can encourage flowering in long-day plants by lengthening stems and branching, increasing leaf area, and spore development (Z. Zheng *et al.,* 2019. Light, is an essential physical factor responsible for growth and developmental the plant processes in their complete life cycle and directly impacts on the developmental and biochemical and physiological processes of plants which can be expressed in the form of plant reproducibility and synthesis of antioxidant or secondary metabolites with medicinal properties (Mishra & S. Singh, 2006). The blue and red light majorly studied experimental light in combination or alone, while combining red and far-red light can promote blooming, leaf growth, spore generation, proliferation, stem and branch growth in long-day plants (Zheng *et al.,* 2019). Impact of LED on its physiological, biochemical and growth behavior and its symbiotic systems has been less studied and scarcely reported taking this in account present work was performed with the aim to study role of red and blue light on growth and assessment of important secondary metabolites primary and focusing on chlorophyll, carbohydrate and protein content of *Azolla.*

Effect of LEDs on Secondary Metabolite of *Azolla*

Plants produce a huge array of compound essential or nonessential for their growth, apart from primary metabolite essential for pant growth, secondary metabolite, are known to play a crucial role in preventing or inhibiting oxidative damage caused by free radicals (Alrifai *et al.,* 2019a). The antiradical or antioxidative properties are of these compounds are thought to have the potential to improve human health either directly by reducing oxidative stress or indirectly through controlling the activities of antioxidant enzymes (Hasan *et al.,* 2017a)**.** Flavonoids anthocyanins, carotenoids, phenol, tannin, lignin isoprenoid, and alkaloid are examples of secondary metabolite produce in very in low quantity compared with primary metabolites play important role in plant defense against several stress and help in plant survival (Thoma *et al.,* 2020). Recently lot of research are carried out on animal and human trial to find role of antioxidants for evoking immune response, anti-microbial and anti-inflammatory activity at cellular level (Rudrapal *et al.,* 2022). Plants have specialized photoreceptor activated in response with light quality and quantity defined pigment-protein complexes (Kopsell *et al.,* 2015). Unique specific gene are responsible for individual photoreceptors and often share high degree of similarity in same family (Dutta Gupta & Pradhan, 2017). The light-absorbing characteristics of important photoreceptors protein and amounts required for interaction of photoreceptor protein and chromophore are shown (Fig.4) (Folta & Carvalho, 2015) cryptochromes, phototropin,

phytochromes, and UV-B resistant are principal plant photoreceptors responsible for plant morphology and development (Alrifai *et al.,* 2019a).
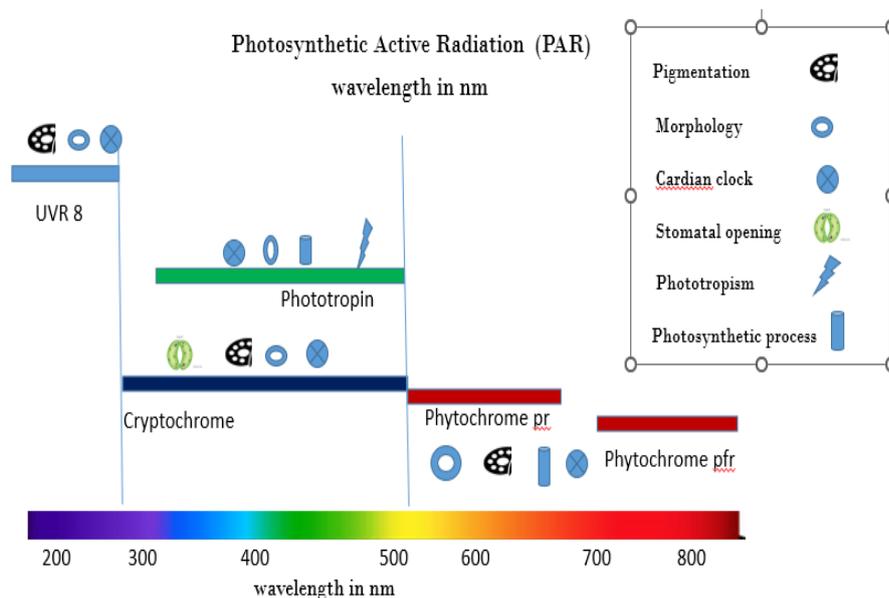
Figure 2: Absorption bands of photoreceptors in plants and their affected quantities in order to address secondary metabolites in plants slightly modified from Thoma *et al.* (2020b)

Azolla as Biofertilizer

Rice is important staple food and about half of the world's population consume rice (*Oryza sativa L.*) in their dietary meal, more than half of people eat rice (*Oryza sativa*) as a primary diet. Asia consumes 90% of the total rice production in the world (H. I. Khan, 2018), India accounts for more than 110,000 kinds of rice varieties are reported but *Oryza sativa* is the most popular. As of right now, the increased use of chemical fertilizer at a geometric rate is linked to the rising productivity of rice. Significant limiting aspect, however, is undoubtedly the widespread application of chemical fertilize therefore, it is crucial to create environment friendly alternative resources of nitrogen fertilizer (H. I. Khan, 2018). Bio-fertilizers, defined as mixtures of friendly microorganisms, help to support plant growth by providing the availability of nutrients. They are formulations that comprise active or dormant cells of effective species of microorganisms that aid agricultural plants in absorbing nutrients through interactions with the rhizosphere. In sustainable farming, bio-fertilizers are primarily used to increase the crop productivity and soil fertility (Adhikari *et al.,* 2020). The most common microorganisms used for the biofertilizer are nitrogen fixers, growth-promoting rhizobacteria (PGPRs) like *Azotobacter* and *Azospirillum,* and phosphorus solubilizing bacteria (PSB) like *Pseudomonas sp.* and *Bacillus sp.,* as well as endo and ectomycorrhizal fungi, cyanobacteria, and other useful bacteria (Yasin *et al.,* 2012). Oppositely to synthetic fertilizer, biofertilizers are more beneficial and affordable, for restoring the environment and strengthening soil structures for enhancing agriculture, therefore bio-fertilizers are viewed as an alternative to chemical fertilizer because produce capability to fix atmospheric nitrogen and reproduce very fast (Yasin *et al.,* 2012). India is a large producer of the

cereal crop rice (*Oryza sativa L.*) (Yasin *et al.,* 2012). Nitrogen is most important component for the yield of grain in rice plant in general, nitrogen (N) is regarded as a fundamental and essential plant nutrient for crop growth. nitrogen containing chemical fertilizer urea or ammonium sulphate are commonly used by farmers as nitrogen fertilizers because its effectiveness is less than 40% and also not good for human health, to overcome from such problems *azolla* could be a used as bio fertilizer which can help in fixing the atmospheric nitrogen due to symbiotic association with cyanobacteria in leaf cavity (Adhikari *et al.,* 2020).

Azolla a free-floating, widely dispersed aquatic fern has a lot of potential as a supply of nitrogen for rice farming. In North Vietnam in 1957, the value of fern as an organic manure for rice was first established in China, *Azolla* had been widely used as biofertilizer or green manure as a cheap source of N before the 1960s (Lumpkin & Plucknett, 1980). Fern has been used as green manure due to its rapid reproduction and high nitrogen content (3-6% N by dry weight). Use of pesticide and chemical fertilizer in agriculture practices are now great concern due to their adverse effect on human health and environment, countries are now focusing toward the bioorganic farming with blue green algae and *Azolla* Species for agriculture practices, *Azolla* an aquatic fern fix atmospheric nitrogen in association with cyanobacteria and fixes nitrogen as high as 3-5 Kg per day (Lumpkin & Plucknett, 1980). Rice is the best crop to use with *Azolla* as biofertilizer because they both require the same growth and environmental condition. *Azolla's* characteristic that makes it excellent source of biofertilizer in rice production because of need shallow watery habitat, rapid growth, high nitrogen capacity, speedy decomposition, and growth without completion for survival factors are among its qualities (Savaner. *et al.,* 2025). Inoculation of *Azolla* bio fertilizer in field also enhances the biological health of soil. The crop plant receives nitrogen from *Azolla,* which readily decomposes in the soil has improved the physical and chemical characteristics of the soil, especially nitrogen, organic matter, and other cations released into the soil, such as magnesium, calcium, and sodium, mineralization also raised the soil's microbiological status by enhancing the biological health of the soil and have been proven to be greatly improved by the application of fern (Bhuvaneshwari K & Ajay Kumar, 2013).

CO$_2$ Sequestration by *Azolla*

Rapid urbanization and industrial evolution are key the factors responsible for release of carbon dioxide in the atmosphere, as per the date estimated billion of tons of CO_2 are released by different human anthropogenic activities is responsible for global warming and greenhouse gas emissions (Ballantyne *et al.* 2012). The ratio of release of carbon dioxide is higher when compared to the ratio of absorption; this is mainly due to climatic changes, excessive use of fossil fuel and deforestation. The problem associated with deforestation and global warming changes has increased environmental concern all across the world. Therefore, worldwide research is focusing on the appropriate solution for lowering atmospheric carbon dioxide level. Carbon sequestration by plant through photosynthesis is economic and ecofreindy method for improving the condition of climate change. A*zolla* is an ideal fern recognize to absorb part of the

CO_2 that is released into the atmosphere annually, potentially reducing global warming and climate change. In general, moderate temperatures ($18–28^0$C), moderate to high relative humidity (55–83%), and shade (15–18 Klux) are ideal growing conditions for *azolla* (Sadeghi and Zarkami, 2013). *Azolla's* ability to effectively sequester carbon dioxide from the atmosphere has gained a lot of interest from environmental researchers. This ability is a result of the fern's high multiplication rate and nitrogen fixation capability due to symbiotic relationship with the blue-green algae *Anabaena azollae*, additionally, research have shown that *azolla's* carbon sequestration ability can be far higher than that of many land-based plant species, indicating that it plays a key role in the climate resilience. According to number of studies. This fern's long-standing function in controlling atmospheric CO_2 levels is demonstrated by historical data from the Eocene "Azolla bloom," which suggests that its widespread expansion may have contributed to global cooling (Yuan *et al.,* 2024). According to current estimations, one hectare of *Azolla* may absorb more than 21 metric tons of CO_2 annually. Large-scale *Azolla* coverage may also be able to offset a significant amount of present carbon emissions, according to modeling studies. Large-scale farming covering hundreds of thousands to more than a million square kilometers may significantly limit the increase of atmospheric CO_2, according to sensitivity analyses. *Azolla* is a promising biological tool for carbon management and climate-resilient agricultural systems, according to both historical data and current research (Hamdan and Houri, 2022).

Economic Importance of *Azolla*

Bioremediation an Important Property of *Azolla*

Heavy metals are among the most serious environmental contaminants. Exceeding metals contaminants that cannot be broken down by biological or chemical processes severely affect ecosystems (Selvi *et al.,* 2019a). Among all water pollutants, heavy metals are of most important concern because of their long lasting persistent and bio-accumulative tendency in environments (Selvi *et al.,* 2019b). Heavy metal pollution has adverse impacts on the environment, human health, and soil production. Lead, cadmium, arsenic, chromium, thallium and mercury examples of heavy metals are extremely poisonous and have adverse effects at very low amounts. Water crisis is major problem experiencing by farmers, this has led to an overuse of ground water supplies and a lowering of the ground water level (Soman *et al.,* 2018a). Therefore, conventional wastewater treatment are used to overcome this problem which includes physical chemical and biological methods but expensive. Hence, cost effective and efficient method of wastewater treatment through the use of constructed wetland has gained its importance. Bioremediation is one of the most effective methods to mitigate the pollutant of environment by using microorganism or plant and is one of the most innovative and cost-effective method used in wastewater treatment (Sood *et al.,* 2012). The process bioremediation an integrated multidisciplinary approach used heavy metal removal from contaminated soils and water, it incorporates the fields of plant physiology, chemistry, soil and water microbiology, as well as genetically altered plants that have the ability to gather, degrade, or get rid of contamination (Prasad *et al.,* 2003). Although phytoremediation is a cost-effective approach, its limitations can

be solved by using plants with large biomass, rapid development, and extensive environmental adaptability. The ability of the free-floating water fern *Azolla t*o grow quickly in N-deficient conditions, be known to endure a broad range of pollutants, and acquire various metals from polluted soil suggest that it may be a more promising tool for phytoremediation in future (Umali *et al.,* 2006) and therefore used for municipal sewage water treatment (Soman *et al.,* 2018b) . Sustainable source that can control the process include chemical and metal concentrations like alkalinity, ionic strength and salinity among various heavy metals remediation.

Azolla as Livestock Feed Supplement

India is developing country and majorly population for income depends nutritional and livelihoods, for these ruminants are a vital source of food and income security. The milk production and demand are increasing for nutrition of population in country. Farmers are depending on traditional supplement livestock feed only oilseed cake as concentrate or an unbalanced concentrate without taking into account the quality or quantity of the feed. As a result, the animals suffered from a variety of issues, including late maturity, low milk yield, a short milking period, a long dry period, milk fever, prolapsed uteruses, repeat breeding, and others.The quest for substitutes to fodder crops brought researchers to a magnificent plant that has the potential to produce sustainable livestock feed for animals with high nutritional source (el Naggar & El-Mesery, 2022). The search ends up on *Azolla* a super plant having a very high nutritive value and major source of protein, vitamins, macro and micronutrient and thus can be suggested as unconventional feed with protein source for many species including grazing animals, fish, poultry birds and pigs. *Azolla* contains high nutritional value 25 and 35 percent protein by dry weight, 10 to 15 percent minerals, and 7 to 10 percent amino acids, bioactive, and biopolymers. (Rana *et al.,* 2017). *Azolla* when fed to milch animals have increased the milk production by 20.96% in cows and 16.9% in buffalo. The increase in milk quantity and quality like content in cows and buffaloes respectively and thus increased the quality and quantity of milk along with fat content as above mentioned. *Azolla pinnata* due to its property of easy cultivation and high biomass production, can be used as feeder for broiler chicken (O.A. Alalade & E.A. Iyayi, 2006) (K Balaji *et al.,* 2009), (Dhumal *et al.,* 2009; KC *et al.,* 2016) and buffalo calves (Gowda *et al.,* 2015). *Azolla* dietary improves grill chicken weight and encourages layer egg production in poultry birds (O.A. Alalade & E.A. Iyayi, 2006). *Azolla* has been reported one of the most economic and efficient feed substitutes for livestock, particularly as can be easily digested by livestock due to its high protein and low lignin content.

Azolla and Bioenergy

High use of fossil fuel and its negative impact on environment condition have drawn significant attention toward alternative and renewable source of energy, for that biofuel is conventional way to replace the petroleum products (Huntley & Redalje, 2007). Biodiesel gaining great importance because it's similar physical and chemical properties with conventional diesel and can be directly use in engine. Currently commercial biodiesel is produced from edible oil seed crops and animal fat, waste frying oil are used as first generation biodiesel stock. An extensive investigation for

the next generations of energy crops that can grow on marginal areas has been sparked because the harmful influence of extensive use of arable lands for the production of biofuels. Consequently, the focus on microalgae that grow rapidly, high photosynthesis ability, ability to grow in the blackish water, fixes the large amount of CO_2 and lipid profile suitable for production of biodiesel (Brouwer *et al.,* 2016a). Even though, considering their fast growth rate and essential lipid profile, one of the major obstacles to exploiting microalgae for the synthesis of biofuel is the high cost of harvesting (Miranda *et al.,* 2018). Currently more focus on aquatic plants which can rapidly grow on wetland, easy maintenance, easy harvest and bioremediation property has attracted the great attention (Dixit *et al.,* 2015b). Seven species of the genus *Azolla,* is found in natural ponds, ditches, and wetlands all over the world, in both temperate and tropical climates and commonly known as the mosquito fern or water fern. This aquatic plant is one of the quickest growing plants, and it may double its biomass in just two to three days (Kollah *et al.,* 2016b). High biomass production and presences of specific lipid which is higher than any other conventional source used such as soybean, sunflower, rapeseed and oil palm, this property of fern used as best research application for biofuel production (Salehzadeh *et al.,* 2014). feed, human food, medicine, hydrogen fuel, water purification, and the creation of biogas.

Conclusion

Light plays a central role in regulating the growth and morphogenetic of plants. Interaction between light spectrum and plant growth recently gained as modern sustainable agriculture practices. The development of LED technology in advanced agriculture practices enables researchers and farmers to study control light spectrum for increasing growth performance and morphogenetic features in an energy-efficient way. *Azolla* considered as a magical fern and a particularly promising species because of significant application like fast-grower, fixes atmospheric nitrogen, carbon sequestration, animal nutrition, and sustainable biofertilizer production. *Azolla* in response to LED technology has opened new possibilities for enhancing the considerable agriculture values. Different wavelengths of light significantly affect the growth and characteristic of *azolla* in different manners as reported in studies. Previous research reported that red light significantly doubles the biomass and overall increases the yield of plants. On the other hand, blue light is commonly associated with increases in primary metabolite production, compact structure development and antioxidant capacity of plants. Red and blue wavelengths frequently work in concert to enhance both metabolic function and structural integrity.LED controlled environment condition can affect growth behavior and morphogenesis character of *azolla* and also its symbiotic association which is directly connected with its nitrogen fixing capacity.

Therefore, these light inducing properties of plants can allow the research to utilize the *azolla* in intended agricultural application, biofertilizer production, animal feed supplementation, wastewater treatment and climate resilience. In respect to sustainable development.

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SKYWARD SUSTAINABILITY THROUGH UNMANNED AERIAL SYSTEMS DRIVING PRECISION AGRICULTURE AND SMART FARM ECOSYSTEMS

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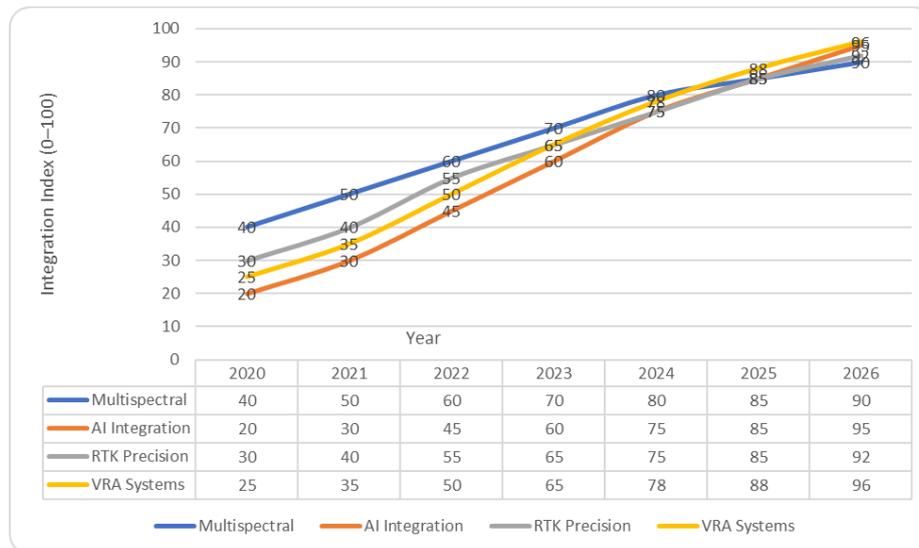
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Abstract

Sustainable agriculture demands innovative technologies capable of enhancing productivity while conserving natural resources and reducing environmental degradation. Unmanned Aerial Systems (UAS), commonly known as drones, have emerged as transformative enablers of precision agriculture by integrating aerial sensing, targeted agrochemical application, real-time crop diagnostics, and intelligent decision support systems. This chapter synthesizes recent advances (2020–2026) in UAV platforms, multispectral and thermal sensing, LiDAR mapping, artificial intelligence integration, irrigation optimization, and allied agricultural applications. A dedicated mathematical modeling section examines aerodynamic performance, payload optimization, and spray calibration dynamics. Indian state-wise case studies illustrate operational deployment in Karnataka, Punjab, Maharashtra, Tamil Nadu, and Andhra Pradesh. Economic feasibility, environmental sustainability, regulatory compliance, and scalable adoption frameworks are critically evaluated. The integration of UAVs with IoT and AI-driven analytics represents a decisive shift from reactive farming toward predictive and prescriptive smart farm ecosystems. Strategic recommendations are proposed to support large-scale sustainable deployment.

Keywords: Unmanned Aerial Systems, Precision Agriculture, Sustainable Farming, NDVI, Aerodynamic Modeling, Variable Rate Application, Smart Irrigation, AI-Based Agronomy.

1.   Global Imperative for Sustainable Intensification

A noticeable increase in research output is observed after the 2007–2008 global food price crisis, indicating heightened scientific attention toward agricultural resilience and modeling approaches. The steady rise in multi-model studies reflects a shift toward more integrative and comparative analytical frameworks in agricultural research. Agriculture has entered a decisive structural transition in which incremental efficiency gains are no longer sufficient to ensure food security or ecological stability. By 2050, global food demand is projected to rise by nearly 60–70 percent, driven by population growth, dietary shifts, and urban expansion. At the same time, the global agricultural resource base is under measurable stress. Arable land per capita continues to decline, groundwater tables are receding in major food-producing regions, and soil fertility losses are accelerating due to erosion, salinization, and nutrient depletion. Climate change compounds these pressures by increasing the frequency of droughts, heat waves, and erratic rainfall patterns,

thereby amplifying production volatility. The cumulative effect is clear: agriculture must produce more output from fewer and more fragile resources.

	2020	2021	2022	2023	2024	2025	2026
Multispectral	40	50	60	70	80	85	90
AI Integration	20	30	45	60	75	85	95
RTK Precision	30	40	55	65	75	85	92
VRA Systems	25	35	50	65	78	88	96

Figure 1: Growth of Core UAS Technologies in Agriculture (2020–2026)

Figure 1 illustrates the rapid technological convergence of core UAS components in agricultural applications between 2020 and 2026. Multispectral sensing shows steady growth, indicating its early adoption as a foundational precision agriculture tool. AI integration demonstrates the steepest acceleration, particularly after 2022, reflecting the shift toward predictive and prescriptive farming models. RTK precision systems exhibit consistent expansion, driven by the demand for centimeter-level operational accuracy in variable-rate applications. Overall, the synchronized upward trends confirm the transformation of agricultural drones from basic imaging platforms into fully integrated smart farm ecosystems. The conventional production model centered on blanket fertilizer application, broad-spectrum pesticide spraying, and uniform irrigation—was engineered for yield maximization under relatively stable environmental conditions.

Between 2020 and 2026, a substantial body of peer-reviewed research has identified Unmanned Aerial Systems (UAS) as a foundational enabler of this transformation. Comprehensive reviews by Zhang *et al.,* Tsouros *et al.,* and Radoglou-Grammatikis et al. collectively demonstrate that UAV-based sensing significantly enhances crop monitoring accuracy while reducing agrochemical overuse. More recent syntheses published in journals such as Drones (2024–2025 issues) and book chapters in Springer Nature volumes on smart agriculture further consolidate evidence that UAS platforms have transitioned from experimental tools to operational infrastructure in precision farming systems.

Operationally, UAS integration compresses decision latency from weeks to days. Nutrient deficiencies can be corrected during early vegetative phases rather than after yield potential has already been compromised. Irrigation schedules can be adjusted based on canopy temperature differentials, reducing water waste. With UAS integration, it becomes technically feasible and economically defensible. The literature from 2020–2026 consistently converges on this

conclusion: UAV-enabled precision agriculture is not a peripheral enhancement but a structural pillar of next-generation farming systems. For water-stressed and smallholder-dominated regions, including large parts of South Asia, the strategic implications are particularly significant. Service-based drone cooperatives and shared deployment models reduce capital barriers while democratizing access to advanced sensing technologies. In such contexts, UAS adoption is not merely about modernization; it is about safeguarding productivity under tightening ecological constraints.

Agriculture now confronts hard resource ceilings rather than marginal optimization challenges. The transition from uniform input application to data-driven, spatially explicit resource management is unavoidable. Within this transition, Unmanned Aerial Systems represent the operational backbone enabling sustainable intensification to move from concept to implementation.

## 2.   Technological Convergence: From Aerial Imaging to Smart Farm Ecosystems
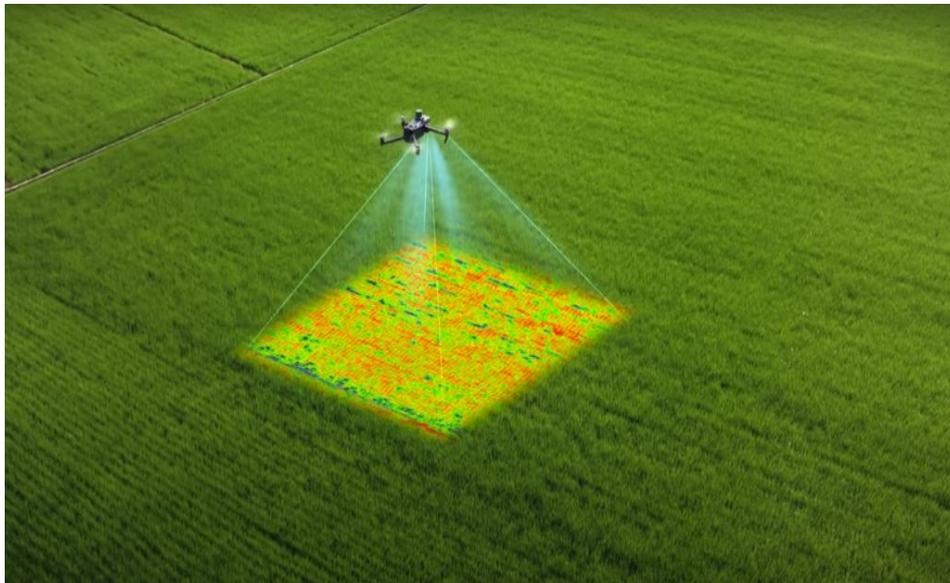
Figure 2: UAV-Based Multispectral Crop Monitoring for Precision Agriculture

Figure 2 illustrates a drone equipped with multispectral sensing technology conducting high-resolution crop health assessment over an agricultural field. The color-coded map represents spatial variability in vegetation indices, enabling detection of nutrient deficiencies and stress zones. Such UAV-based monitoring supports targeted intervention strategies, improving input efficiency and overall crop productivity.

Unmanned Aerial Systems in agriculture have undergone a rapid technological evolution between 2020 and 2026, transitioning from remote imaging tools into integrated cyber-physical platforms embedded within intelligent farm ecosystems. Early-generation agricultural drones primarily functioned as aerial cameras for visual crop inspection. Modern systems, however, incorporate multispectral and hyperspectral imaging arrays, thermal modules, LiDAR terrain mapping, GNSS-RTK centimeter-level positioning, onboard edge computing, and real-time IoT

connectivity. This convergence transforms drones from passive observers into active decision-support infrastructure.

The consequence of this convergence is epistemological rather than merely technological. Agricultural analytics move beyond descriptive models ("what happened?") toward predictive ("what is likely to happen?") and prescriptive ("what intervention is optimal?") frameworks. Studies published in Computers and Electronics in Agriculture (2020–2025) consistently report nitrogen-use efficiency improvements of 15–30 percent and pesticide reductions approaching 25 percent when UAV-guided variable-rate systems are deployed. These gains are not marginal—they reflect structural efficiency enhancements rooted in spatial intelligence.
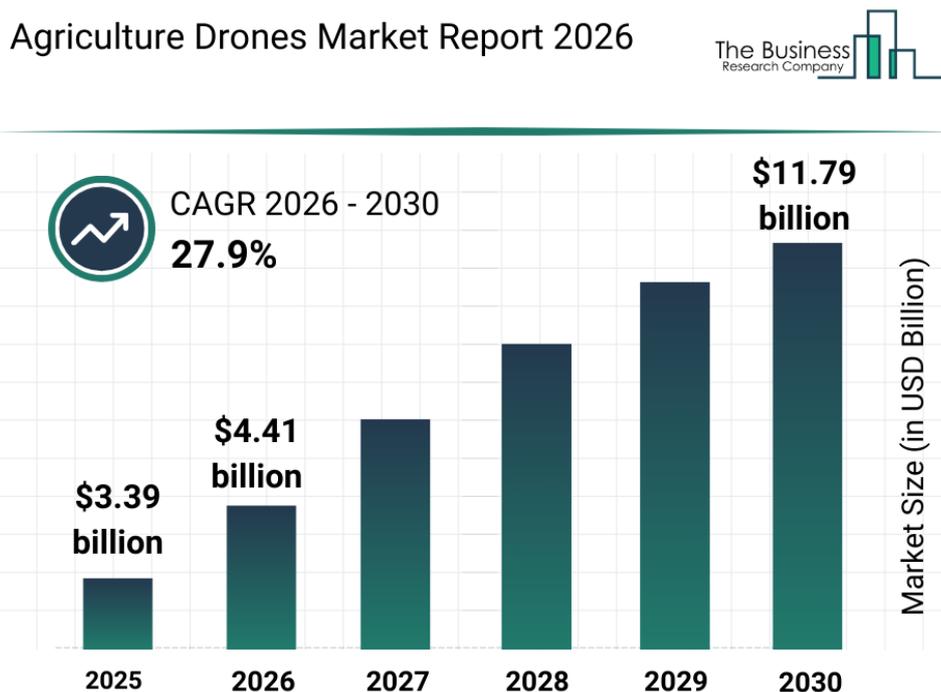
**Figure 3: Global Agriculture Drones Market Growth Forecast (2025–2030)**

Figure 3 presents the projected expansion of the global agriculture drone market from 2025 to 2030. The market is expected to grow from $3.39 billion in 2025 to $11.79 billion by 2030, reflecting a strong compound annual growth rate (CAGR) of 27.9%. The rapid increase highlights accelerating adoption of UAV technologies in precision agriculture, driven by demand for efficiency, automation, and data-driven farm management. Recent research clusters applications into three dominant domains: crop health diagnostics using vegetation indices, variable-rate application (VRA) systems, and irrigation stress mapping via thermal integration. Each cluster represents a different layer of intelligence—diagnostic, operational, and optimization.

3. Scientific Foundations: Remote Sensing and Vegetation Indices

The scientific foundation of drone-enabled precision agriculture rests on spectral reflectance theory. Healthy vegetation absorbs strongly in the red band due to chlorophyll activity while reflecting near-infrared radiation due to internal leaf structure. The most widely applied index remains the Normalized Difference Vegetation Index (NDVI):

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

While NDVI remains foundational, recent literature (2021–2026) expands toward more sensitive indices capable of capturing mid-to-late growth nitrogen stress and subtle chlorophyll variations. These include NDRE, GNDVI, Thermal Stress Index (TSI), and Water Deficit Index (WDI).
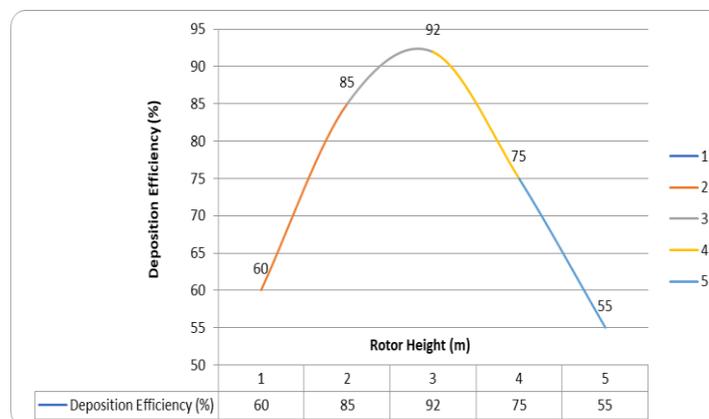
Figure 4: Spray Deposition Efficiency vs UAV Flight Height.

Graph 4 illustrates the relationship between UAV rotor height and spray deposition efficiency. Deposition increases significantly as flight height rises from 1 m to approximately 3 m, where peak efficiency is observed. Beyond 3 m, efficiency declines due to increased spray drift and droplet dispersion. The results indicate that optimal spray performance occurs within the 2–3.5 m operational window. This confirms the importance of aerodynamic calibration in minimizing chemical loss and maximizing canopy penetration.

Table 1: Comparative Vegetation Indices Used in UAV-Based Agriculture (2020–2026)

Index	Spectral Bands	Primary Application	Strength	Limitation
NDVI	Red, NIR	General crop vigor	Widely validated	Saturation in dense canopy
NDRE	Red Edge, NIR	Nitrogen status	Sensitive mid-growth	Requires advanced sensor
GNDVI	Green, NIR	Chlorophyll detection	Early stress detection	Calibration variability
WDI	Thermal + NIR	Water stress	Irrigation optimization	Environmental sensitivity

These vegetation indices provide complementary insights into crop health by leveraging different spectral bands to capture physiological variability. While NDVI remains the most widely validated indicator of general vigor, advanced indices such as NDRE, GNDVI, and WDI enhance sensitivity to nitrogen status and water stress, albeit with higher sensor and calibration requirements.

Figure 5: Spatial Variability Analysis Using NDRE and Thermal Imaging in Precision Agriculture

Figure 5 compares NDRE-based vegetation index mapping (left) with thermal imaging temperature distribution (right) across the same agricultural fields. The NDRE map highlights nitrogen variability and crop vigor differences, while the thermal image identifies canopy temperature variations linked to water stress. Compared to satellite platforms, UAV systems provide centimeter-level resolution and flexible temporal acquisition, dramatically enhancing sub-field variability detection. Satellite imagery may offer broader coverage, but its revisit time and atmospheric interference reduce temporal precision. UAV deployment removes this constraint.

4. Aerodynamic and Payload Engineering in Agricultural UAS

A critical yet under-discussed domain in agricultural UAV research involves aerodynamic optimization and spray mechanics. Unlike surveillance drones, agricultural UAVs must manage payload masses ranging from 10 to 40 liters while maintaining stability, lift efficiency, and droplet deposition accuracy.

Figure 6: Agricultural UAV with 16–30 Liter Payload Tank for Precision Spraying

Figure 6 shows a multi-rotor agricultural drone equipped with a 16–30 liter liquid payload tank designed for precision spraying operations. The integrated tank and fluid delivery system enable controlled application of fertilizers and pesticides across targeted field zones. Such payload configurations balance chemical capacity, flight stability, and operational efficiency in site-specific crop management.

The rotorcraft lift equation governing operation remains:

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

Where ρ denotes air density, V represents rotor velocity, S corresponds to rotor disk area, and C_L is the lift coefficient. Spray efficiency depends heavily on downwash airflow dynamics. Recent modeling studies (2023–2026) demonstrate optimal droplet deposition at rotor heights between 2.0–3.5 m above canopy. Field trials conducted in India and China (2024) indicate that droplet sizes of 200–300 μm significantly reduce drift compared to tractor-mounted sprayers while enhancing canopy penetration. The aerodynamic–agronomic coupling is non-trivial. Improper spray calibration negates the benefits of precision sensing. Thus, technological integration must extend beyond sensing into fluid mechanics and atomization modeling.

## 5. AI Integration and Predictive Agronomy

Artificial intelligence represents the differentiating layer transforming UAS into autonomous agronomic advisors. CNN-based disease detection systems now achieve accuracy rates exceeding 92 percent under controlled field conditions. Machine learning regression models such as Random Forest and XGBoost enable yield prediction within ±5–10 percent error margins.

Table 2: AI Applications Integrated with UAV Systems (2020–2026)

| Application	Algorithm	Accuracy	Field Impact
Leaf disease detection	CNN / ResNet	88–95%	Early pathogen control
Yield prediction	Random Forest	±5–10%	Market forecasting
Weed classification	Deep Learning	>90%	Herbicide reduction
Water stress mapping	ML regression	85–92%	Irrigation efficiency

These AI-driven applications demonstrate how machine learning algorithms enhance decision accuracy in UAV-based precision agriculture. By enabling early disease detection, accurate yield forecasting, targeted weed control, and efficient irrigation management, these models significantly improve resource optimization and crop productivity.

Figure 5 presents a convolutional neural network architecture (Inception-based) used for multi-class crop disease classification from leaf images. The model achieves high training and validation accuracy, as reflected in the performance metrics and confusion matrix. The strong diagonal pattern in the confusion matrix confirms reliable disease discrimination, supporting AI-driven precision crop health monitoring.
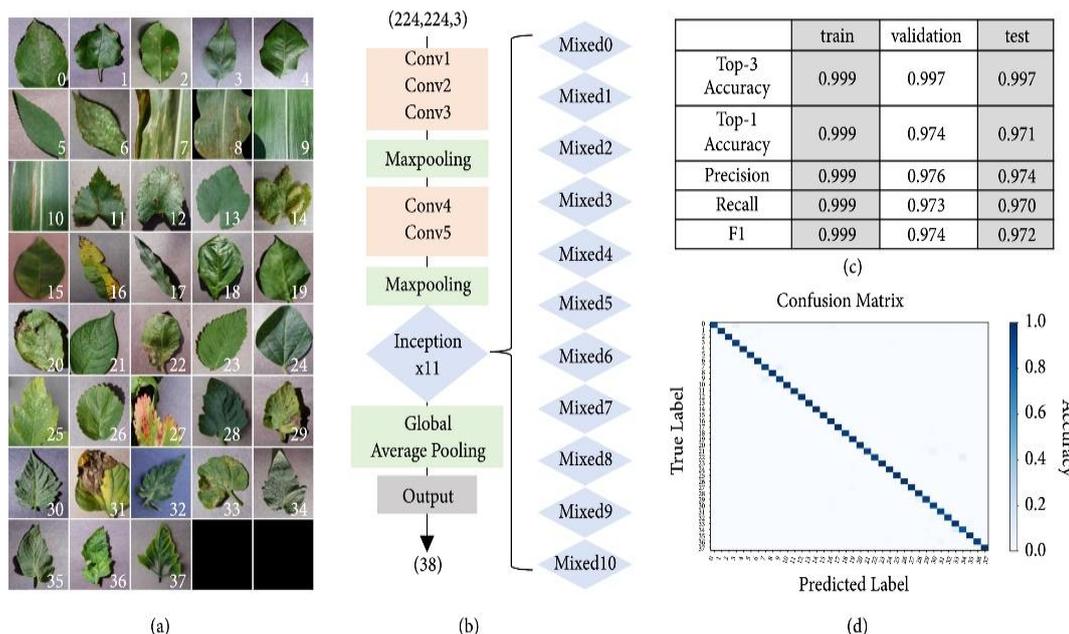
**Figure 7: Deep Learning Framework for UAV-Based Crop Disease Classification**

2025 multi-country study reports crop-loss reductions nearing 18 percent when AI-integrated UAV systems are deployed compared to manual scouting methods. The key transformation lies in predictive intervention rather than reactive correction.
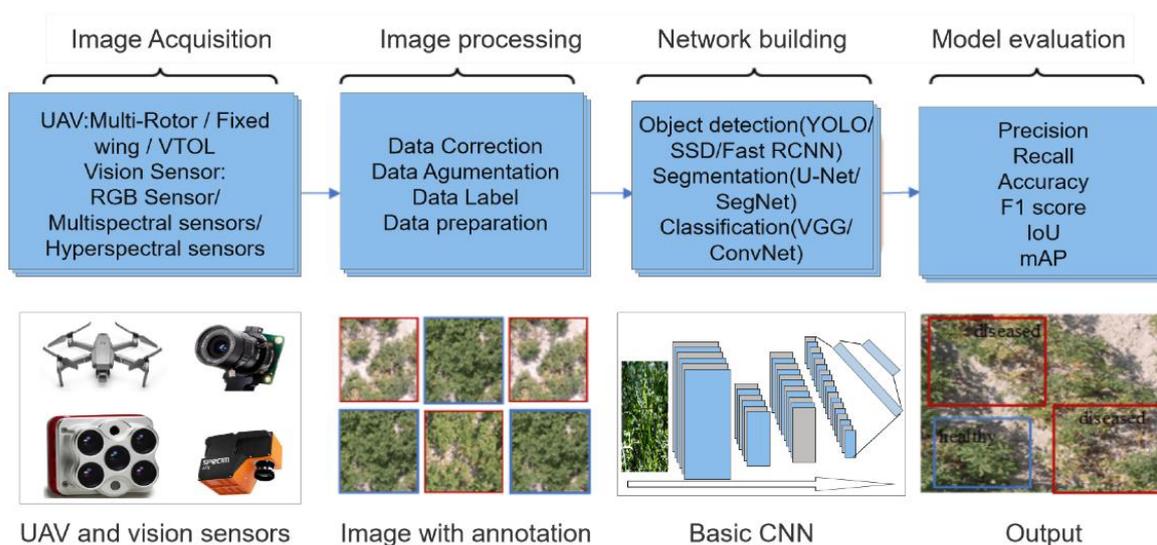
Figure 8: End-to-End UAV-Based Computer Vision Workflow for Precision Agriculture

Figure 8 illustrates the complete pipeline for UAV-driven agricultural image analysis, from image acquisition using multispectral and RGB sensors to AI-based model evaluation. The workflow includes data preprocessing, annotation, network training (YOLO, U-Net, CNN), and performance validation using metrics such as precision, recall, and mAP.

Figure 9 compares the predictive accuracy of different AI algorithms applied to UAV-based crop analysis. Deep learning architectures such as ResNet and CNN demonstrate higher accuracy levels compared to traditional machine learning models.
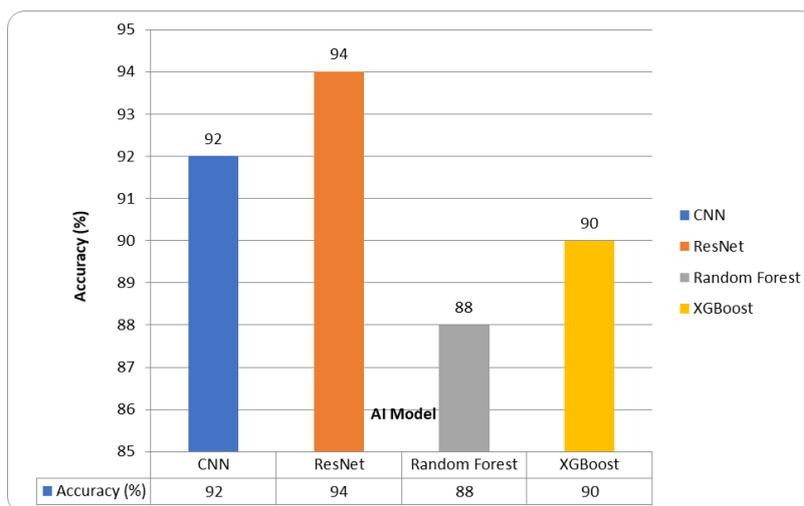
Figure 9: Comparative Performance of AI Models in UAV-Based Crop Monitoring.

6. Indian Deployment Landscape

India has emerged as one of the fastest-growing agricultural drone markets following regulatory reforms post-2021. Deployment models vary across states, reflecting agro-climatic diversity and cropping systems.

Table 3: State-Level Applications and Impact of Agricultural Drone Deployment in India

State	Application Focus	Observed Impact
Karnataka	Millet monitoring	Improved nutrient targeting
Punjab	Paddy residue assessment	Environmental compliance
Maharashtra	Cotton pest surveillance	Reduced pesticide load
Tamil Nadu	Precision irrigation	15–22% water savings
Andhra Pradesh	FPO drone services	Lower service costs

Tamil Nadu's semi-arid irrigation mapping initiatives (2024–2025) demonstrate measurable evapotranspiration-based scheduling improvements, reinforcing the relevance of UAS in water-stressed regions.

7. Economic Feasibility and Sustainability Metrics

Economic analyses from 2020–2026 indicate spray-class UAV investments between ₹4–10 lakhs, with payback periods of approximately 1.5–3 years under custom-hiring models. Operational cost reductions of 20–35 percent in chemical inputs have been reported, alongside carbon footprint reductions estimated between 12–18 percent relative to tractor-based spraying.

Graph 4 illustrates the projected regional expansion of the agricultural drone market across North America, Europe, Asia-Pacific, and the Rest of the World from 2016 to 2027. All regions demonstrate consistent growth, with Asia-Pacific and North America contributing significantly to overall market expansion. The upward stacked trend highlights accelerating global adoption of UAV technologies in precision agriculture applications.
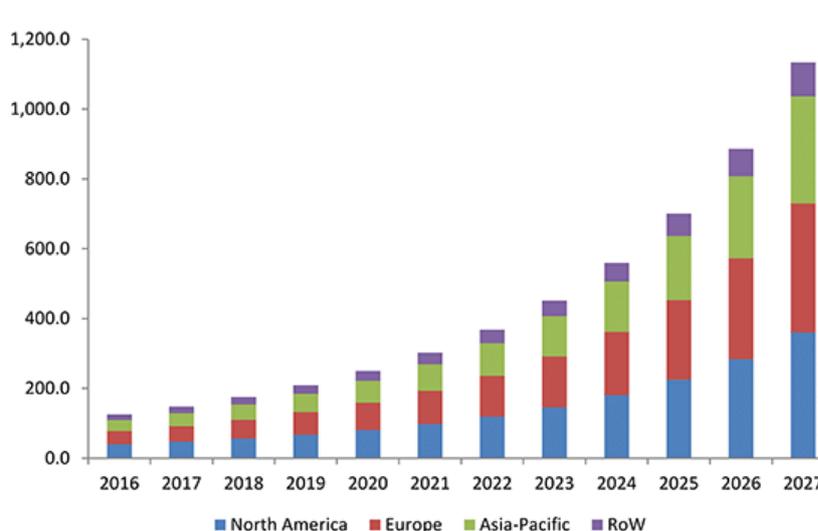
Figure 10: Regional Growth Trends in the Global Agricultural Drone Market (2016–2027)

Beyond economics, UAV spraying reduces soil compaction, limits groundwater contamination risk, and supports biodiversity balance. However, barriers persist, including pilot training shortages, battery lifecycle sustainability concerns, interoperability limitations, and fragmented landholding patterns.
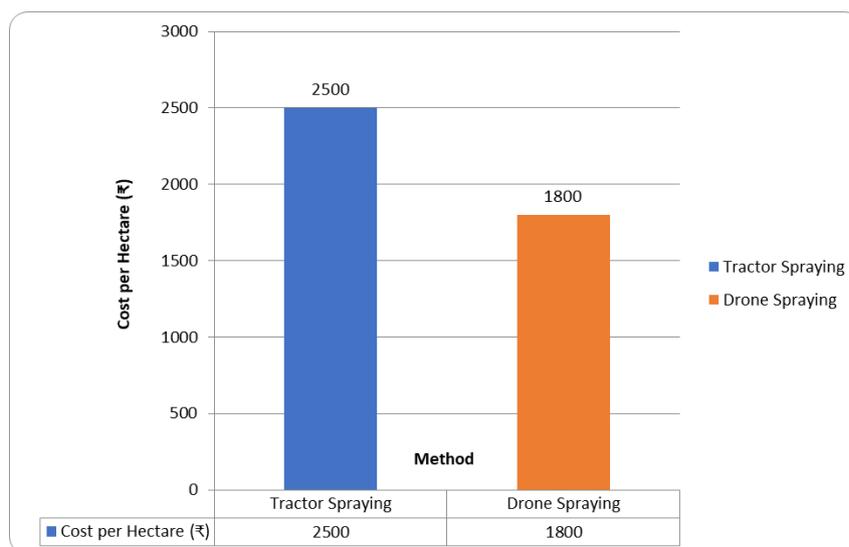
Figure 11: Economic Comparison of Drone vs Conventional Spraying Systems

Graph 11 presents a cost comparison between tractor-based spraying and drone-based spraying per hectare. Drone spraying demonstrates significantly lower operational cost due to reduced labor and optimized chemical usage. Conventional tractor spraying incurs higher expenditure because of fuel, labor, and excess input application. The cost difference indicates improved economic efficiency under UAV-based systems. This supports the financial viability of drone deployment in precision agriculture models.

8. Regulatory and Policy Evolution (India, 2021–2026)

India's liberalized drone policy environment post-2021 catalyzed rapid agricultural adoption. Simplified Drone Rules, FPO subsidies, pilot certification frameworks, and emerging UAS Traffic Management (UTM) systems collectively signal structural commitment toward agritech

modernization. Policy support has shifted drone use from pilot experimentation to scalable deployment.

Conclusion

The 2020–2026 scientific corpus establishes UAS-based precision agriculture as a structural pillar of smart farming ecosystems. Its integration with multispectral sensing, aerodynamic optimization, AI analytics, and supportive policy frameworks positions it not merely as a productivity enhancer but as a sustainability catalyst. However, technological optimism must be grounded in engineering rigor. Without spray calibration modeling, AI validation under field variability, economic scaling analysis, and data interoperability frameworks, deployment risks underperformance. The future lies not in isolated drone deployment but in integrated drone–IoT–AI ecosystems capable of delivering predictive, adaptive, and resilient agricultural systems.

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TECHNOLOGICAL INNOVATIONS IN SUSTAINABLE AGRICULTURE

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Abstract

Artificial intelligence (AI) plays a transformative role in this endeavor by bridging sectorspecific solutions and integrating them to promote environmental protection and food security. AI is revolutionizing sustainable agriculture, ensuring both food security and environmental protection. Sustainability is a holistic goal that can be effectively achieved through the combined efforts of agriculture and its allied sectors. Advances in sustainable agriculture are essential for simultaneously optimizing food production while preserving the environment. Sustainable agriculture promotes practices that are environmentally sound, economically viable, and socially equitable. Equally important are agro ecological practices, including crop rotation, organic farming, and agroforestry. These methods enhance soil fertility, reduce reliance on synthetic pesticides, improve water retention, and promote biodiversity. By combining technological innovation with ecological principles, sustainable agriculture offers a holistic pathway to ensuring long-term food security while safeguarding natural resources for future generations. This approach involves the application of advanced technologies such as precision farming, the development of genetically modified crops to achieve higher yields and enhanced disease resistance, and the integration of renewable energy sources into agricultural practices to improve efficiency and reduce environmental impact.

Introduction:

The world population is about to reach 9.9 billion by 2050.The food demand is rising Talaviya *et al.* (2020) as a result of the increasing population Merrill *et al.* (2018). Addressing this demand sustainably is a critical challenge Chandel *et al.* (2024), as the existing traditional agricultural practices faced numerous challenges and have resulted in resource depletion and environmental deterioration Sonnino (2018). In the face of escalating global challenges such as climate change, soil degradation, biodiversity loss, and increasing food demand, the concept of sustainable agriculture has never been more crucial. The essence of sustainable agriculture lies not only in enhancing crop yield but also in preserving natural resources, maintaining ecological balance, and ensuring the well-being of farming communities. Therefore, modern agricultural practices are required to address these challenges to attain sustainability Conventional farming techniques, though effective for mass food production, pose serious threats to environmental sustainability due to excessive resource utilization, pollution, and degradation of biodiversity. Additionally, sustainable agriculture supports the use of local resources and traditional knowledge to maintain ecological balance while ensuring consistent and resilient food production for present and future generations. Farmer training and public awareness campaigns can increase understanding and

acceptance of sustainable practices, leading to wider adoption. Overall, the adoption of sustainable agricultural practices is not just a choice but a necessity for ensuring food security and environmental conservation in the future.

In agriculture, sustainability means that the land and resources used for farming are preserved and maintained in a healthy, productive state so they can be passed down to future generations. This ensures that future farmers can continue cultivating the land while meeting their needs without degrading the environment lands, water and other resources in such a way that future generations can profit from sustainable development as well. Modern agriculture is primarily focused on enhancing productivity and improving the quality of produce. Agricultural advancement does not always rely solely on entirely new technologies; it often involves adapting and refining existing innovations to suit local conditions and emerging challenges. In this context, sustainable development refers to meeting present human needs and improving living standards without depleting natural resources or compromising the ability of future generations to meet their own needs. Recent advances in sustainable agriculture and allied sciences are transforming food production systems through the integration of digital technologies, artificial intelligence (AI), nanotechnology-based bio-inputs, and climate-smart practices. These innovations aim to reduce chemical dependency, enhance resource-use efficiency, and strengthen resilience against climate change. Artificial intelligence (AI) has emerged as a transformative force across various sectors, including agriculture. It refers to the simulation of human intelligence in machines programmed to think, learn, and make decisions. In agricultural contexts, AI is widely applied in crop health monitoring, pest and disease detection, soil health assessment, and yield prediction. In countries like India, agriculture plays a vital role in the economy, contributing significantly to GDP and employment. Despite rapid urbanization, a large proportion of the population still resides in rural areas and depends on agriculture for their livelihoods. Therefore, fluctuations in agricultural growth directly affect employment, income levels, and overall economic stability. If agriculture underperforms, the consequences can be severe for national development.

Today, there is a growing shift toward organic farming and reduced reliance on chemical pesticides. This transition has stimulated the development of innovative agricultural products and sustainable input alternatives. Sustainable agriculture includes practices such as crop rotation, integrated pest management, conservation tillage, and organic farming; all aimed at increasing productivity while minimizing environmental impact. At the same time, data security has become an essential component of modern agricultural systems. With the widespread use of sensors, drones, satellite imagery, and IoT-enabled devices, vast amounts of sensitive farm data are generated. Protecting this data is critical to ensuring farmer privacy, preventing misuse, and maintaining trust in digital agricultural ecosystems.
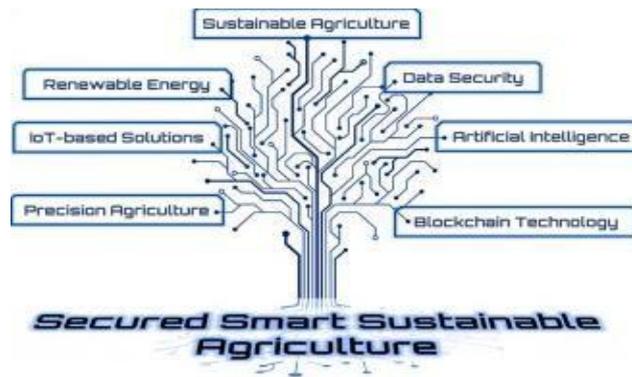
Agriculture Innovation System:

Adopting innovative ideas in agriculture is a challenging process. The difficulty increases when those promoting the innovation appear to have clear advantages over the intended adopters. In rural areas or less developed societies—new practices can be hard to implement because farming methods are deeply rooted in traditions shaped by generations of trial and error. As

Sharp and Spicer (1952) observed, changing people's beliefs can be even more delicate than performing surgery. Agricultural Innovation Systems (AISs) are characterized by two main elements: the number of participants involved and the dynamic interactions among them French *et al.* (2014). Key factors include farmers and farmer organizations; providers of inputs, financial services, and technical support; institutions that facilitate knowledge exchange and learning; stakeholders engaged in value addition and production; and those who enable market access. AISs also encompass research and technology development organizations, as well as governmental and non-governmental extension services, which play crucial roles in providing information and building capacity.

Advancements in Sustainable Agriculture

- Artificial Intelligence (AI) & Precision Agriculture: AI, machine learning, and IoT sensors are used for precise planting, disease detection, and automated irrigation, enhancing yields and reducing chemical use.

- Nano-Agri-Inputs: Nanotechnology is applied to develop specialized fertilizers and pesticides, which reduce environmental emissions and increase nutrient efficiency.

- Genetic Innovation: Development of climate-resilient and pest-resistant GM crops, alongside biotechnological advancements, contributes to sustainable yield improvements.

- Integrated Management Systems: Adoption of Integrated Weed Management (IWM), Integrated Nutrient Management (INM), and Integrated Pest Management (IPM) to minimize chemical reliance.

- Conservation Agriculture: Focus on minimal soil disturbance, crop residue retention, and rotation to enhance soil health and minimize erosion.

Advancement in Allied Sciences

- Smart Farming Machinery: Increased use of autonomous robots and drones for monitoring and targeted application of inputs.

- Sustainable Food Science: Advancements in processing and reducing waste through valorization techniques.
- AI can really make a difference in allied sectors like forestry, fisheries, and animal husbandry. It is helping in the predicting of crop yields, monitoring wildlife, or optimizing resource allocation.

Given the interconnected nature of agriculture and its allied sectors, such as animal husbandry, food science, fisheries, horticulture, forestry, agricultural marketing and engineeringsustainability cannot be achieved by focusing on farming alone Begum (2022). Agricultural practices affect and influenced by these interrelated allied disciplines, resulting in an intricate web, where changes in one discipline can have a major impact on others. However, there is a lack of comprehensive review that covers the AI application in agriculture along with its interrelated disciplines for achieving sustainability. So sustainable agriculture fills the gap by offering an integrative synthesis of AI application in agriculture and its allied sectors.

Application of AI in agriculture sector

The integrating AI into agriculture and Its allied sectors offer significant benefits that outweigh potential drawbacks, thereby fostering sustainable practices and environmentally friendly innovations.AI-driven solutions have significantly transformed the agricultural landscape by enhancing pest and disease management, weather forecasting, soil health assessment, weed management, crop protection, greenhouse farming, precision agriculture, irrigation and yield management.
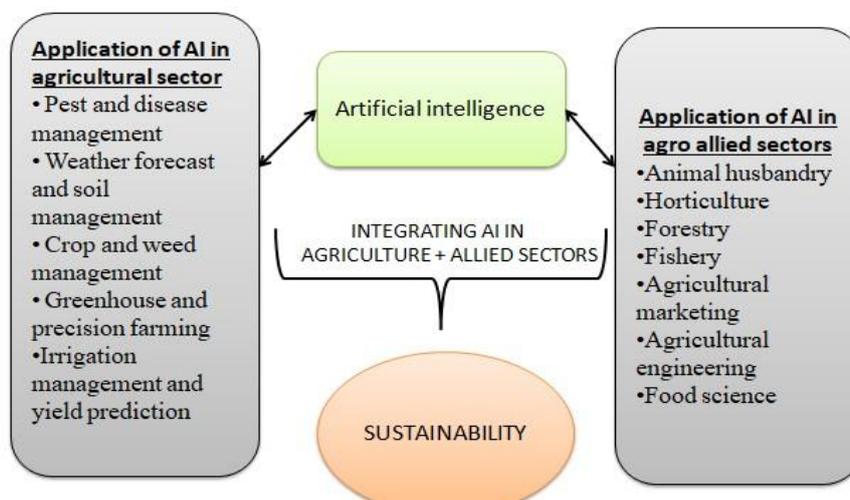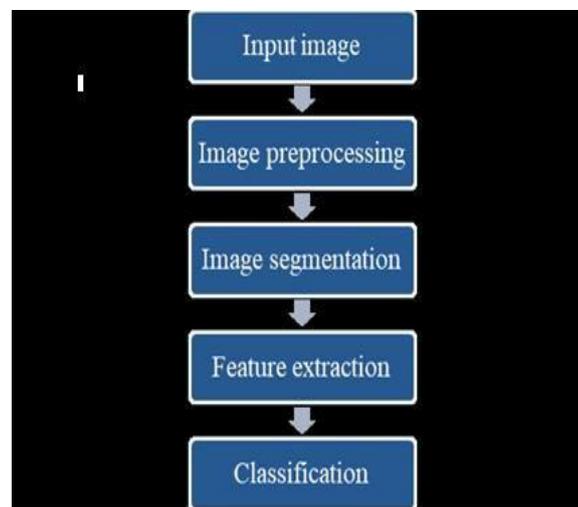

Pest Management

AI-based technologies provide timely pest identification and offer control recommendations (PRS India, 2022). The earliest possible action is taken by the precise identification of pests from the images by AI-driven image recognition systems that use deep learning Mekha and Parthasarathy (2022). Drones and IoT sensors powered with AI track insect activity and apply pesticides more efficiently, using fewer chemicals and thus resulting in a lesser environmental impact. When pests are detected, farmers receive mobile alerts with tailored recommendations, enabling timely action and minimizing crop losses Susheel and Rajkumar (2023).

Disease Management

Artificial intelligence (AI) and machine learning (ML) have emerged as transformative technologies in plant disease detection and management, offering highly accurate, scalable, and real-time diagnostic solutions.AI-driven solutions enhance plant disease management by facilitating early identification, diagnosis and prevention Patil *et al.* 2024). Disease lesions and leaf discolorations are examined by deep learning algorithms to identify diseases with the help of images captured by the smartphones and AI driven drones and IoT sensors Shoaib *et al.* (2023). AI powered chat bots and advisory systems give real time and personalized disease management advice to the farmers, which results in less dependence on chemical treatments Storey *et al.* (2022). The process of disease recognition generally involves five stages: image acquisition, image pre-processing, image segmentation, feature extraction and finally image classification Karar *et al.* (2021). This step by step process is illustrated in the form of flowchart.

AI-driven plant disease management utilizes computer vision, machine learning (ML), and IoT sensors for real-time detection, identification, and, in some cases, treatment of crop diseases to improve yields. By analyzing images from smartphones or drones, AI algorithms—particularly Convolutional Neural Networks (CNNs)—achieve over 95% accuracy in diagnosing diseases, allowing for timely, targeted interventions that reduce pesticide use.

- **Image-Based Diagnostics:** Smartphone applications and cameras detect, classify, and diagnose plant diseases in real time by analyzing leaf images, with models like CNNs, SVM, and Random Forest achieving high accuracy.
- **Early Detection and Monitoring:** AI systems, including drones and sensors, allow for continuous, remote monitoring of large-scale crops, detecting infections before symptoms are visible to the human eye.
- **Predictive Analytics:** By analyzing satellite imagery, weather, and historical data, AI helps predict disease outbreaks, aiding in proactive, precision, and sustainable agricultural management.
- **Technological Tools:** o **Apps & Tools:** Technologies like Plantics and custom CNN models (e.g., ResNet50DPA, this CNN model) analyze leaf images for diagnosis.

> ➢ **Image Classification:** CNNs are used to identify disease patterns in leaves.
> ➢ **Data Analysis:** Algorithms process data to assist in decision-making.

Weather Forecasting

Weather prediction and forecasting, impact assessment of climate change are some of the applications of AI that helps the farmers to take immediate action regarding the weather related issues that affect agriculture Javaid *et al.* (2023). Incorporating weather data provided by AI technologies, by analyzing the historical weather patterns with farm operation enhances precision agriculture. Early prediction of disasters such as flood and drought by the AI systems, aids the farmers in mitigating the risks by providing early warning to the farmer's phone Adikari *et al.* (2021).

AI-driven weather forecasting systems,, such as RNN (Recurrent Neural Networks) or, CNN (Convolutional Neural Networks), analyze satellite data,, sensor networks, and historical records to predict rainfall, temperature, and extreme events with high accuracy, enabling optimized irrigation, planting, and pest management

Key Aspects of AI-Driven Weather Management

- **Hyper-Local Forecasting:** AI provides field-level weather intelligence, moving away from coarse, regional forecasts to precise predictions for specific farms.
- **AI Models:** The Neural GCM and ECMWF's AIFS have shown to outperform traditional models in predicting the onset of monsoons and other weather patterns.
- **Actionable Insights:** AI translates data into actionable advice, such as, the best time for irrigation or when to apply fertilizers, improving yield and reducing waste.
- **Risk Management:** AI, models can, forecast, heatwaves, frosts, droughts, and pest outbreaks, enabling proactive measures to prevent, damage.
- **Performance Metrics:** AI-based forecasting systems for smart agriculture have demonstrated, high, accuracy, often reaching up to 98.76%.
- **Economic Impact:** The implementation of AI in weather, forecasting can, provide, a, high return on investment, for farmers, with, potential benefits, far outweighing the costs

Soil Management

The assessment of soil health, soil nutrient content and soil parameters such as pH, soil moisture content, soil texture and soil type by the AI driven technologies, such as sensors, drones and robots assist the farmers in taking management practices by giving the real time information Awais *et al.* (2023). Using AI technologies for soil management reduces the fertilizer usages, which enhances the soil fertility and lessen the adverse environmental impacts Javaid *et al.* (2023).

AI-powered soil management revolutionizes agriculture by using machine learning, IoT sensors, and satellite imagery to monitor, analyze, and optimize soil health in real-time. These systems predict nutrient needs, erosion risks, and moisture levels, enabling precise, sustainable farming practices that improve yields while reducing fertilizer use.

Key aspect of AI-driven soil management applications include:

- **Real-Time Monitoring and Analysis:** IoT sensors and drones collect data on soil moisture, temperature, pH levels, and nutrient content, providing instantaneous insights into field conditions.

- **Predictive Modeling for Soil Health:** AI analyzes historical data and weather patterns to predict long-term soil health trends, allowing for proactive management of erosion or nutrient degradation.

- **Precision Fertilizer and Nutrient Application:** AI algorithms determine the exact amount of fertilizer required for specific spots in a field, reducing waste and minimizing environmental impact.

- **Sustainable Land Management:** AI assists in mapping soil organic carbon and developing strategies for crop rotation and conservation, promoting overall ecosystem sustainability.

- **Digital Soil Mapping and Diagnosis:** Machine learning models (such as random forest or neural networks) process large datasets to map soil properties, identifying issues not visible to the naked Eye.

Crop Protection and Management

AI driven devices such as drones, sensors and robots frequently monitor the crop health by predicting the early signs of pest and disease outbreaks and give alerts to the farmers so that they can take immediate management actions and thereby enhancing the productivity and reducing crop losses. Machine learning algorithms monitor the plant growth indicators that aids in easy crop management Bilal *et al.* (2023).

Weed Management

Weed management has become easy with the help of AI technologies that precisely identifies the weed and gives control measures. Images taken from drones and smartphones identify weeds by differentiating them from other crops by using machine learning and image recognition systems and gives alerts to farmers Etienne *et al.* (2021). Reduced herbicide use and targeted weed control are the advantages of using AI driven robotic sprayers.

AI-powered weed management utilizes computer vision, drones, and robotics to detect and remove weeds with pixel-level precision, reducing herbicide use by up to 80%. These systems employ convolutional neural networks (CNNs) to distinguish crops from weeds, enabling targeted spraying or mechanical removal.

AI Weed Management Technologies:

- **Computer Vision & Imaging:** High-resolution cameras and sensors identify weeds in realtime, even distinguishing between similar-looking species.

- **Targeted Spraying:** AI-driven spot spraying systems, such as Bilberry, activate nozzles only over weeds, significantly reducing chemical runoff.

- **Robotic Weeders:** Autonomous robots like Carbon Robotics' Claws use AI to identify and eliminate weeds with laser pulses, eliminating chemical use.
- **Drone Technology:** UAVs are used for aerial surveying, mapping weed hotspots, and spottreating fields.
- **Predictive Modeling:** AI models forecast weed growth patterns and optimize treatment timing.

Greenhouse farming

In greenhouse farming, plants are grown under controlled conditions. AI technologies aids in attaining sustainability by monitoring parameters such as temperature, pH and humidity which helps in increasing the crop yields and enhancing efficient usage of water and fertilizer. Etienne *et al*. (2021) and Maraveas (2022). AI driven sensors predict the occurrence of pest and disease inside the greenhouse. Robots powered with AI automate the operation in greenhouses such as harvesting and weeding Codeluppi *et al.* (2020).

Irrigation management

AI driven smart irrigation systems precisely use water by predicting the irrigation needs of the crop Fernando *et al.* (2020). Irrigation systems such as sprinkler and drip are managed by automated AI systems efficiently use the water based on the water needs and thus reducing the water loss as well as assisting the farmers in handling the water issues Tace *et al.* (2022). AI based digital application called AIDSII is used in irrigation management Wei *et al.* (2022). AI-driven irrigation management systems revolutionize agriculture by utilizing IoT sensors, satellite imagery, and weather data to automate, optimize, and personalize water application for crops. By leveraging machine learning models to analyze real-time soil moisture and plant stress, these systems reduce water wastage by over 90%, enhance yield, and enable, and enable predictive, sustainable water management.

- **Real-Time Data Analytics:** AI systems analyze data from soil moisture, temperature, and nutrient sensors, along with satellite imagery to detect plant stress, diseases, or nutrient deficiencies.
- **Predictive Scheduling:** Instead of acting solely on present conditions, AI models analyze weather forecasts and past data to anticipate future water needs, making irrigation proactive rather than reactive.
- **Automated Decision-Making:** AI algorithms control automated irrigation systems, turning pumps on/off or adjusting valves, reducing human intervention and ensuring precise, waterefficient delivery.
- **Sustainability and Efficiency:** By using AI-driven precision irrigation, farmers can significantly conserve water, improve soil health, reduce groundwater depletion, and decrease energy usage.
- **Infrastructure Monitoring:** AI can detect leaks by monitoring flow and pressure data, allowing for maintenance of irrigation infrastructure.

Precision agriculture

Integrating AI with precision agriculture enhances efficiency, effectiveness and sustainability of agricultural practices. AI optimizes input utilization, thereby enhancing crop yield and resource efficiency Raouhi *et al.* (2023). Crop monitoring, efficient water use, assessing soil health, pest and disease detection and yield prediction are the advantages of using artificial intelligence in precision agriculture Alazzai *et al.* (2023).

Yield prediction and management

By analyzing the weather, soil and crop conditions, the AI technologies predict and manage the yield of the crops. These predictions enable farmers to make data-driven decisions that maximize yield potential and reduce uncertainty in agricultural planning. AI-powered yield prediction in agriculture, utilizing machine learning, satellite imagery, and IoT sensors, enables up to 90%+ accuracy in forecasting, reducing economic uncertainty by up to 40%. By analyzing historical data, weather, and soil conditions, AI transforms reactive farming into proactive management, allowing optimized resource allocation, early pest detection, and improved financial planning.

Components of AI Yield Management

- **Data Sources:** Systems analyze satellite imagery (e.g., Sentinel-2), meteorological data, soil sensors (pH, moisture), and historical crop data.
- **AI Models:** Techniques include Random Forest, LightGBM, Artificial Neural Networks (ANN), and Deep Learning to handle complex, nonlinear agricultural data.
- **Real-time Insights:** AI provides dynamic updates to predict yield months before harvest, allowing for adjustments in fertilization or irrigation.

Application of AI in agricultural allied sectors

Artificial Intelligence (AI) is revolutionizing agri-allied sectors such as animal husbandry, agricultural marketing, forestry, fishery, food science, agricultural engineering and horticulture by improving operational efficiency, productivity and sustainability. AI has been used for automated milking in cattle. Robotics combined with AI also support vaccination processes in poultry Patel *et al.* (2022). AI has been used to evaluate the vocalizations of livestock and aided in recognizing distress and comfort calls Neethirajan (2023). The diagnosis of optimum artificial insemination timing has also been done by the artificial intelligence.

Agricultural marketing

Most of the farmers are not aware of the market prices and they are exploited by the middleman who makes them to sell their produce at a lower rate. This can be avoided with the help of AI since it forecast the market prices to the farmers and assist in data driven decision making. The marketing industry can greatly benefit from artificial intelligence Haleem *et al.* (2022). AIpowered models facilitate in developing a market approach that is customer-driven and builds a cohesive market strategy. It enables marketers to find future trends and forecast them. Artificial intelligence has helped marketers to analyze customer behavior. AI-driven supply chain optimization aids in supply optimization by identifying potential risks and opportunities and

helps in resource optimization. AI also plays a vital role in agricultural product management Hongbing *et al.* (2022).

Forestry

Artificial intelligence predicts the forest fire. It assists in forest classification and mapping, identifying the illegal felling and wood trafficking, tracking ecosystem health and conserving biodiversity Shivaprakash *et.al* (2022). AI powered robots assist in tree trunk detection. AI technologies are also used for the classification of forests and mapping, as well as in the quantification of the resources of the forest, which results in the conservation of forests.

Fishery

Artificial intelligence ensures sustainable fisheries. DL, which is a subset of artificial intelligence assisted in live fish identification. It aids in fish stock monitoring and management. One of the AI techniques, SVM, assisted in disease detection in fish by identifying infected fish from fresh fish. AI-driven technologies keep in check the pollution that affects the fish Mohale *et al.* (2023).

Food Science

One of the applications of AI in Food science is that it reduces the food shortage crisis and food waste. There are many AI-based food processing strategies. AI-driven technologies assess the food quality. AI-driven technologies also play a major role in maintaining food safety and managing the agro-food waste Kutyauripo *et al.* (2023). Artificial intelligence can be used to make eco-friendly food packaging for food and beverages. It also aids in maintaining the viability of the high-quality food production.

Agricultural Engineering

Agricultural engineering has brought about various strategies for reducing risk in agricultural practices. AI powered Agricultural engineering technologies enhance crop production and pest resistance. AI driven robots assisted farmers in doing various agricultural operations. Various AI-driven smart machineries have been developed for doing operations such as seedbed preparation, harvesting, threshing and weeding Subeesh and Mehta (2021). ANN was used to forecast the performance of the tractor engine Nagar *et al.* (2024).

Horticulture

Horticulture is the branch of agriculture dedicated to the cultivation of fruits and vegetables. Modern agricultural systems use artificial intelligence to identify and classify fruits and vegetables by analyzing their physical attributes-such as size, shape and color and comparing them to established standard criteria and biological characteristics. It is used for crop grading and quality assessment of fruits by checking their moisture levels Singh *et al.* (2022). The maturity of fruits and vegetables can be determined by AI technologies. AI detects the pest and disease infestation as well as nutrient deficiency of fruits and vegetable crops and assists the farmers in taking management measures and thus optimizing yield and reducing the crop loss. Gardening can be made fully automatic with AI-driven robots. It also plays a major role in lawn management and landscaping. AI driven IoT system reduces the spoilage of the horticultural crops during transportation. AI also used to find that the fruit has been ripened naturally or

artificially and in identifying plant stress. AI-powered robots have been used for harvesting, pruning and weeding and thus automate the labor-intensive works. Additionally, AI is used in postharvest stages to monitor temperature, extend shelf life and maintain product quality.

Results and Discussion

The AI play versatile role in transforming agriculture and related fields. AI- driven solutions enable data-informed decision making, optimize resource utilization and enhance productivity across each area such as pest and disease management, precision and greenhouse farming, soil health monitoring, yield prediction, weather forecasting and irrigation management. In agriallied sectors, such as horticulture, fisheries, forestry, agricultural marketing, animal husbandry and food science-AI has facilitated disease detection in crops and livestock, streamlined supply chains and improved food safety practices.

However, challenges remain the widespread adoption of AI is hindered by high implementation costs, lack of infrastructure, low digital literacy, intermittent connectivity, data privacy, lack of trust in AI systems and resistance to adoption. In India, for example, the studies show that although AI-driven mobile advisory platforms have potential, farmers lack of trust in AI technologies, their low literacy level and those in rural areas tend not to use them. The key advantages of AI include efficient resource management, enhanced productivity and reduced environmental impact through precision practices.

Conclusion

Agriculture development is essential for a country's economic growth. Even developed countries priorities agricultural development. There is a great scope for agriculture development through innovation in agriculture and developing entrepreneurship amongst farmers. Educating the farmers through agri-extension services, print and digital media, organizing workshops, *etc*., promoting commercial crops, medicinal crops, floriculture crops and other plantation crops under different farming systems. The current article also emphasized innovations for sustainable development in agriculture to reap the benefits of improving livelihood, enhancing productivity, creating employment opportunities, industrial growth, food supply and increasing foreign trade.

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ADVANCED SOIL AND WATER CONSERVATION ENGINEERING FOR SUSTAINABLE AGRICULTURE

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Introduction

The global agricultural landscape is currently at a critical crossroads, facing the dual pressure of a burgeoning population-projected to reach nearly 10 billion by 2050—and a rapidly degrading natural resource base. At the heart of this challenge lies the management of soil and water, the two most fundamental pillars of terrestrial life and food production. Advanced Soil and Water Conservation Engineering (ASWCE) has emerged as a sophisticated, multidisciplinary field that transcends traditional "erosion control" to become the cornerstone of Sustainable Agriculture. Historically, conservation efforts were reactive, often limited to the construction of rudimentary physical barriers to slow down runoff. However, the modern engineering paradigm is proactive and integrative; it utilizes a systems-based approach that merges hydraulic engineering, soil physics, hydrology, and agronomy with cutting-edge digital technologies. This evolution is necessitated by the fact that soil is essentially a non-renewable resource on a human timescale, requiring centuries to form a few centimeters of topsoil, while freshwater availability for irrigation is increasingly threatened by over-exploitation and the erratic precipitation patterns driven by global climate change.

The "Advanced" nature of this discipline is defined by its transition from empirical, one-size-fits-all solutions to precision-engineered, site-specific interventions. In the contemporary era, the integration of Geospatial Technologies-including Geographic Information Systems (GIS), Remote Sensing (RS), and Global Positioning Systems (GPS)- allows engineers to model watershed behavior with unprecedented accuracy. We no longer simply build a terrace; we simulate the hydrologic response of a specific hillslope using digital elevation models (DEMs) and optimize the design to handle extreme weather events while maximizing biomass production. Furthermore, the advent of the Internet of Things (IoT) and Artificial Intelligence (AI) has introduced real-time monitoring into the conservation equation. Soil moisture sensors, automated weather stations, and drone-based multispectral imaging now provide a continuous stream of data, enabling "Smart Conservation." This allows for the dynamic management of resources, such as precision irrigation scheduling and the targeted application of soil conditioners, ensuring that every drop of water and every gram of nutrient is utilized with maximum efficiency, thereby minimizing the environmental footprint of farming operations.

Sustainability in this context is not merely an ecological buzzword but a rigorous engineering objective. Sustainable agriculture requires a "neutral-to-positive" impact on the environment,

meaning that the rate of soil formation and water recharge must meet or exceed the rate of extraction. Advanced conservation engineering achieves this by balancing Mechanical Measures with Biological Strategies. While mechanical structures like graded bunds, gabions, and advanced drop spillways provide the immediate structural stability needed to prevent catastrophic land degradation and gully formation, biological measures such as conservation tillage, cover cropping, and agroforestry ensure the long-term vitality of the soil matrix. These biological components improve soil organic carbon (SOC) levels, which enhance the soil's "sponge-like" capacity to hold water and resist the erosive energy of raindrops. By treating the soil as a living ecosystem rather than just a physical medium, advanced engineering fosters a regenerative cycle where increased soil health leads to better water infiltration, reduced runoff, and higher crop resilience against drought and floods.

Precision Digital Monitoring

Modern soil and water conservation engineering utilized advanced geospatial tools to track this soil health, Erosion at the millimeter level, Climate health of crops. Vegetation, etc.

Figure 1: Precision Digital Monitoring

1. Satellite Based Sensing

It has revolutionized how we monitor the earth's surface, shifting from reactive, ground-based Survey's to proactive, Data driven, and continuous monitoring. These technologies allow us to track structural changes, agriculture health, and resources with high precision.

- **InSAR (Interferometric Synthetic Aperture Radar):** Monitoring ground elevation InSAR is satellite-based radar technology that measures ground movement subsidence (sinking) or uplift (rising) with incredible Precision, often down to a few millimeters.
- **How it works:** SAR satellite (like sentinal-1, COSMO Sky Med) emit radar pulses (Microwaves) towards the earth and record the return signals strength (amplitude) and timing (phase).
- ➤ The "interferometry" aspect: - InSAR compares 2 or more images taken of the same spot at different times.
- ➤ Fringe Patterns: - A "Fringe" (Color changes in an inferogram) indicates a change in groundwater elevation. Each complete Color cycle usually represents half a wavelength of movement (e.g. ~2.8cm for C- band SAR).

Key Applications

- ➢ Ground subsidence monitoring
- ➢ Landslide detection
- ➢ Healthy infrastructure
- ➢ Volcanic activity

2. Drone based Sensing: (Multispectral Imagery)

While InSAR monitors structural changes in the land. multispectral Drone imagery focuses on the "health" of the surface Soil, water and vegetation with high resolution on demand data.

How it works: multispectral sensors: -Drones carry sensors that capture data across several specific bands of the electromagnetic spectrum. Not just a visible red, green and blue (RGB)

Key Spectral Bands

- ➢ Near infrared (NIR)
- ➢ Red Edge
- ➢ Thermal Infra-red
- ➢ Vegetation indices (VIs): -

NDVI (Normalized Difference Vegetation Index)

$$NDVI = \frac{NIR\text{-}RED}{NIR\text{+}RED}$$

Explanation: NDVI relies on the spectral signatures of green vegetation—high absorption of red light (0.6–0.7) by chlorophyll and high scattering of Near-Infrared (NIR) light (0.7–1.1) by leaf cell structure.

Interpretation:

- • 0.6 to 0.9: Dense, healthy vegetation.
- • 0.2 to 0.4: Sparse vegetation, shrubs, or grasslands.
- • < 0.1: Barren soil, rock, or snow.
- • Negative Values: Water bodies.
- • Applications: Crop yield estimation, drought monitoring, vegetation mapping.

PRI (Photochemical Reflectance Index)

$$PRI = \frac{R_{531} - R_{570}}{R_{531} + R_{570}}$$

(Utilizing narrow bands around 531 nm and 570 nm).

Explanation: PRI measures changes in the xanthophyll cycle pigments (zeaxanthin, antheraxanthin, and violaxanthin) which are closely linked to the efficiency of light-use in photosynthesis. When a plant is under stress (e.g., drought, high light), the pigment conversion causes a change in reflectance at 531 nm relative to a reference wavelength.

- • Interpretation: A higher (less negative) PRI value generally indicates higher photosynthetic efficiency, while a lower (more negative) value indicates stress.
- • Applications: Detecting water stress, measuring light-use efficiency (LUE), and monitoring photosynthetic performance

Agronomic Practices

Soil and water are the fundamental natural resources supporting agricultural production. However, increasing land degradation, soil erosion, declining groundwater levels, and climate variability have intensified the need for advanced soil and water conservation (SWC) strategies. While structural engineering measures such as bunds, terraces, check dams, and percolation tanks play a vital rol in controlling runoff and erosion, agronomic practices provide biological and management-based solutions that ensure long-term sustainability.

Agronomic measures modify crop cover, soil structure, root systems, and surface roughness, thereby influencing hydrological processes such as infiltration, evapotranspiration, runoff generation, and sediment transport. In India, research and promotion of these practices are strongly supported by institutions like the Indian Council of Agricultural Research and policy initiatives under the Ministry of Agriculture & Farmers Welfare.

1. Conservation Tillage & Minimum Soil Disturbance

- **No-Till / Zero-Tillage (Zero-Tillage):** This method involves planting directly into the undisturbed residue of the previous crop, without any plowing or harrowing.
  - ➢ Detailed Impact: It leaves the soil structure intact, allowing for better, permanent macro-pores that increase water infiltration. It acts as a shield, reducing water and wind erosion by up to 90% compared to conventional tillage.
  - ➢ Implementation: Seeders or planters cut a narrow slot in the soil to place the seed, often using specialized machinery. Weed control relies more on crop rotation or herbicides.

- **Reduced/Minimum Tillage:** A system that limits soil disturbance frequency and intensity, with the requirement that at least 30% of the soil surface remains covered with residue after planting.
  - ➢ Detailed Impact: It minimizes the impact of heavy rain (splashing) and wind, which are primary causes of erosion. It maintains higher soil organic matter and improves soil structure compared to conventional methods.
  - ➢ Implementation: Often uses tools like chisel plows or vertical tillage, which disturb the soil less deeply and do not turn the soil over.

- **Subsoiling/Deep Tillage:** A targeted, vertical tillage practice used to break up compacted subsoil layers, or "hardpan," often created by years of conventional trafficking.
  - ➢ Detailed Impact: It does not turn over the topsoil (maintaining surface residue) but rather penetrates deep into the ground (usually 10-20 inches) to break restrictive layers.
  - ➢ Benefits: It significantly improves deep root penetration and increases water infiltration and storage, which is crucial for maximizing crop yields in dryland farming areas.

2. Advanced Land Configuration (In-situ conservation)

i. Broad-Bed and Furrow (BBF) System

- Purpose: Developed by ICRISAT for Vertisols (black soil) to manage heavy rainfall (prevent waterlogging) and store moisture for the dry season (rabi).
- Structure: Consists of raised, wide beds (90-120 cm) for planting, separated by sunken, narrow furrows (50 cm) for drainage.

- Mechanism: During high rain, excess water drains into the furrows. In dry spells, roots access the subsoil moisture stored beneath the beds.
- Best for: Vertisols with high clay content prone to waterlogging.

ii. Compartmental Bunding

- Purpose: Maximize soil moisture storage in dryland/drought-prone black soils.
- Structure: The field is divided into small, enclosed, checkerboard-like compartments (ranging from 3x3m to 6x6m) using low-height, earthen bunds.
- Mechanism: Rainwater is trapped within each compartment, forcing it to infiltrate into the soil rather than running off. It ensures uniform water distribution across the field.
- Best for: Semi-arid regions with black soil for growing rabi crops on stored moisture.

iii. Contour Farming and Strip Cropping (Combined Approach)

- Contour Farming: Cultivation (plowing, sowing) is done across the slope (along lines of equal elevation) rather than up-and-down. This acts as a barrier to water flow.
- Strip Cropping: Alternating strips of crops.
- Erosion-permitting crops (e.g., maize, sorghum): Row crops that don't cover the soil fully.
- Erosion-resisting crops (e.g., legumes, groundnut): Close-growing crops that bind the soil.
- Mechanism: The contour lines slow down water velocity, while the dense, alternating strips act as filters, trapping soil particles and promoting infiltration.
- Best for: Slopy, erosion-prone lands.

3. Soil Cover and Residue Management

i. Organic/Stubble Mulching (Surface Covering)

- What it is: Leaving crop residues (straw, stalks, husks) on the soil surface after harvest rather than tilling them in or burning them.
- Detailed Action: Creates a physical barrier that intercepts raindrops, preventing soil particle detachment (splash erosion). It acts as insulation to keep soil cooler in summer and warmer in winter while drastically reducing water evaporation.
- Key Benefit: Builds organic matter, boosts soil moisture, and protects soil structure.

ii. Live/Green Mulching (Cover Cropping)

- What it is: Planting low-growing plants (legumes like cowpea, green gram) between rows of the main crop.
- Detailed Action: The cover crop acts as a "living blanket." It suppresses weeds by outcompeting them for light/nutrients, improves soil structure with roots, and fixes atmospheric nitrogen, reducing fertilizer needs.
- Key Benefit: Combines soil protection with fertility improvement and erosion control.

iii. Plastic Mulching (Synthetic Covering)

- What it is: Covering soil beds with specialized plastic films (usually black or reflective) in high-value horticulture (fruits/veg).
- Detailed Action: Forms an impermeable barrier. It eliminates surface evaporation, elevates soil temperature for faster crop maturity, prevents fruit rot (by separating plant from soil), and completely stops weed growth.
- Key Benefit: Maximizes water-use efficiency and crop yield in intensive farming.

v. Cropping Systems and Biological Barriers

- Diverse Crop Rotation & Intercropping: Alternating crops with different rooting depths to improve soil structure and water uptake efficiency.
- Vegetative Barriers/Strips: Planting hedges or stiff grasses (e.g., Vetiver, Napier) on contours to trap sediment and reduce runoff velocity.
- Alley Cropping: Planting agricultural crops between rows of permanent, leguminous, nitrogen-fixing trees or shrubs to reduce erosion and recycle nutrients.
- Agroforestry & Silvi-pasture: Integrating trees/shrubs and shrubs/grasses with crops or livestock to stabilize soil, especially in marginal or degraded lands.

vi. Advanced Water Management

- Micro-irrigation (Drip and Sprinkler): Delivering water directly to the root zone to maximize water use efficiency (WUE) and reduce soil erosion.
- In-situ Rainwater Harvesting: Using structures like farm ponds and checking dams to capture runoff for life-saving irrigation.
- Vertical Mulching: Filling trenches with crop stubble (e.g., sorghum) to act as intake points for runoff, guiding water into deeper soil layers.

vii. Soil Health Enhancements

- Bioengineering /Geotextiles: Utilizing natural, biodegradable mats (jute, coir) on steep or degraded slopes to stabilize soil and retain moisture.
- Organic Amendments: Regular application of compost, biochar, and vermicompost to increase organic carbon, improving aggregate stability and water-holding capacity.

Structural Measures

Soil and water are the two most critical natural resources for agricultural production. However, rapid population growth, intensive cultivation, deforestation, unscientific land use, and climate variability have accelerated land degradation and water scarcity across many regions of the world, particularly in semi-arid and tropical countries like India. Soil erosion by water and wind, declining groundwater levels, sedimentation of reservoirs, nutrient depletion, and increasing frequency of droughts and floods have made sustainable agriculture a major engineering and environmental challenge.

Structural measures in soil and water conservation engineering refer to permanent or semipermanent physical constructions designed to control runoff, reduce soil erosion, enhance groundwater recharge, and regulate water flow in agricultural landscapes. Unlike agronomic practices that focus on crop and soil management, structural measures physically modify land

topography, drainage patterns, and hydraulic behavior to stabilize the ecosystem. These measures form the backbone of watershed management and are essential for achieving long-term sustainability in rainfed and irrigated agriculture.

1. Contour and Graded Bunding
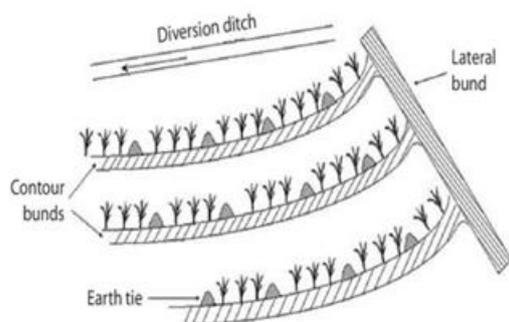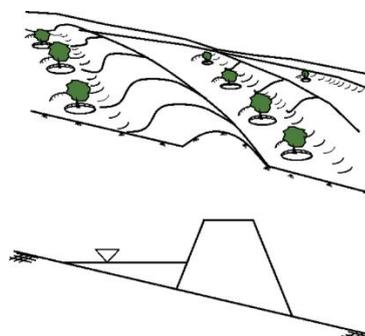

Contour Bunding   **Graded Bunding**

Bunding systems form the first line of defense in arable lands by breaking the slope length and reducing the kinetic energy of overland flow.

- Contour Bunding: Constructed strictly along contour lines, these earthen embankments are designed to impound runoff, allowing maximum time for infiltration. They are highly effective in highly permeable soils and areas with low annual rainfall (typically less than 600 mm).
- Graded Bunding: In areas with higher rainfall or relatively impermeable soils (like heavy clay or black cotton soils), retaining all water can cause crop waterlogging. Graded bunds are constructed with a precise longitudinal grade (usually 0.1% to 0.2%) to safely channel excess runoff toward a designated grassed waterway.

2. Terracing Systems

Terracing involves transforming a steep, continuous slope into a series of level or nearly level platforms, drastically altering the topographical and hydrological profile of the land.
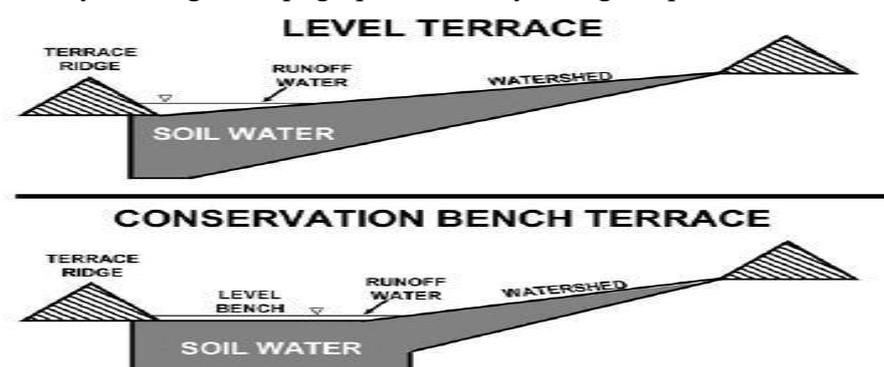
- Bench Terracing: Used on steep slopes (typically 16% to 33%), bench terraces convert the land into step-like fields. Depending on rainfall and soil drainage capabilities, they are designed as level (for highly permeable soils), inward-sloping (for high rainfall areas to safely channel water to a hillside ditch), or outward-sloping (for lower rainfall areas to maximize moisture retention).
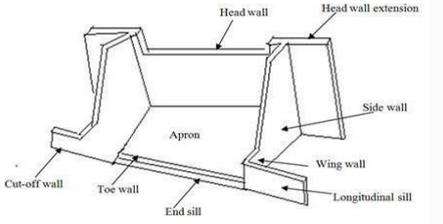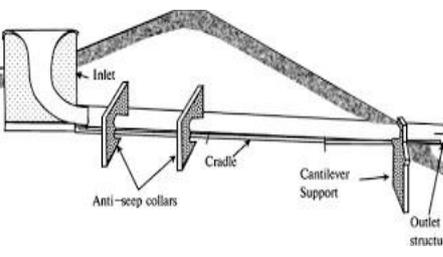
- Broad-Base Terraces: Designed for mechanized farming on gentler slopes, these terraces have a wide base and shallow channel, allowing agricultural machinery to operate smoothly over them.

3. Gully Control Structures (Grade Stabilization)

When rill erosion advances into gully erosion, massive soil displacement occurs. Engineering structures must be introduced to stabilize the gully bed profile, safely dissipate the kinetic energy of flowing water, and trap sediment.

- Hydrologic and Hydraulic Design Note: The design of permanent structures requires calculating the peak runoff rate, often utilizing the Rational Formula $q = CIA/360$ (where q is peak discharge in m^3/s, C is the runoff coefficient, I is rainfall intensity, and A is catchment area), followed by meticulous hydraulic and structural stability checks against overturning, sliding, and piping.

Table 1: Applications and design characteristics of Gully Control Structures

Application/Head Fall	Design Characteristics	Diagrams
Drop Spillway Low to medium falls (up to 3 meters)	Features a straight drop. Water flows over a weir, drops onto a stilling basin (apron) where the kinetic energy is dissipated through a hydraulic jump before continuing downstream.	
Drop-Inlet Spillway High head falls; often used in earth dams and road crossings.	Consists of a vertical riser pipe connected to a horizontal conduit through the embankment. Requires careful design to handle transitioning flow regimes (weir, orifice, and pipe flow).	
Chute Spillw Conveying water down steep slopes or deep gullies.	Water flows through an open channel at supercritical velocities. Energy dissipation at the toe is managed using SAF (St. Anthony Falls) or USBR stilling basins.	
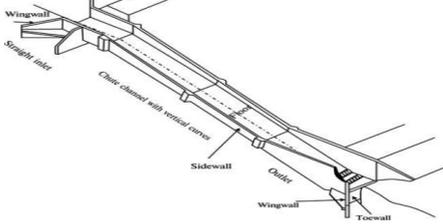
4. Runoff Harvesting and Recharge Structures

Sustainable agriculture relies heavily on maintaining groundwater tables and ensuring water availability during dry spells.

- Contour and Staggered Trenching: Excavated in non-arable lands or agroforestry systems, trenches intercept runoff. Staggered trenches are discontinuous and arranged in alternating rows, ensuring that water bypassing one trench is caught by the next.

- Percolation Tanks: Highly engineered earthen dams constructed across natural depressions. Their primary function is not surface storage but rather creating a hydraulic head to drive water into the aquifer. Deep understanding of the specific yield, transmissivity, and hydrodynamic dispersion of the underlying aquifer is critical for site selection.
- Farm Ponds: Excavated or embankment structures designed to capture localized farm runoff for life-saving irrigation during critical crop growth stages.

5. Advanced Subsurface Drainage

While we often focus on keeping water in the soil, sustainable agriculture in irrigated commands also requires safely removing excess water to prevent secondary salinization and waterlogging.

- Pipe and Tile Drains: Corrugated perforated pipes wrapped in synthetic, or gravel envelopes are installed below the root zone. These intercept the rising water table and safely discharge it, maintaining the aerated state of the soil.
- Mole Drainage: A specialized trenchless technique where a bullet-shaped plow creates unlined cylindrical channels in heavy clay soils. These channels function as temporary subsurface drains.

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CUSTARD APPLE AND KARONDA:

PROFITABLE ORCHARD SYSTEMS FOR SUSTAINABLE DRYLAND AGRICULTURE

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1. Dryland Horticulture and the Strategic Role of Minor Fruit Crops

Dryland agriculture represents one of the most extensive yet vulnerable production systems in the world. According to FAO (2019), drylands account for over 40 percent of the global land area and are characterized by erratic rainfall, high evapotranspiration, soil degradation, and frequent climatic stress. In India, nearly 68 percent of the cultivated area is rainfed, contributing substantially to national food production but with relatively low productivity compared to irrigated systems.

Conventional rainfed crops such as sorghum, pearl millet, and pulses often provide unstable returns under climate variability. Diversification toward perennial horticultural crops has therefore emerged as a viable strategy for enhancing income stability, ecological sustainability, and nutritional security. Fruit-based systems reduce soil erosion, enhance carbon sequestration, and improve microclimatic conditions compared to annual cropping systems.

Among underutilized fruit crops suited to semi-arid and arid ecosystems, custard apple (*Annona squamosa L.*) and karonda (*Carissa carandas L.*) are particularly promising. These species demonstrate remarkable tolerance to drought, adaptability to marginal soils, and comparatively low input requirements. Chadha (2001) emphasized the importance of minor fruit crops in strengthening sustainable horticulture in resource-constrained environments. Similarly, Pareek (2001) highlighted the role of hardy fruit species in arid and semi-arid agro-ecosystems for improving farmer income.

The economic potential of fruit-based dryland systems is further supported by National Horticulture Board (NHB, 2022) statistics, which indicate increasing area and production under minor fruits, reflecting growing market demand and farmer adoption.

2. Botanical Features and Genetic Resources

2.1 Custard Apple (*Annona squamosa L.*)

Custard apple belongs to the family Annonaceae and is believed to have originated in tropical America before spreading widely across India. The plant is a small semi-deciduous tree reaching 4–8 meters in height. It possesses a deep taproot system that enables efficient extraction of soil moisture from deeper horizons, contributing to drought resilience.

The leaves are simple, alternate, and oblong-lanceolate. Flowers are hermaphrodite and exhibit protogynous dichogamy, a trait that often limits natural fruit set. The fruit is an aggregate

syncarp composed of loosely fused carpels. Mature fruits typically weigh between 200 and 500 grams and contain creamy pulp with total soluble solids ranging from 15 to 22°Brix (Morton, 1987). Natural fruit set is generally low due to asynchronous pollen release and stigma receptivity. However, improved cultivars such as 'Balanagar' and 'Arka Sahan' have demonstrated enhanced productivity and fruit quality under Indian conditions (Chadha, 2001).

2.2 Karonda (*Carissa carandas L.*)

Karonda belongs to the family Apocynaceae and is indigenous to the Indian subcontinent. It is a hardy evergreen shrub or small tree growing 2–5 meters tall with characteristic forked thorns. The plant thrives under harsh climatic conditions and tolerates degraded and slightly saline soils. The flowers are fragrant, white to pink, and borne in clusters. The fruits are berry-type, rich in vitamin C and iron, and contain moderate total soluble solids with relatively high acidity, making them particularly suitable for pickling and processing (Morton, 1987). Pareek (2001) noted that karonda is one of the most adaptable minor fruits for arid and semi-arid regions due to its hardiness and low management requirements. Both crops possess significant genetic variability. Indigenous germplasm collections maintained by ICAR institutes provide valuable resources for future breeding aimed at improving yield, fruit quality, and stress tolerance.

3. Production Technology for Dryland Orchards

Successful cultivation of custard apple and karonda under dryland conditions depends on careful site selection, propagation techniques, nutrient management, and moisture conservation.

Both crops perform well in regions receiving 500–1200 mm annual rainfall with well-drained soils. Custard apple prefers sandy loam to clay loam soils with pH between 5.5 and 8.0, whereas karonda tolerates a wider pH range and relatively poorer soils (Chadha, 2001).

Vegetative propagation ensures uniformity and early bearing. Custard apple is commonly propagated through softwood grafting and budding techniques. Karonda is propagated by seed, air-layering, and grafting, though vegetative methods are preferred for maintaining varietal purity (Pareek, 2001).

Orchards are generally established at spacings of 5 × 5 meters for custard apple and 4 × 4 meters for karonda. Incorporation of well-decomposed farmyard manure during pit preparation enhances soil structure and microbial activity. During the juvenile phase, intercropping with legumes can improve soil fertility and provide additional income.

Integrated nutrient management involving organic manures and balanced fertilization supports sustainable productivity. Although both crops are drought tolerant, supplemental irrigation during flowering and fruit development significantly enhances yield. Mulching, contour bunding, and in-situ rainwater harvesting are effective strategies for moisture conservation in dryland orchards (FAO, 2019).

4. Plant Protection, Harvesting and Value Addition

Major pests affecting custard apple include fruit borers and mealybugs, while karonda is relatively less susceptible to severe pest infestations. Anthracnose may occur in humid conditions, particularly during the flowering and fruiting stages. Integrated pest management

involving orchard sanitation, pruning, and biological control agents helps maintain ecological balance.

Harvesting at appropriate maturity is critical for maintaining fruit quality. Custard apple fruits are harvested when segments are fully developed and slight softening is observed. Karonda fruits are harvested at different stages depending on intended use—immature fruits for pickling and mature fruits for fresh consumption or processing (Morton, 1987).

Value addition significantly enhances economic returns. Custard apple pulp is widely used in beverages, desserts, and frozen products. Karonda is processed into pickles, jams, jellies, and candies due to its high acidity and pectin content. Development of small-scale processing units in rural areas can generate employment and reduce post-harvest losses.

5. Economic Potential, Constraints and Future Outlook

Fruit-based dryland systems offer higher profitability compared to conventional rainfed cropping systems. According to NHB (2022), minor fruit crops are gaining commercial importance due to increasing urban demand and processing opportunities. Custard apple and karonda orchards typically begin economic bearing within three to four years and remain productive for two decades or more.

Despite their potential, certain constraints remain. Low fruit set in custard apple, limited organized marketing channels, and inadequate post-harvest infrastructure hinder full commercialization. Strengthening farmer producer organizations, expanding cold storage facilities, and promoting processing enterprises can address these challenges.

Future research should focus on improving fruit set through better pollination management, enhancing drought tolerance through rootstock development, and extending shelf life through improved post-harvest technologies. As emphasized by Chadha (2001) and Pareek (2001), minor fruit crops hold immense potential for sustainable horticultural development in arid and semi-arid regions.

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