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ADVANCES IN SUSTAINABLE AGRICULTURE AND ALLIED SCIENCES VOLUME II

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Advances in Sustainable Agriculture and Allied Sciences Volume II

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PREFACE

The growing challenges of climate change, resource depletion, biodiversity loss, and food insecurity have underscored the urgent need for sustainable approaches in agriculture and allied sciences. *Advances in Sustainable Agriculture and Allied Sciences, Volume II* is a continuation of our commitment to explore innovative, practical, and research-driven solutions that promote environmental stewardship while ensuring agricultural productivity and resilience.

This volume brings together a diverse collection of scholarly contributions from researchers, academicians, and practitioners across various disciplines. The chapters reflect recent advancements in sustainable farming practices, soil health management, integrated pest management, climate-smart agriculture, agroecology, and the application of modern technologies such as biotechnology, precision agriculture, and data-driven decision-making systems. Additionally, significant emphasis has been placed on allied sectors including fisheries, animal husbandry, horticulture, and agroforestry, recognizing their crucial role in strengthening rural livelihoods and ensuring holistic agricultural development.

One of the key strengths of this volume lies in its interdisciplinary approach, bridging traditional knowledge systems with modern scientific innovations. The contributors have provided insights into sustainable resource utilization, conservation strategies, and policy perspectives that are essential for addressing current and future agricultural challenges. Case studies, experimental research, and review articles included in this book offer valuable perspectives for both academic research and field-level applications.

We believe that this volume will serve as a valuable resource for students, researchers, policymakers, and stakeholders involved in agriculture and allied sciences. It aims not only to disseminate knowledge but also to inspire collaborative efforts toward building a more sustainable and resilient agricultural future.

We express our sincere gratitude to all authors, reviewers, and contributors for their dedicated efforts and scholarly inputs. We also acknowledge the support of the publishing team in bringing out this volume successfully. We hope this book will contribute meaningfully to the advancement of sustainable agriculture and scientific research.

- Editors

TABLE OF CONTENT

Sr. No.	Book Chapter and Author(s)	Page No.
1.	BIOCHAR PRODUCTION FROM TEA PRUNING RESIDUES: A SUSTAINABLE APPROACH FOR SOIL HEALTH AND CARBON SEQUESTRATION Beatris Topno and Supriya Sonowal	1 – 5
2.	BIO-INSPIRED MICRO AERIAL SYSTEMS FOR POLLINATION AND SMART CROP MONITORING IN SUSTAINABLE AGRICULTURE Vijayakumar P and Rajasubramanian V	6 – 22
3.	PRECISION WATER MANAGEMENT IN SMART AND SUSTAINABLE AGRICULTURAL SYSTEMS S. Praveena, Sridhara M R, A. Uma Maheswari and J. Krupa Amrutha	23 – 39
4.	SPIDERS AS POTENTIAL BIOLOGICAL PEST CONTROLLERS IN AGROECOSYSTEMS OF MAHARASHTRA: A REVIEW Prashant Dharmanand Kamble	40 – 46
5.	AGRITEC INNOVATION IDENTIFIED BY GLOBAL RESEARCH AND DEVELOPMENT ON SERIC SECTOR Sanjai Kumar Gupta	47 – 68
6.	INFERENCE STATISTICS: FROM SAMPLE TO POPULATION INSIGHTS Girish Mahajan	69 – 83
7.	PROBABILITY AND RANDOM EXPERIMENTS: BASICS OF UNCERTAINTY Girish Mahajan	84 – 93
8.	SUSTAINABLE AGRICULTURAL PRACTICES FOR A FOOD SECURE INDIA Ranjana Roy Mishra	94 – 102
9.	ADVANCES IN SUSTAINABLE AGRICULTURE IN INDIA: ROLE OF AGRITECH, PRECISION FARMING TECHNIQUES AND GOVERNMENT INITIATIVES DRIVING SUSTAINABILITY Sasikumar S	103 – 108

10.	PLANT-DERIVED BIOACTIVES IN AGRICULTURE: FUNDAMENTALS, CLASSIFICATION, MECHANISMS, APPLICATIONS, AND FUTURE PROSPECTS Siddhesh Santosh Bandekar, Vrushali Vijay Patil, M. S. Palled and Shailendra Sanjay Suryawanshi	109 – 115
11.	CLIMATE SMART SOIL AND WATER CONSERVATION STRATEGIES FOR SUSTAINABLE AGRICULTURE Ajith Mali Patil, Sarika Wandre, Mangal Patil and Vinayak Shinde	116 – 123
12.	CIRCULAR ECONOMY APPROACHES IN AGRI-WASTE UTILIZATION: A COMPREHENSIVE REVIEW K. Prabhu	124 – 134
13.	MICROBIAL DIVERSITY AND NUTRIENT TRANSFORMATION IN AGRICULTURAL ECOSYSTEMS Priyanka Kande Patil	135 – 145
14.	MICROBIAL CONSORTIA IN SUSTAINABLE AGRICULTURE: INTEGRATIVE ROLES IN BIOFERTILIZATION AND BIOPESTICIDE DEVELOPMENT Poojasri Sowndarajan, Bhuvanewari Shanmugam and Deepthi Sri Sathiyamurthy	146 – 153
15.	BIODEGRADABLE MULCHES AS SUSTAINABLE ALTERNATIVES TO PLASTIC MULCHING IN AGRICULTURE Deepthi Sri Sathiyamurthy, Sai Sakthi Sridevi Kumaran, Bhuvanewari Shanmugam and Poojasri Sowndarajan	154 – 161
16.	TEMPORAL TREND OF SUGARCANE AREA IN MAHARASHTRA Samadhan Surwase, Abhinandan Patil, Anil Mundhe, Prakash Kadu and Ashok Kadlag	162 – 169

BIOCHAR PRODUCTION FROM TEA PRUNING RESIDUES: A SUSTAINABLE APPROACH FOR SOIL HEALTH AND CARBON SEQUESTRATION

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Abstract

Tea plantations produce a large amount of biomass every year, mainly in the form of pruning residues. In many cases, this material is either burned or left unused, leading to environmental concerns such as air pollution and greenhouse gas emissions. At the same time, this biomass represents a valuable resource that can be utilized more efficiently. One practical and eco-friendly approach is converting tea pruning residues into biochar. Biochar is a stable, carbon-rich product obtained by heating organic material in a limited oxygen environment. Its application in soil has shown multiple benefits, including improved soil fertility, better water retention, and enhanced microbial activity. More importantly, biochar acts as a long-term carbon storage material, helping reduce atmospheric carbon levels. This chapter focuses on the availability of tea pruning residues, methods of converting them into biochar, and their role in improving soil properties and storing carbon. It also discusses findings from recent studies and highlights the environmental and economic advantages of adopting biochar-based practices in tea cultivation systems.

1. Introduction

Tea (*Camellia sinensis* L.) is one of the most widely cultivated plantation crops, and India is among the leading producers globally. Within India, Assam plays a particularly important role in tea production, contributing significantly to both domestic use and export. During the cultivation of tea, regular pruning is carried out to maintain plant shape, encourage fresh growth, and sustain yield. This process generates a considerable amount of plant material such as leaves, twigs, and woody stems. Traditionally, farmers either burn this biomass or allow it to decompose naturally in the field. Although natural decomposition helps return some nutrients to the soil, it is not always efficient. Nutrients can be lost during the process, and gases like carbon dioxide and nitrous oxide may be released into the atmosphere. Burning, on the other hand, causes direct environmental pollution and wastes valuable organic matter. With the growing emphasis on sustainable agriculture, attention has shifted toward converting such residues into useful products. One promising method is transforming tea pruning waste into biochar, which not only improves soil health but also contributes to climate change mitigation.

2. Tea Pruning Residues: Availability and Potential

Tea estates generate a substantial quantity of pruning residues every year. These materials are mainly composed of lignocellulosic compounds and contain nutrients such as nitrogen, potassium, and trace elements. However, if these residues are not managed properly, they can create environmental issues. Studies have indicated that simply incorporating raw residues into soil may increase emissions of gases like nitrous oxide, which has a strong warming effect on the climate. Instead of allowing these materials to go to waste, converting them into biochar offers a more efficient solution. This process stabilizes the carbon present in the biomass and reduces harmful emissions, while also producing a material that improves soil quality.

3. Biochar Production from Tea Pruning Residues

3.1 Concept of Biochar

Biochar is formed when organic materials are heated at high temperatures in an environment with very little oxygen. This process, known as pyrolysis, converts unstable organic compounds into a more stable carbon form that breaks down very slowly in soil. Because of its stability, biochar can remain in the soil for a long time, making it useful both for improving soil properties and for storing carbon.

3.2 Production Process

The preparation of biochar from tea pruning residues generally involves a few basic steps:

- Collection of pruning materials from the field
- Drying to reduce moisture content
- Cutting or crushing into smaller pieces
- Heating at temperatures ranging from 300°C to 500°C under limited oxygen conditions
- Cooling and storing the final product

Experiments conducted in tea-growing regions like Assam have shown that both traditional methods (such as earthen kilns) and improved systems (like controlled furnaces) can be used effectively to produce good-quality biochar from tea waste.

3.3 Properties of Tea-Based Biochar

Biochar made from tea residues has several useful characteristics:

- It has a highly porous structure
- It generally shows an alkaline reaction
- It can hold nutrients effectively due to high cation exchange capacity
- It improves water retention in soil

These features make it especially suitable for use in tea-growing areas, where soils are often acidic and may require improvement.

4. Impact of Biochar on Soil Health

4.1 Chemical Properties of Soil

When biochar is added to soil, it can improve nutrient availability and reduce nutrient loss. It often raises soil pH, which helps in reducing acidity and improving the uptake of essential nutrients by plants. Research findings indicate that biochar application can increase the levels of important nutrients such as phosphorus, potassium, and magnesium. It also helps in reducing nutrient leaching, thereby improving the efficiency of fertilizers.

4.2 Physical Properties of Soil

The structure of biochar plays an important role in improving soil physical conditions. Its porous nature helps in increasing soil aeration and reducing compaction. This allows plant roots to grow more easily. In addition, biochar improves the ability of soil to retain water, which is particularly useful in areas facing irregular rainfall or drought conditions.

4.3 Biological Properties of Soil

Biochar also has a positive effect on soil microorganisms. Its porous surface provides a suitable habitat for beneficial microbes, which play a key role in nutrient cycling. Studies have shown that soils treated with biochar often exhibit higher microbial activity and diversity, which contributes to overall soil health and productivity.

4.4 Reduction of Soil Contaminants

Another important advantage of biochar is its ability to bind harmful substances. It can reduce the availability of toxic elements such as arsenic, cadmium, and chromium in the soil. This helps in lowering the uptake of these elements by tea plants, ultimately improving the safety and quality of the final product.

5. Biochar and Carbon Sequestration

One of the most significant benefits of biochar is its role in carbon storage. During pyrolysis, a large portion of carbon in the biomass is converted into a stable form that remains in the soil for a long time. Compared to raw biomass, biochar produces fewer greenhouse gas emissions when applied to soil. Research has shown that using biochar derived from tea residues can significantly reduce emissions of nitrous oxide. By increasing soil organic carbon levels and storing carbon for extended periods, biochar contributes to reducing the impact of climate change.

6. Application of Biochar in Tea Plantations

Biochar can be used in tea fields in several ways:

- Mixing with soil during planting
- Applying around the base of tea bushes
- Combining with compost or organic manures

Field observations suggest that the use of biochar improves soil condition, enhances nutrient availability, and may lead to better crop yield and quality. It can also reduce the reliance on chemical fertilizers, supporting more sustainable farming practices.

7. Environmental and Economic Benefits

7.1 Environmental Benefits

- Utilization of agricultural waste
- Reduction in greenhouse gas emissions
- Improvement in soil quality and biodiversity
- Long-term storage of carbon in soil

7.2 Economic Benefits

- Lower expenditure on fertilizers
- Conversion of waste into valuable input
- Possibility of earning through carbon credit schemes

Overall, biochar supports a circular approach to agriculture by turning waste into a useful resource.

8. Challenges and Limitations

Despite its advantages, the use of biochar is not yet widespread. Some of the main challenges include:

- Initial cost of setting up production systems
- Limited awareness among farmers
- Differences in quality depending on production method
- Lack of large-scale field studies in tea plantations

To overcome these issues, there is a need for better research support, awareness programs, and policy-level encouragement.

9. Prospects

The use of biochar in tea cultivation has strong potential for growth. Future developments may include:

- Combining biochar with microbial biofertilizers
- Designing low-cost production technologies
- Expanding its use in large plantation areas
- Including biochar practices in climate-smart agriculture policies

With continued innovation, biochar can become an important part of sustainable tea production.

Conclusion

Converting tea pruning residues into biochar offers an effective way to manage agricultural waste while improving soil health. Biochar enhances soil structure, supports microbial activity, and helps store carbon for long periods. Its use in tea plantations can increase productivity, reduce environmental impact, and support sustainable farming systems. With proper awareness and supportive policies, biochar has the potential to play a major role in future tea cultivation practices.

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BIO-INSPIRED MICRO AERIAL SYSTEMS FOR POLLINATION AND SMART CROP MONITORING IN SUSTAINABLE AGRICULTURE

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Abstract

Sustainable agriculture requires innovative technological solutions capable of improving productivity while minimizing environmental degradation and resource consumption. Bio-inspired micro aerial vehicles (MAVs) have emerged as promising tools that combine aeronautical engineering, robotics, and agricultural science. These systems mimic biological flight mechanisms observed in insects and birds and enable advanced agricultural applications such as crop monitoring, artificial pollination, and environmental sensing. Zhang and Kovacs (2012) explained that unmanned aerial vehicles significantly improve precision agriculture by enabling high-resolution crop monitoring and optimized resource utilization. Tsouros *et al.* (2019) further reported that UAV-based sensing systems enhance crop monitoring efficiency and reduce operational costs. Recent advances in artificial intelligence, lightweight sensors, and swarm robotics have expanded the capabilities of UAV systems. Wood *et al.* (2013) demonstrated the feasibility of insect-scale robotic flyers capable of stable hovering and manoeuvrability. These MAV systems enable plant-level monitoring and precision farming applications. This chapter examines the interdisciplinary integration of aeronautical engineering and sustainable agriculture through bio-inspired aerial robotics. Aerodynamic modelling, computational fluid dynamics analysis, payload optimization, mission planning, and droplet aerodynamics are discussed to highlight the engineering foundations of UAV-based agricultural technologies.

Keywords: Micro Aerial Vehicles, Precision Agriculture, Pollination Robotics, Aerodynamic Modelling, Swarm Robotics, Smart Farming.

1. Introduction

Agriculture plays a critical role in ensuring global food security, supporting rural livelihoods, and sustaining economic stability across many regions of the world. As the primary source of food production, agriculture not only provides essential nutritional resources but also contributes significantly to employment and national economies, particularly in developing countries. However, modern agricultural systems are increasingly facing complex challenges that threaten their sustainability and productivity. These challenges include climate variability, soil degradation, declining biodiversity, water scarcity, and rapid population growth. Climate change has led to irregular rainfall patterns, prolonged droughts, and extreme weather events, all of

which significantly affect crop growth cycles and agricultural yields. At the same time, excessive use of chemical fertilizers and pesticides has contributed to soil nutrient depletion and environmental contamination, further complicating the long-term sustainability of agricultural production systems.

According to the Food and Agriculture Organization (FAO, 2022), global agricultural productivity must increase substantially in order to meet the rising food demands of the growing population. The United Nations (2023) estimated that the global population may reach approximately 9.7 billion by the year 2050. This population expansion will place enormous pressure on existing agricultural resources, including arable land, freshwater supplies, and energy resources. Consequently, the agricultural sector must adopt innovative technologies and sustainable practices to enhance productivity while minimizing environmental impacts.

Traditional agricultural practices often rely on uniform field management strategies, where fertilizers, pesticides, and irrigation water are applied evenly across entire fields regardless of variations in soil fertility, crop health, or moisture levels. Such practices frequently result in inefficient resource utilization, increased production costs, and unnecessary environmental pollution. For instance, excessive fertilizer application can lead to nutrient runoff into nearby water bodies, causing eutrophication and ecological damage. Similarly, uniform pesticide application may expose non-target organisms to harmful chemicals while failing to effectively control localized pest outbreaks.

To address these limitations, precision agriculture has emerged as a promising technological approach that integrates advanced sensing, data analytics, and automated farming systems to optimize agricultural productivity. Precision agriculture aims to manage spatial variability within agricultural fields by applying the right amount of resources at the right place and time. Technologies such as global positioning systems (GPS), geographic information systems (GIS), remote sensing, and unmanned aerial vehicles (UAVs) have become essential tools for implementing precision farming practices.

Zhang and Kovacs (2012) demonstrated that UAV-based remote sensing technologies provide high-resolution spatial imagery capable of monitoring crop conditions with exceptional accuracy. UAV platforms equipped with multispectral, hyperspectral, and thermal sensors can capture detailed information about plant health, canopy temperature, soil moisture, and vegetation indices such as the Normalized Difference Vegetation Index (NDVI). These data enable farmers to identify nutrient deficiencies, irrigation requirements, and disease outbreaks at early stages. Early detection of crop stress allows farmers to implement targeted interventions, reducing resource waste and improving overall farm efficiency.

Furthermore, UAV technology significantly reduces the time and labor required for field inspections compared with traditional manual monitoring methods. Large agricultural areas that would normally require several days of field surveys can now be analyzed within a few hours

using UAV-based aerial imaging systems. The integration of UAV data with artificial intelligence and machine learning algorithms further enhances the capability of precision agriculture systems. These intelligent systems can automatically analyze crop images, detect anomalies, predict yield outcomes, and provide decision-support recommendations for farmers. Another major concern affecting agricultural productivity is the decline in pollinator populations. Potts *et al.* (2016) reported substantial global reductions in bee populations due to pesticide exposure and habitat loss. Bio-inspired aerial robots have therefore been proposed as a potential technological solution for artificial pollination and crop monitoring.

2. Integration of Aeronautical Engineering with Smart Agriculture

UAV platforms equipped with advanced sensing technologies such as multispectral cameras, thermal imaging sensors, hyperspectral scanners, and environmental monitoring devices play a critical role in modern precision agriculture. These aerial systems are capable of capturing high-resolution spatial and spectral data from agricultural fields, enabling detailed assessment of crop health and environmental conditions. Multispectral sensors measure reflectance in different wavelength bands, allowing the calculation of vegetation indices such as the Normalized Difference Vegetation Index (NDVI), which is widely used to evaluate plant vigor and photosynthetic activity.

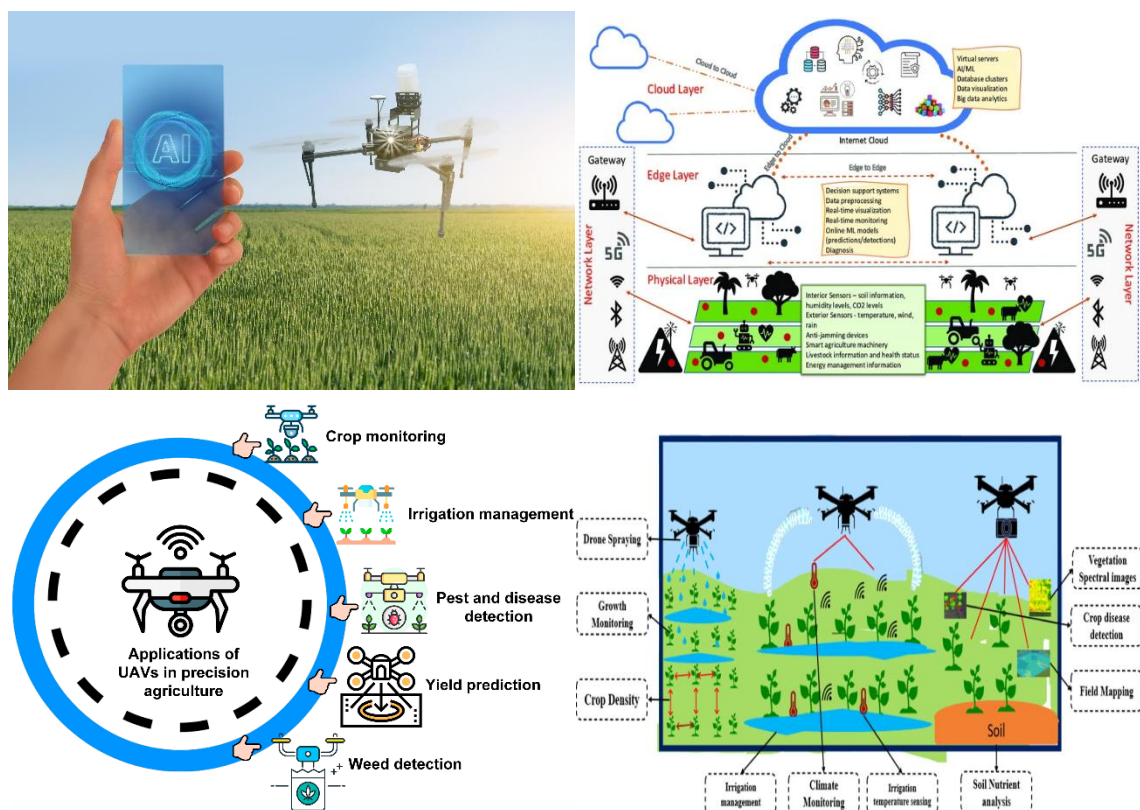


Figure 1: Integration of UAV Technology with Smart Agriculture Systems

Thermal cameras detect variations in canopy temperature, which can indicate plant water stress, irrigation inefficiencies, or disease onset. In addition, environmental sensors integrated into UAV platforms can measure parameters such as air temperature, humidity, and atmospheric pressure,

providing valuable context for crop growth analysis. Fig 1 explains Integration of UAV Technology with Smart Agriculture Systems

The data collected by UAV systems are typically transmitted to cloud-based computing platforms where advanced data processing and machine learning algorithms are applied. Artificial intelligence techniques, including deep learning and image classification models, analyze aerial imagery to detect crop stress, nutrient deficiencies, pest infestations, and disease outbreaks at early stages. These analytical results are integrated into decision-support systems that generate actionable recommendations for farmers.

Furthermore, the integration of UAV monitoring systems with Internet of Things (IoT) sensors and farm management software enables the development of real-time smart farming ecosystems. Data from UAV flights can be combined with ground-based sensor networks, weather forecasts, and satellite imagery to create comprehensive crop monitoring platforms. These integrated systems allow continuous tracking of crop development throughout the growing season and support predictive modelling for yield estimation and risk management. As a result, UAV-based data acquisition and cloud-based AI analytics are transforming conventional farming practices into highly efficient, data-driven agricultural systems that promote sustainability, resource optimization, and improved crop productivity.

3. Bio-Inspired Aerodynamics in MAVs

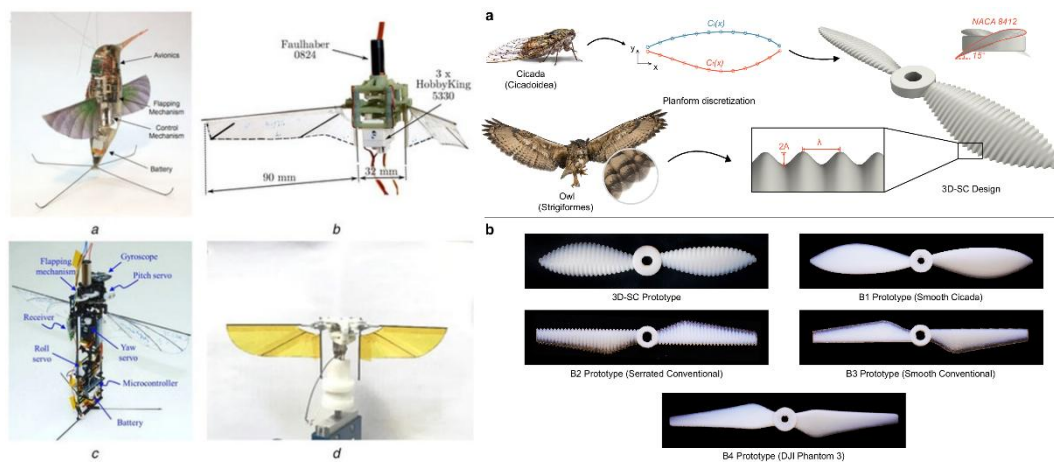


Figure 2: Bio-Inspired Flapping Wing Micro Aerial Vehicle

Ellington (1984) conducted pioneering research on the aerodynamics of insect flight and demonstrated that insects generate lift through complex unsteady aerodynamic mechanisms rather than conventional steady-state aerodynamics used in fixed-wing aircraft. One of the most significant phenomena identified in his studies is the formation of leading-edge vortices (LEVs) during the flapping motion of insect wings. When an insect moves its wings in a rapid flapping motion, the airflow separates at the leading edge of the wing and forms a rotating vortex. This vortex creates a region of low pressure above the wing surface, significantly increasing lift generation beyond what would be predicted by conventional aerodynamic theory. Fig 2 shows bio-inspired flapping wing micro aerial vehicle.

Unlike traditional aircraft wings that rely on continuous forward motion to generate lift, insect wings operate in low Reynolds number flow regimes, typically ranging between 10^3 and 10^5 . In these conditions, unsteady aerodynamic effects become dominant. The leading-edge vortex remains attached to the wing during the downstroke phase, allowing insects to maintain high lift coefficients even at low flight speeds. Ellington (1984) showed that this vortex stability enables insects to generate lift forces that exceed their body weight, making hovering flight possible.

Another important mechanism identified in Ellington's work is the rotational circulation generated during wing rotation at the end of each stroke. As the wing changes direction between the downstroke and upstroke phases, additional vortices are produced that further enhance lift production. This unsteady aerodynamic interaction between wing motion and surrounding airflow significantly improves flight efficiency. Furthermore, the interaction between successive wing strokes creates a wake capture effect, where insects can recover energy from previously generated airflow structures.

These aerodynamic mechanisms have inspired the development of bio-inspired flapping-wing micro aerial vehicles (MAVs). Engineers and researchers study insect flight dynamics to design MAV platforms capable of hovering, maneuvering in confined environments, and operating efficiently at small scales. By mimicking the flapping motion and vortex generation mechanisms observed in insects, MAV systems can achieve enhanced lift generation and improved aerodynamic efficiency compared with conventional rotary-wing drones operating at similar scales.

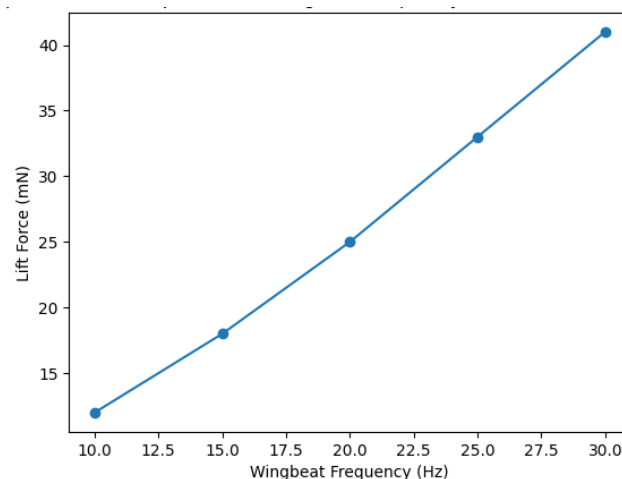


Figure 3: Relationship Between Wingbeat Frequency and Lift Generation in Micro Aerial Vehicles

Figure 3 illustrates the relationship between wingbeat frequency (Hz) and the lift force generated (mN) in flapping-wing micro aerial vehicles (MAVs). The graph shows a clear positive relationship between the two variables, indicating that as the wingbeat frequency increases, the lift generated by the system also increases.

At lower frequencies, such as 10 Hz, the MAV generates relatively small lift forces (approximately 12 mN). This level of lift is typically insufficient to support sustained hovering flight for most MAV systems. As the wingbeat frequency increases to 15 Hz, the lift force increases to around 18 mN, demonstrating the direct impact of wing motion speed on aerodynamic performance.

A more significant increase in lift occurs between 20 Hz and 30 Hz, where lift values rise from 25 mN to 41 mN. This rapid growth in lift generation is primarily due to stronger leading-edge vortex formation around the flapping wing surface. When wings oscillate faster, airflow separation at the leading edge produces stable vortices that create low-pressure regions above the wing surface, thereby enhancing lift production. This aerodynamic phenomenon is commonly observed in insect flight and is a key principle used in the design of bio-inspired MAVs.

The graph also highlights an important operational range for MAV flight stability, which typically occurs between 20 Hz and 30 Hz. Within this frequency range, lift generation becomes sufficient to balance the gravitational force acting on the vehicle, allowing stable hovering or slow forward flight. Engineers designing MAV systems often optimize wing geometry, stroke amplitude, and flapping frequency within this range to maximize aerodynamic efficiency.

From an engineering perspective, the relationship shown in Graph.1 emphasizes the importance of flapping frequency optimization in MAV design. Increasing frequency improves lift generation; however, it also increases power consumption and mechanical stress on wing structures. Therefore, MAV designers must balance lift performance with energy efficiency and structural durability. Overall, the graph demonstrates that wingbeat frequency is one of the most critical parameters influencing lift generation in bio-inspired flapping-wing aerial systems, making it a key design variable in the development of agricultural micro aerial vehicles for crop monitoring and pollination applications.

4. Aerodynamic Modelling of MAV Flight

Lift equation:

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

The lift equation represents the fundamental aerodynamic relationship used to estimate the lift force generated by a wing or airfoil moving through a fluid medium such as air. Lift is the aerodynamic force that acts perpendicular to the direction of airflow and is essential for maintaining flight in aerial vehicles, including micro aerial vehicles (MAVs) used in agricultural applications.

In this equation:

- L represents the lift force generated by the wing or airfoil (N).
- ρ denotes the density of the surrounding air (kg/m^3). Air density influences the aerodynamic forces acting on the wing because denser air contains more mass, allowing greater momentum exchange with the wing surface.

- V represents the velocity of the airflow relative to the wing (m/s). The lift force increases proportionally to the square of the velocity, indicating that even small increases in flight speed can significantly enhance lift generation.
- S denotes the wing surface area (m²). Larger wing areas provide greater surface exposure to airflow, enabling the generation of stronger aerodynamic forces.
- C_L is the lift coefficient, a dimensionless parameter that characterizes the aerodynamic performance of the wing. It depends on factors such as wing shape, angle of attack, Reynolds number, and airflow characteristics.

The lift equation demonstrates that lift generation depends on both aerodynamic design parameters and flight conditions. In conventional aircraft, lift is primarily produced through steady airflow over fixed wings. However, in bio-inspired micro aerial vehicles, lift generation often involves unsteady aerodynamic mechanisms such as flapping wing motion, vortex formation, and wake interaction. These mechanisms can significantly increase the effective lift coefficient compared with traditional fixed-wing configurations.

For MAV systems operating at low Reynolds numbers, the lift equation still provides a useful approximation for aerodynamic analysis, although additional factors such as vortex dynamics and wing flexibility must also be considered. Engineers designing agricultural MAV platforms often use the lift equation during the initial stages of aerodynamic modelling to estimate wing dimensions, determine optimal flight speeds, and evaluate payload capacity.

Understanding the relationship between airflow velocity, wing area, and lift coefficient is essential for optimizing the performance of MAV systems used in agricultural applications such as crop monitoring, pollination assistance, and aerial spraying. By adjusting these parameters, engineers can design UAV platforms capable of stable flight while carrying sensors, cameras, and other agricultural monitoring equipment.

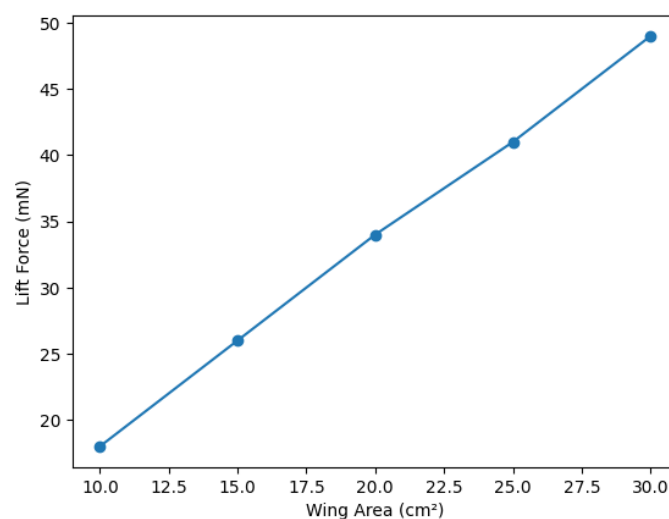


Figure 4: Relationship Between Wing Area and Lift Generation in Micro Aerial Vehicles

Figure 4 illustrates the relationship between wing surface area and the lift force generated in micro aerial vehicles (MAVs). The graph demonstrates a direct positive correlation between the

two parameters, indicating that as the wing area increases, the lift generated by the aerodynamic surface also increases.

At a smaller wing area of 10 cm², the generated lift is approximately 18 mN, which represents the minimum lift capability of the system. As the wing area increases to 15 cm², the lift increases to about 26 mN, indicating a significant improvement in aerodynamic performance. Further increases in wing area to 20 cm², 25 cm², and 30 cm² correspond to lift values of 34 mN, 41 mN, and 49 mN, respectively.

From an engineering perspective, this relationship highlights the importance of wing geometry optimization in MAV design. Increasing wing area improves lift production and payload capability; however, excessively large wings may increase structural weight and aerodynamic drag. Therefore, designers must balance wing size with structural efficiency and energy consumption.

For agricultural UAV applications such as crop monitoring and pollination assistance, optimizing wing area is essential to ensure stable flight while carrying sensors, cameras, and communication devices. Proper aerodynamic design enables MAV systems to operate efficiently at low flight speeds, which is particularly important when flying close to crops for detailed monitoring tasks.

5. Computational Fluid Dynamics Analysis

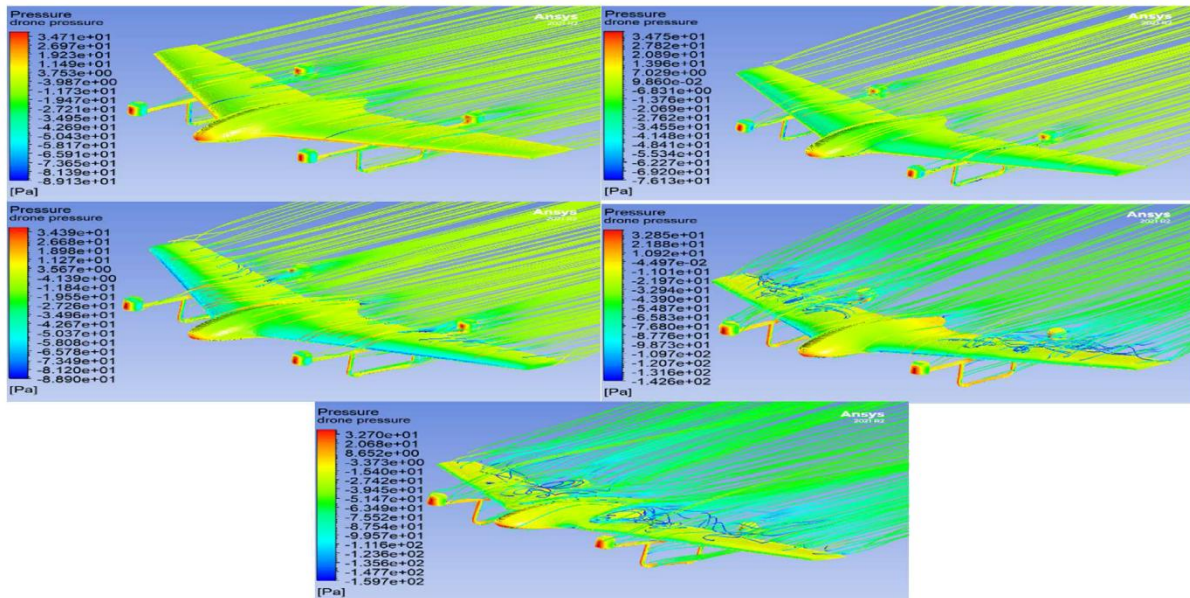


Figure 5: CFD Airflow Simulation around MAV Wing

Computational Fluid Dynamics (CFD) analysis plays a crucial role in understanding the aerodynamic behavior of micro aerial vehicles (MAVs). CFD simulations allow researchers to visualize airflow patterns, pressure distribution, vortex formation, and aerodynamic forces acting on UAV wings without relying solely on expensive experimental testing. By numerically solving the governing equations of fluid motion primarily the Navier–Stokes equations CFD models provide detailed insights into how air interacts with the MAV wing surfaces during flight.

The CFD visualization shown in figure 5 represents the pressure distribution and airflow behavior around the wing structure of a micro aerial vehicle. The color contours illustrate variations in static pressure across the wing surface. Regions with warmer colors (such as red and yellow) represent areas of relatively higher pressure, typically observed near the leading edge of the wing where airflow stagnates. Conversely, cooler colors (such as blue and green) represent regions of lower pressure that develop over the upper wing surface due to airflow acceleration. This pressure difference between the upper and lower surfaces of the wing generates the lift force necessary for sustained flight.

One of the most significant aerodynamic phenomena visible in the CFD simulation is the formation of vortices near the wing tips and trailing edges. As airflow moves over the wing, pressure differences cause air from the lower surface to move toward the upper surface at the wing tips, creating swirling airflow structures known as wingtip vortices. These vortices contribute to induced drag but also influence lift generation and wake structure behind the aircraft. Understanding these vortex patterns is essential for optimizing wing design and improving aerodynamic efficiency.

In addition to steady aerodynamic behavior, the CFD analysis also provides insights into unsteady flow characteristics, particularly relevant for bio-inspired MAV systems that utilize flapping or oscillating wings. Studies on bird flight and insect flight have shown that vortex formation and wake interaction play an important role in lift enhancement. The second image illustrates vortex structures generated by flapping wings, where rotating airflow regions form behind the wing during each stroke cycle. These vortex structures contribute to additional lift through mechanisms such as leading-edge vortex stability and wake capture, which are commonly observed in biological flyers.

The third set of images shows CFD simulations of airflow around a UAV platform generated using ANSYS software. The colored streamlines represent airflow velocity and pressure distribution around the aircraft body and wings. Smooth airflow patterns indicate efficient aerodynamic performance, while disturbed regions highlight areas where turbulence and flow separation may occur. Engineers analyze these flow patterns to identify design improvements such as optimizing wing geometry, adjusting wing angles, or modifying fuselage shapes to reduce drag and improve lift generation.

CFD simulations are particularly valuable in the design of agricultural UAVs because they allow engineers to evaluate multiple design configurations before manufacturing prototypes. By analyzing aerodynamic performance through numerical simulation, designers can optimize parameters such as wing shape, airfoil profile, aspect ratio, and angle of attack. This process significantly reduces development costs while improving flight efficiency and stability.

Overall, CFD analysis provides a powerful computational tool for investigating airflow behavior, pressure distribution, and vortex dynamics in MAV systems. These insights are essential for

designing aerodynamically efficient UAV platforms capable of carrying sensors and monitoring equipment for agricultural applications such as crop monitoring, pollination assistance, and precision spraying.

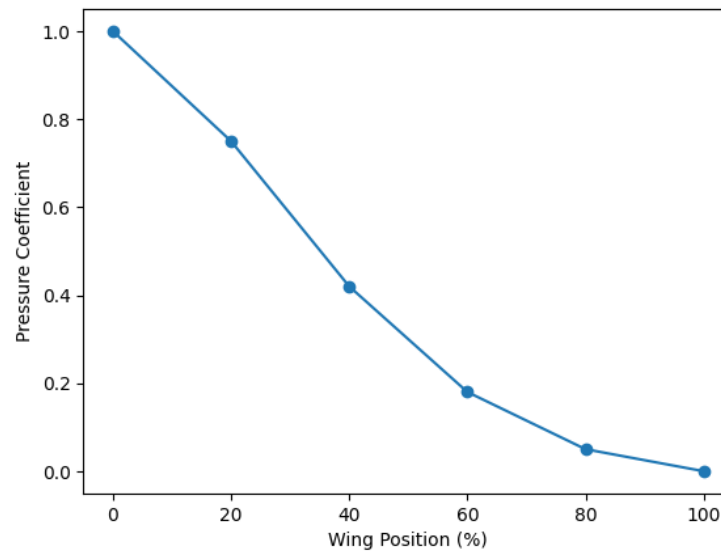


Figure 6: Pressure Distribution Along MAV Wing

Figure 6 illustrates the variation of pressure distribution along the surface of a micro aerial vehicle (MAV) wing, represented as a function of wing position from the leading edge (0%) to the trailing edge (100%). The data show a gradual reduction in pressure as airflow moves along the wing surface.

Between 20% and 60% of the wing chord, the pressure drops significantly from 0.75 to 0.18. This pressure reduction is associated with increased airflow velocity over the wing's upper surface. According to Bernoulli's principle, higher airflow velocity corresponds to lower static pressure, which contributes to lift generation.

Toward the trailing edge (80–100%), the pressure approaches nearly zero. At this stage, the airflow begins to recover and merge with the surrounding flow field behind the wing. The gradual pressure recovery helps maintain stable airflow and prevents flow separation, which could otherwise increase aerodynamic drag.

This pressure distribution pattern is fundamental to aerodynamic lift generation. The difference in pressure between the upper and lower surfaces of the wing creates the upward force that supports the weight of the aerial vehicle.

From an engineering design perspective, analyzing pressure distribution through Computational Fluid Dynamics (CFD) helps researchers optimize wing profiles, angle of attack, and aerodynamic surfaces. By adjusting these parameters, MAV designers can enhance lift generation, reduce drag, and improve flight endurance for agricultural applications such as crop monitoring, pollination, and precision spraying.

6. Artificial Pollination



Figure 7: Robotic Pollination Drone

Artificial pollination using robotic systems has emerged as an innovative technological solution to address the growing decline in natural pollinator populations such as bees and butterflies. Pollination is a fundamental biological process in which pollen grains are transferred from the male reproductive organ (anther) of a flower to the female reproductive organ (stigma), enabling fertilization and seed formation. Approximately 70–75% of global food crops rely on animal-mediated pollination, making pollinators essential for agricultural productivity and ecosystem sustainability. However, factors such as pesticide exposure, habitat loss, climate change, and disease have led to significant reductions in pollinator populations worldwide. As a result, researchers have begun exploring robotic alternatives to support natural pollination systems.

Figure 7 illustrates examples of bio-inspired robotic pollination drones designed to replicate the pollination behavior of insects such as bees. These miniature aerial robots are typically equipped with flapping or rotary wings that allow them to maneuver around flowers and hover near plant structures. The first image depicts a robotic drone inspired by insect morphology, highlighting how engineers mimic biological flight mechanisms to achieve efficient hovering and manoeuvrability in confined agricultural environments. Such bio-inspired designs enable drones to access flowers located deep within dense crop canopies.

The second image demonstrates a micro robotic pollination device interacting directly with a flower surface. These systems often use soft brushes, electrostatic materials, or adhesive gels attached to the drone's body to collect pollen grains from one flower and transfer them to another. Electrostatic forces play an important role in this process, as pollen particles naturally adhere to charged surfaces. By controlling drone movement and contact with floral structures, robotic pollination systems can simulate the natural pollination process performed by insects.

Modern robotic pollination platforms are typically integrated with **computer vision systems**, artificial intelligence algorithms, and onboard sensors. Cameras and machine learning models allow the drone to identify flowers, determine optimal landing positions, and navigate complex crop environments autonomously. Image recognition algorithms can distinguish between flower species, detect flowering stages, and guide the drone to target plants that require pollination.

From an engineering perspective, robotic pollination systems require precise aerodynamic stability, lightweight materials, efficient energy systems, and high maneuverability. Micro aerial

vehicles designed for pollination must operate at low flight speeds and maintain stable hovering positions near flowers without damaging delicate plant structures. Researchers therefore focus on optimizing wing design, flight control algorithms, and energy consumption to enable extended operational time in agricultural environments.

Although robotic pollination technology is still in its developmental stages, it has significant potential to complement natural pollinators in future agricultural systems. When integrated with UAV-based crop monitoring systems, robotic pollination drones could form part of a broader precision agriculture ecosystem, where aerial robots monitor crop health, detect flowering stages, and perform targeted pollination. Such systems could help improve crop yield, enhance food security, and support sustainable farming practices in regions where natural pollinator populations are declining.

Table 1: Natural vs Robotic Pollination

Parameter	Natural	Robotic
Agent	Bees	Drone
Efficiency	Weather dependent	Controlled
Coverage	Limited	Scalable

Table 1 presents a comparison between natural pollination performed by biological pollinators (such as bees) and artificial pollination using robotic drones or micro aerial vehicles (MAVs). The comparison highlights the differences in operational characteristics, efficiency, and scalability of the two pollination approaches in modern agricultural systems.

The first parameter considered in the table is the pollination agent. In natural ecosystems, pollination is primarily carried out by insects such as bees, butterflies, and other pollinating species that transfer pollen while visiting flowers for nectar. Bees are particularly important because their body structures and behavior allow them to efficiently transport pollen between plants. In contrast, robotic pollination systems use drones or micro aerial vehicles equipped with artificial pollen collectors, such as soft brushes or electrostatic materials, to simulate the pollination process. These robotic systems are designed to replicate the movements and interactions of natural pollinators within crop environments.

The second parameter in the table is pollination efficiency. Natural pollination is highly effective under favourable environmental conditions; however, it is strongly influenced by factors such as weather, temperature, wind, and seasonal variations. For example, heavy rainfall or strong winds can significantly reduce bee activity, thereby limiting pollination efficiency. Robotic pollination systems, on the other hand, offer a controlled operational environment, allowing pollination activities to be scheduled and executed independent of natural pollinator behavior.

The third parameter examined is coverage capability. Natural pollinators typically operate within limited foraging ranges, which means that the pollination coverage of large agricultural fields depends on the density and activity of pollinator populations. In contrast, robotic pollination

systems are designed to be highly scalable, enabling multiple drones to operate simultaneously across large agricultural areas. Swarm-based drone systems can coordinate their movements to cover extensive farmland efficiently, thereby improving pollination rates in large-scale crop production systems.

Overall, the comparison presented in Table.1 demonstrates that while natural pollinators remain essential for maintaining ecological balance, robotic pollination technologies have the potential to complement natural pollination processes. By integrating UAV-based pollination systems with precision agriculture technologies, farmers may enhance crop productivity, especially in regions where natural pollinator populations are declining or agricultural intensification has reduced pollinator habitats.

7. Energy Systems

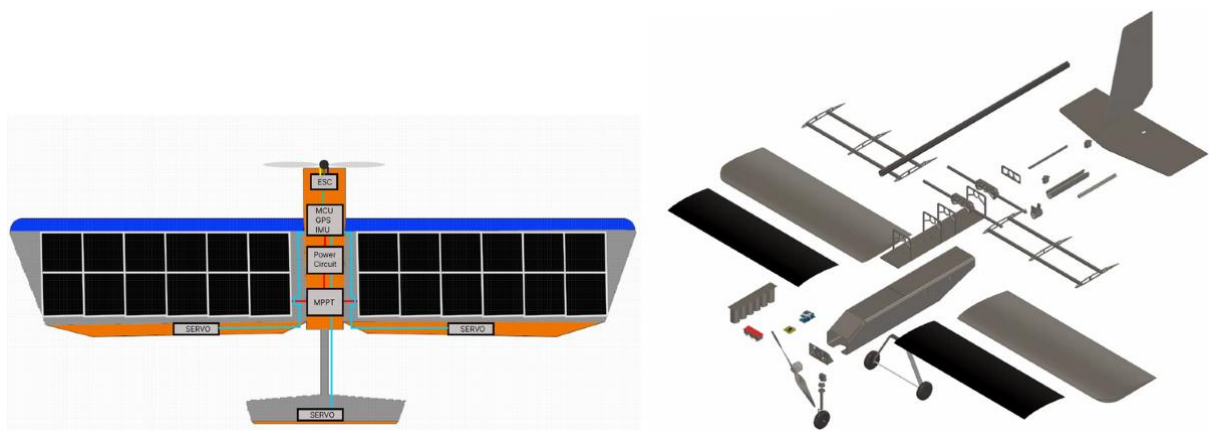


Figure 8: Solar Powered Agricultural UAV

Figure 8 illustrates the conceptual design and structural configuration of a solar-powered unmanned aerial vehicle (UAV) developed for agricultural monitoring and precision farming applications. The figure presents two important perspectives of the UAV system. The first image shows the top view of a solar-powered fixed-wing UAV equipped with photovoltaic panels, while the second image depicts an exploded structural view of the aircraft components, highlighting the internal assembly of the UAV platform.

In the first illustration, solar panels are mounted along the surface of the UAV wings. These photovoltaic modules capture solar radiation during flight and convert it into electrical energy. The generated energy is used to power the propulsion system, onboard sensors, communication modules, and flight control systems. By continuously harvesting solar energy, the UAV can significantly extend its flight endurance compared with conventional battery-powered drones. This capability is particularly advantageous for large-scale agricultural monitoring, where UAVs may need to cover extensive farmland for long durations.

The exploded view in the second illustration provides a detailed representation of the UAV's internal structure. It highlights key components such as the fuselage, wings, tail assembly, landing gear, propulsion motor, electronic speed controllers, batteries, and sensor modules. The

modular design enables efficient integration of solar panels and lightweight structural materials, which are essential for maintaining aerodynamic efficiency and minimizing energy consumption during flight. Engineers typically use lightweight composite materials such as carbon fiber or reinforced polymers to reduce the overall structural weight of the aircraft.

Solar-powered UAVs are particularly well suited for agricultural applications because they can perform long-duration aerial surveillance missions without frequent battery replacement or recharging. These UAVs can carry multispectral cameras, thermal sensors, and environmental monitoring equipment used to analyze crop health, soil moisture levels, pest infestations, and irrigation efficiency. Continuous aerial monitoring allows farmers to detect crop stress conditions early and implement precision farming strategies to improve productivity and reduce resource wastage.

The table presented below the figure compares the flight endurance of different UAV types used in agricultural monitoring. Conventional quadcopter drones typically operate for approximately 25 minutes, primarily due to high energy consumption required for maintaining hover flight. Fixed-wing UAVs offer improved aerodynamic efficiency and can achieve flight durations of around 60 minutes. However, solar-powered UAV systems can extend operational time to approximately 90 minutes or more, depending on solar radiation intensity and battery storage capacity.

Overall, solar-powered UAV technology represents an important advancement in sustainable aerial monitoring systems. By integrating renewable energy harvesting with aerodynamically efficient aircraft designs, solar UAVs can support long-duration agricultural surveillance missions while reducing dependence on conventional battery power. This technology contributes to the development of energy-efficient precision agriculture systems capable of improving crop productivity and environmental sustainability.

8. UAV-Based Agricultural Monitoring in India: Current Applications and Future Directions

Field trials conducted in Coimbatore, Tamil Nadu, have demonstrated that UAV-based multispectral monitoring can significantly enhance precision agriculture practices by identifying variations in crop health, soil moisture, and nutrient distribution in crops such as paddy and cotton. The aerial data collected through UAV sensors enables farmers to apply fertilizers and irrigation more efficiently, thereby improving crop productivity while reducing input costs and environmental impact. Looking toward future developments, the integration of UAV platforms with Internet of Things (IoT) sensors, satellite remote sensing, and artificial intelligence-based data analytics will enable the creation of advanced predictive agriculture systems. These integrated technologies will support real-time crop monitoring, early detection of plant stress, and data-driven decision-making, ultimately leading to more sustainable and efficient agricultural management.

Conclusion

Bio-inspired micro aerial systems represent one of the most promising technological innovations in sustainable agriculture. By integrating aeronautical engineering principles with robotics, artificial intelligence, and advanced sensing technologies, MAV platforms enable unprecedented capabilities for crop monitoring, pollination assistance, and precision farming.

Flapping-wing MAV systems inspired by insect flight provide superior maneuverability and energy efficiency compared with conventional rotor-based drones. Aerodynamic modelling and computational fluid dynamics analyses highlight the complex vortex interactions that enhance lift generation in these systems. Payload optimization models and energy consumption analyses further demonstrate the importance of engineering design in maximizing MAV performance.

The integration of swarm robotics allows multiple UAVs to operate cooperatively across large agricultural landscapes, significantly improving monitoring efficiency and reducing operational costs. Multi-sensor UAV platforms equipped with multispectral and thermal imaging technologies enable early detection of crop stress conditions, allowing farmers to implement targeted interventions and improve resource utilization.

In addition to monitoring applications, UAV-based spraying systems provide efficient crop protection through optimized droplet deposition dynamics. Aerodynamic modelling of spray droplets reveals the importance of droplet size distribution in maximizing canopy penetration and minimizing chemical drift.

Despite these technological advances, several challenges remain. Limited battery capacity, regulatory restrictions, and high equipment costs continue to hinder large-scale deployment of UAV technologies in agriculture. Future research should focus on improving energy storage systems, developing autonomous swarm coordination algorithms, and integrating UAV platforms with satellite data and IoT-based smart farming networks.

With continued technological innovation and interdisciplinary collaboration, bio-inspired aerial robotics is expected to play a critical role in transforming global agriculture into a more efficient, sustainable, and data-driven system capable of meeting future food security challenges.

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PRECISION WATER MANAGEMENT IN SMART AND SUSTAINABLE AGRICULTURAL SYSTEMS

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Abstract

Water scarcity has emerged as one of the major constraints to sustainable agricultural production worldwide. Precision water management represents an advanced approach that integrates modern sensing technologies, remote sensing, data analytics and automated irrigation systems to optimize water application according to crop requirements. This chapter discusses the concept, principles and technologies associated with precision irrigation including soil and plant sensing, remote sensing, variable rate irrigation and decision support systems. Case studies demonstrating the effectiveness of precision irrigation in improving water productivity are also presented. Adoption of precision water management can significantly enhance water use efficiency, reduce environmental impacts and support sustainable crop production under conditions of increasing water scarcity.

Keywords: Precision Irrigation, Remote Sensing, Smart Agriculture, Variable Rate Irrigation.

Introduction

Water is one of the most critical natural resources supporting global agricultural production and food security. Agriculture is the largest consumer of freshwater resources worldwide, accounting for nearly 70 per cent of global freshwater withdrawals (Food and Agriculture Organization, 2021). Although approximately 70 per cent of the Earth's surface is covered with water, only about 2.5% constitutes freshwater and an even smaller fraction is readily accessible for agricultural and human use. As the global population continues to increase, ensuring adequate food production while managing limited freshwater resources has become one of the major challenges facing modern agriculture. Efficient water management in agriculture is therefore essential for sustaining crop productivity and maintaining environmental balance.

Globally, about 300 million hectares of land are currently irrigated, representing nearly 20% of the total cultivated land, yet this irrigated area contributes approximately 40% of the global food production (FAO, 2020). In India, irrigation plays a vital role in stabilizing agricultural production, with nearly 48.8% of the total net sown area being irrigated, while the remaining 51.2% depends on rainfall. Despite this significant contribution from irrigated agriculture, rainfed agriculture dominates the global agricultural landscape, covering nearly 80% of the world's cultivated land and contributing about 60% of the total food production. However,

rainfed farming systems are highly vulnerable to rainfall variability, droughts and climate change, which can significantly affect agricultural productivity.

The demand for water in agriculture is expected to increase substantially in the coming decades due to rapid population growth, urbanization and changing dietary patterns. At the same time, water resources are becoming increasingly scarce because of groundwater depletion, climate variability and competition among agricultural, domestic and industrial sectors. According to projections by Charlotte de Fraiture and colleagues (2009), global water demand for agriculture could increase significantly by 2050, depending on improvements in irrigation efficiency, expansion of irrigated areas, cropping patterns and international trade policies. Scenario analyses conducted as part of the Comprehensive Assessment of Water Management in Agriculture indicated that global water diversions for agriculture may increase by 5 to 57 per cent by 2050 under different development pathways. These projections highlight the urgent need for more efficient and sustainable agricultural water management practices.

Traditional irrigation practices often involve uniform water application across fields without accounting for spatial variability in soil characteristics, crop water requirements and microclimatic conditions. Such practices frequently lead to inefficient water use, nutrient leaching, yield variability and environmental degradation. In this context, precision water management (PWM) has emerged as an important component of precision agriculture, focusing on the application of the right amount of water, at the right time and at the right place based on crop requirements and field variability. By integrating modern technologies such as soil moisture sensors, remote sensing, geographic information systems (GIS) and automated irrigation systems, precision water management aims to improve water productivity, optimize irrigation scheduling, enhance crop yields and promote sustainable use of water resources in modern agriculture.

Global Water Resources and Agricultural Demand

Global demand for freshwater resources is increasing rapidly due to population growth, industrial development and expansion of irrigated agriculture. The Food and Agriculture Organization estimates that irrigated agriculture currently covers about 20 percent of cultivated land but contributes nearly 40 percent of global food production. By 2050, agricultural water demand is expected to increase substantially if improvements in irrigation efficiency are not implemented. Water scarcity is particularly severe in arid and semi-arid regions where rainfall variability limits crop productivity. Efficient water management strategies are therefore essential to ensure sustainable agricultural production and environmental protection.

Concept of Precision Water Management (PWM)

Precision Agriculture

Precision agriculture is an advanced farm management approach that focuses on observing, measuring and responding to spatial and temporal variability within agricultural fields. It aims to

optimize the use of agricultural inputs such as water, fertilizers, pesticides and energy while maximizing crop productivity and minimizing environmental impacts. According to Hendrik Sourell (2017), precision agriculture can be defined as a management system that measures and responds to spatial and temporal variability within fields in order to optimize returns on inputs while conserving natural resources. This approach recognizes that agricultural fields are not uniform; variations in soil texture, fertility, moisture availability, topography and microclimate significantly influence crop growth and yield.

The fundamental principles of precision agriculture include site-specific crop management, data-driven decision making, efficient resource utilization and environmental sustainability. Modern precision agriculture relies heavily on digital and geospatial technologies such as remote sensing, Geographic Information Systems (GIS), Global Positioning Systems (GPS), wireless sensor networks and automated farm machinery. These technologies enable farmers to collect detailed spatial information about soil properties, crop health and climatic conditions, allowing them to apply inputs precisely where and when they are required. By addressing field variability at a sub-field scale, precision agriculture improves resource efficiency, enhances crop productivity and reduces negative environmental impacts. Within this broader framework, precision water management (PWM) or precision irrigation represents a critical component aimed specifically at improving irrigation efficiency and water productivity. Efficient irrigation management is essential because water availability is becoming increasingly limited due to population growth, climate change and competing sectoral demands.

Precision Irrigation

Precision irrigation refers to the accurate and controlled application of irrigation water according to the spatial and temporal water requirements of crops. It integrates advanced sensing, monitoring and control technologies to deliver water precisely where and when it is needed. According to Steven R. Raine *et al.* (2007), an effective precision irrigation system should possess four fundamental capabilities:

- (1) Knowing what to do,
- (2) Knowing how to do it,
- (3) Knowing what it has done and
- (4) Learning from what it has done.

These characteristics indicate that precision irrigation systems are not only responsive but also adaptive, continuously improving irrigation decisions based on feedback and historical data.

In practical terms, precision irrigation involves the precise application of water to individual plants or management zones to meet crop water requirements while minimizing environmental impacts such as nutrient leaching, runoff and deep percolation. This approach emphasizes the concept of applying water at the right time, in the right amount, at the right location and using the appropriate method. By aligning irrigation practices with crop growth stages, soil moisture status and weather conditions, precision irrigation enhances water use efficiency and improves crop performance.

Need for Precision Water Management

The growing scarcity of freshwater resources and increasing demand for food have made efficient water management in agriculture a global priority. The major challenge confronting agricultural water management today is improving water use efficiency while ensuring long-term sustainability of water resources. Conventional irrigation practices often result in significant water losses through evaporation, runoff and deep percolation, which not only waste water but also contribute to soil degradation and groundwater contamination.

Precision water management addresses these challenges by improving crop water productivity, which refers to the amount of marketable crop yield produced per unit of water used by the crop. Through precise irrigation scheduling and application, PWM helps reduce water losses and ensures that a greater proportion of applied water is utilized for crop transpiration and growth. Additionally, improved soil and water management practices enhance soil water storage within the crop root zone, ensuring that plants have adequate moisture during critical growth stages.

Furthermore, precision water management reduces non-productive water losses such as soil evaporation, allowing more water to be available for plant uptake. At farm and catchment scales, the adoption of PWM contributes to better groundwater conservation, improved irrigation efficiency, enhanced crop yields and reduced environmental impacts. As climate variability increases and water resources become more constrained, precision water management is expected to play a crucial role in achieving sustainable and climate-resilient agricultural production systems.

Precision Irrigation Cycle

Precision irrigation operates through a systematic decision-making framework commonly referred to as the precision irrigation cycle. This cycle integrates data collection, analysis and automated irrigation control to ensure that water is applied efficiently according to crop requirements and field variability. The cycle typically consists of four interconnected stages:

- Data acquisition,
- Data interpretation,
- Control and
- Evaluation

These stages form a continuous feedback loop that enables irrigation systems to adapt and improve over time, thereby enhancing water productivity and resource use efficiency.

Data Acquisition

The first step in the precision irrigation cycle involves data acquisition, which refers to the collection of information on the spatial and temporal variability within the soil–crop–atmosphere continuum. Accurate and timely data are essential for making reliable irrigation decisions. Information is typically gathered from multiple monitoring sources, including soil-based sensors, plant-based sensing systems and weather monitoring instruments.

Soil-based monitoring techniques measure parameters such as soil moisture content, soil water potential and soil temperature, which provide direct information about the water availability within the crop root zone. Instruments such as tensiometers, capacitance probes and time domain reflectometry (TDR) sensors are commonly used for this purpose. Plant-based sensing methods, including canopy temperature sensors, infrared thermometers and spectral vegetation indices, help detect crop water stress and physiological responses to moisture availability. Weather-based monitoring systems measure environmental parameters such as temperature, humidity, solar radiation, wind speed and rainfall, which are used to estimate crop evapotranspiration.

In recent years, the use of wireless sensors, wireless sensor networks and Internet of Things (IoT)-based monitoring systems has significantly improved the efficiency of data acquisition. These technologies enable real-time monitoring at fine spatial resolutions, often at sub-meter scales, providing detailed insights into field variability. Although increasing the number and density of sensors generally improves the accuracy of irrigation decisions, practical considerations such as installation costs, maintenance requirements and data management must also be taken into account.

Data Interpretation

Once the data are collected, the next step involves data interpretation and analysis. Raw data obtained from various sensors and monitoring systems must be processed, integrated and analyzed at appropriate spatial and temporal scales. This step converts the collected information into meaningful insights that can support irrigation decision-making.

Advanced decision support systems (DSS), crop growth models and simulation tools are often used to interpret field data and determine irrigation requirements. These models incorporate multiple factors, including crop growth stage, soil characteristics, climatic conditions, irrigation system performance and management constraints. For example, evapotranspiration models such as the FAO Penman–Monteith method are commonly used to estimate crop water demand based on weather data.

The integration of geospatial analysis, machine learning algorithms and artificial intelligence techniques further enhances the interpretation process by identifying patterns in large datasets and predicting crop water requirements. Accurate interpretation of data ensures that irrigation decisions are scientifically based and tailored to the specific needs of different management zones within a field.

Control

The control stage involves implementing irrigation decisions by adjusting water application according to the requirements identified during the interpretation phase. This step ensures the reallocation and optimization of irrigation inputs across different spatial zones and time periods within the field.

Precision irrigation systems are capable of applying differential irrigation depths based on soil type, crop condition and topographic variation. This variability in water application can be

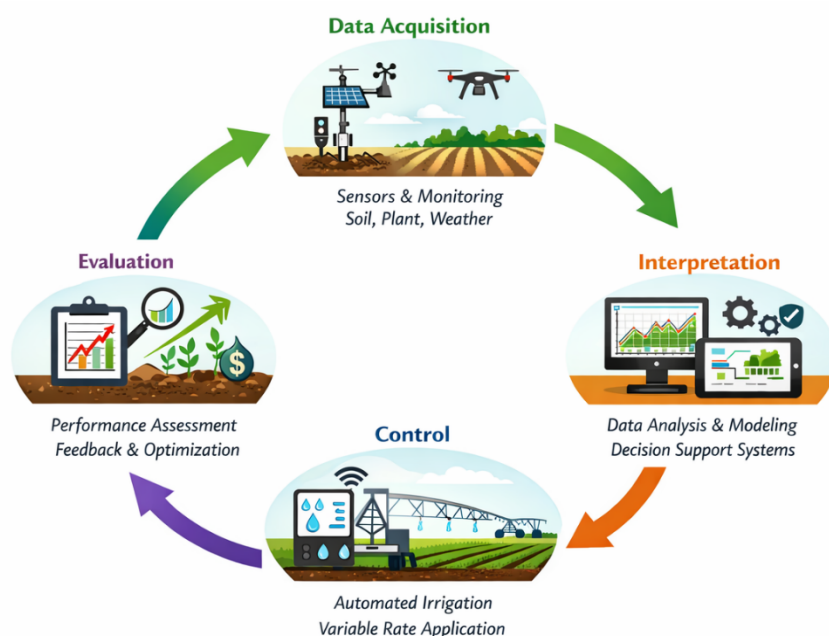
achieved in two main ways: (i) by varying the irrigation application rate or flow rate and (ii) by adjusting the duration or timing of irrigation events. Technologies such as variable rate irrigation (VRI) systems, automated valves and programmable irrigation controllers are widely used for this purpose.

Modern precision irrigation systems increasingly rely on automatic controllers integrated with real-time sensor data. These controllers receive continuous input from soil moisture sensors, weather stations and crop monitoring systems, enabling them to dynamically adjust irrigation schedules. Such automated systems improve irrigation efficiency by minimizing human intervention while ensuring precise and timely water delivery.

Evaluation

The final stage of the precision irrigation cycle is evaluation, often referred to as “closing the loop.” This stage involves assessing the overall performance of the irrigation system in terms of engineering efficiency, agronomic performance and economic returns. Key performance indicators may include water use efficiency, crop yield, energy consumption and operational costs.

Evaluation provides valuable feedback that helps identify areas for improvement in the irrigation strategy. Based on the results obtained, necessary modifications can be made to sensor placement, irrigation scheduling, or control algorithms to enhance the effectiveness of future irrigation cycles. This feedback mechanism distinguishes closed-loop precision irrigation systems from conventional open-loop irrigation practices, as it enables continuous refinement and optimization of irrigation management.



Spatial and temporal variability within agricultural fields significantly influences crop growth and yield potential. Uneven distribution of irrigation water or variations in water quality can create differences in soil moisture distribution, which may lead to spatial variations in crop

performance. Research by E. J. Sadler *et al.* (2000) demonstrated that non-uniform water application across fields can contribute to significant variability in soil moisture conditions and crop yields. By addressing such variability through precise monitoring and adaptive irrigation control, precision irrigation systems can significantly improve both water productivity and yield stability.

Tools and Technologies for Precision Water Management

Precision Water Management (PWM) relies heavily on advanced monitoring and information technologies to measure variability in the soil–plant–atmosphere continuum and to support informed irrigation decisions. Modern precision irrigation systems integrate sensor networks, remote sensing platforms, weather monitoring systems and geospatial technologies to obtain real-time data on crop water status, soil moisture conditions and environmental parameters. These technologies enable farmers and irrigation managers to apply water precisely where and when it is needed, thereby improving irrigation efficiency, enhancing crop productivity and minimizing environmental impacts.



1. Soil-Based Sensors

Soil-based sensing technologies are widely used in precision irrigation to monitor soil moisture dynamics within the crop root zone. Since soil water availability directly influences plant growth and crop yield, accurate measurement of soil moisture is essential for irrigation scheduling and water management.

1.1 Soil Moisture Sensors

Soil moisture sensors provide real-time information on soil water content, enabling farmers to determine when irrigation is required and how much water should be applied. These sensors measure the volumetric water content or water potential of soil at different depths within the root zone.

Recent developments in wireless sensor networks (WSNs) have greatly enhanced soil moisture monitoring capabilities. In these systems, multiple sensor nodes are distributed across the field and connected to a central receiver that collects and transmits data to a computer or cloud-based platform. A notable example is the real-time wireless smart sensor array developed by George Vellidis *et al.* (2008), which consists of several sensor nodes installed across agricultural fields and a central receiver connected to a laptop or control system. These sensors continuously monitor soil moisture and temperature and transmit data at regular intervals (often hourly), allowing farmers to make timely irrigation decisions.

Wireless monitoring systems provide detailed information about spatial variability in soil moisture, which is essential for implementing variable rate irrigation (VRI) strategies in precision water management.

1.2 Time Domain Reflectometry (TDR)

Time Domain Reflectometry (TDR) is a widely used technique for measuring soil water content with high accuracy. The method involves transmitting an electromagnetic pulse through metal probes inserted into the soil. The travel time of the signal along the probes depends on the dielectric properties of the soil, which are strongly influenced by soil water content.

Since water has a much higher dielectric constant compared to soil minerals and air, changes in soil moisture significantly affect the signal propagation time. By measuring this travel time, TDR instruments can estimate the volumetric soil water content. TDR sensors are particularly useful in research and high-precision irrigation systems because they provide reliable and continuous measurements of soil moisture.

1.3 Tensiometers

Tensiometers are simple and widely used devices for measuring soil matric potential or soil moisture tension, which indicates how tightly water is held within the soil matrix. A typical tensiometer consists of a sealed water-filled tube with a porous ceramic cup at the bottom and a vacuum gauge at the top. The ceramic tip is placed in the soil at the desired root zone depth. Water moves between the ceramic cup and the surrounding soil until equilibrium is established. As the soil dries, water is drawn out of the tensiometer, creating a vacuum that is recorded by the gauge. The reading indicates the energy required by plant roots to extract water from the soil. Tensiometers are commonly used for irrigation scheduling in horticultural crops, orchards and vegetable production systems, where precise soil moisture management is critical.

2. Plant-Based Sensors

While soil-based sensors measure water availability in the soil, plant-based sensing techniques provide direct information about the crop's physiological response to water stress. These methods help assess how plants are utilizing available soil moisture and whether irrigation is required.

2.1 Canopy Temperature Sensors

Canopy temperature is an important indicator of plant water status. When plants experience water stress, stomatal closure reduces transpiration, leading to an increase in canopy temperature. Therefore, measuring canopy temperature provides valuable insights into crop water stress conditions. Infrared thermometers and thermal imaging sensors are commonly used to measure canopy temperature without direct contact with the plant. These sensors can provide continuous monitoring of plant energy balance, transpiration rate and physiological activity, making them useful tools for irrigation management.

2.2 Crop Water Stress Index (CWSI)

The Crop Water Stress Index (CWSI) is a widely used indicator derived from canopy temperature measurements and environmental parameters. It provides a quantitative measure of plant water stress by comparing the observed canopy temperature with the theoretical temperature limits under fully transpiring and non-transpiring conditions. CWSI values range from 0 to 1, where lower values indicate well-watered crops and higher values indicate severe water stress. This index is frequently used in precision irrigation systems to determine the optimal timing of irrigation and to prevent yield losses due to water stress.

2.3 Vegetation Indices

Vegetation indices derived from spectral reflectance measurements are widely used to monitor crop health and water status. One of the most commonly used indices is the Normalized Difference Vegetation Index (NDVI), which is calculated using reflectance in the red and near-infrared spectral bands. NDVI provides information about plant vigor, biomass, chlorophyll content and stress conditions. Variations in NDVI values across a field can help identify areas experiencing water stress, nutrient deficiencies, or pest infestations. These indices are often derived from satellite imagery, drone sensors, or ground-based spectral sensors.

3. Weather-Based Monitoring

Weather monitoring plays a crucial role in precision water management because climatic conditions directly influence crop evapotranspiration and irrigation requirements. Weather stations installed in or near agricultural fields measure parameters such as air temperature, solar radiation, wind speed and relative humidity.

These parameters are used to estimate reference evapotranspiration (ET_0) using models such as the FAO Penman–Monteith equation, which is widely accepted for irrigation scheduling. By combining ET_0 with crop-specific coefficients, farmers can determine crop evapotranspiration (ET_c) and accurately estimate the amount of water required by the crop. Integration of soil, plant and weather data provides a comprehensive understanding of spatial and temporal variability in crop water demand, enabling more efficient irrigation scheduling (McCarthy *et al.*, 2008).

4. Remote Sensing

Remote sensing is an important technology in precision agriculture and irrigation management. It involves collecting information about land surfaces without direct contact by measuring reflected or emitted radiation from satellites, drones, or aircraft.

Remote sensing data can be used for a wide range of agricultural applications, including monitoring crop stress, estimating soil moisture, mapping vegetation health, identifying irrigation zones and estimating evapotranspiration. High-resolution satellite platforms such as Landsat, Sentinel and MODIS provide valuable data for large-scale monitoring of agricultural systems. Drone-based remote sensing is increasingly being used for high-resolution field monitoring, enabling detailed assessment of crop conditions and variability within individual fields. These technologies support precision irrigation by identifying zones that require different irrigation rates.

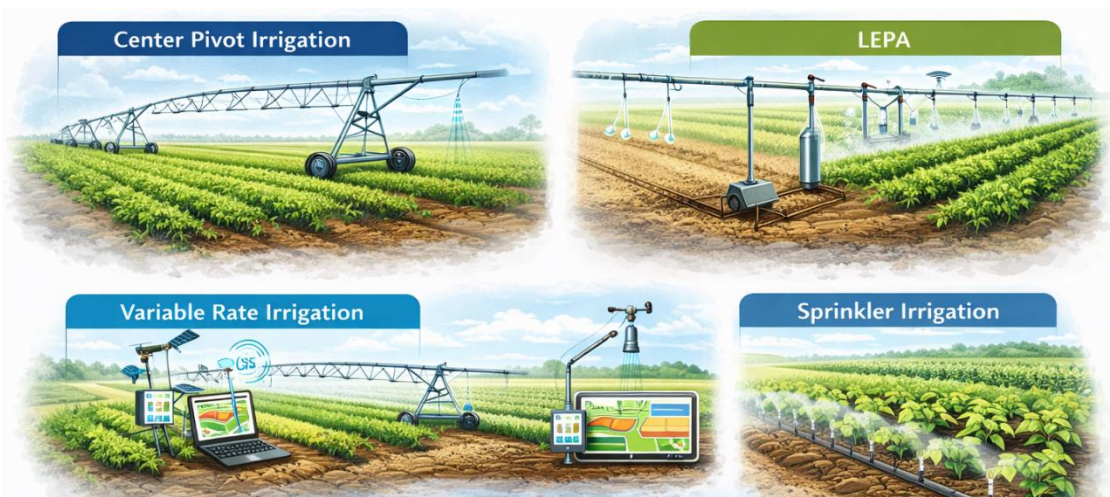
5. Global Positioning System (GPS)

The Global Positioning System (GPS) is a satellite-based navigation system that enables accurate determination of location on or above the Earth's surface. In precision agriculture, GPS plays a critical role in georeferencing field data and enabling site-specific management practices.

GPS technology supports several precision irrigation applications, including field mapping, soil sampling, yield monitoring and variable rate irrigation (VRI). By integrating GPS data with Geographic Information Systems (GIS) and sensor networks, farmers can develop detailed spatial maps of soil properties, crop growth patterns and irrigation requirements.

Furthermore, GPS-guided irrigation systems enable automated and site-specific water application, ensuring that irrigation inputs are distributed according to the variability present within agricultural fields.

Irrigation Systems Used in Precision Water Management



Efficient irrigation systems are fundamental components of Precision Water Management (PWM) because they enable controlled and uniform application of water according to crop requirements and field variability. Modern irrigation technologies integrate automation, sensors and geospatial tools to improve water application efficiency, crop productivity and resource

conservation. Among the various irrigation methods, pressurized systems such as center pivot, sprinkler, drip and variable rate irrigation systems are widely used in precision irrigation due to their ability to deliver water accurately and uniformly.

1. Center Pivot Irrigation

Center pivot irrigation is one of the most widely used mechanized irrigation systems in large-scale agriculture. The system consists of a long pipeline mounted on multiple wheeled towers that rotate around a central pivot point, irrigating fields in a circular pattern. Water is pumped through the pipeline and distributed through sprinkler heads placed at regular intervals along the boom.

The length of a center pivot system generally ranges from 60 m to about 790 m, allowing it to irrigate circular areas of up to 200 hectares depending on the system configuration. Water is supplied to the pivot through a pumping unit and the discharge rate is commonly expressed in gallons per minute (gpm). For example, a system delivering 800 gpm can apply approximately 1.8 acre-inches of water per hour over the irrigated area.

Center pivot systems provide relatively high irrigation efficiency, typically ranging between 80% and 85%, due to controlled water distribution and reduced runoff losses. These systems are also well suited for integration with automation, GPS technology and variable rate irrigation, making them highly compatible with precision irrigation practices.

2. Low Energy Precision Application (LEPA)

Low Energy Precision Application (LEPA) is an advanced modification of center pivot irrigation designed to improve water application efficiency while reducing energy requirements. In LEPA systems, water is applied close to the soil surface using low-pressure drop hoses or applicators, which significantly reduces evaporation and wind drift losses.

LEPA systems operate at lower pressures compared to conventional sprinkler systems, making them energy efficient and economically viable. Water is typically applied in small and frequent irrigation doses directly near the crop root zone, ensuring better infiltration and reduced runoff.

Several types of LEPA applicators are commonly used, including LEPA socks, LEPA bubblers and LEPA sprayers. These devices deliver water either directly onto the soil surface or into furrows, depending on crop type and field conditions. Studies have shown that LEPA systems can achieve water application efficiencies exceeding 90%, while improving crop water use efficiency by 50–75%. In comparison with traditional surface irrigation methods, LEPA systems can achieve water savings of approximately 45–70%, making them highly suitable for water-scarce regions.

3. Variable Rate Irrigation (VRI)

Variable Rate Irrigation (VRI) is a key technology in precision irrigation that allows spatial variation in irrigation water application across different zones of a field. Agricultural fields often exhibit variability in soil texture, topography, water holding capacity and crop growth

conditions. Uniform irrigation may lead to over-irrigation in some areas and water stress in others.

VRI systems address this issue by applying different irrigation depths based on site-specific crop water requirements. In these systems, individual sprinklers or sprinkler groups are equipped with valve control mechanisms connected to wireless nodes mounted along the irrigation boom. A software-based central controller, typically installed at the pivot base, uses GPS technology to determine the exact location of each sprinkler along the field.

Irrigation prescription maps, developed using soil maps, yield maps, remote sensing data, or sensor information, are uploaded into the controller. As the irrigation system moves across the field, the controller automatically adjusts the flow rate or irrigation duration for each sprinkler according to the predefined irrigation zones. By applying water precisely according to field variability, VRI significantly improves water use efficiency, crop productivity and nutrient management.

4. Wheel Move Irrigation

Wheel move irrigation systems are portable sprinkler systems that consist of a pipeline mounted on large wheels connected to a power unit. The system operates by irrigating a particular strip of land and then moving laterally across the field at regular intervals. Typically, the system is rolled 50 to 60 feet laterally using a diesel engine or tractor-powered unit after completing irrigation in one position.

Wheel move systems are commonly used in medium-scale agricultural fields where permanent irrigation infrastructure is not feasible. However, their irrigation efficiency is relatively lower compared to advanced pressurized systems. The application efficiency of wheel move irrigation generally ranges from 39% to 75%, depending on factors such as operating pressure, wind conditions and system management. Despite lower efficiency, wheel move systems are still used in some regions due to their lower installation cost and operational flexibility.

5. Sprinkler Irrigation

Sprinkler irrigation systems apply water through pressurized pipes and rotating nozzles that spray water into the air, simulating natural rainfall. Water is conveyed through pipelines and discharged through sprinklers under operating pressures typically ranging between 2 and 5 kg cm⁻².

Sprinkler irrigation provides relatively uniform water distribution and can be used for a wide range of crops and soil types. The irrigation efficiency of sprinkler systems generally ranges from 80% to 85%, which is considerably higher than traditional surface irrigation methods.

Sprinkler systems are highly adaptable to undulating terrain, sandy soils and areas with limited water availability. Moreover, they can be integrated with automation and sensor technologies to support precision irrigation scheduling and variable rate water application.

6. Drip Irrigation

Drip irrigation is considered one of the most efficient irrigation systems for precision water management. In this system, water is delivered directly to the plant root zone through a network of pipes, laterals and emitters, minimizing water losses due to evaporation, runoff and deep percolation. Surface drip irrigation typically delivers water at rates of approximately 4 L h⁻¹ through emitters, ensuring slow and continuous water application near plant roots. Subsurface drip irrigation (SDI), where drip lines are buried below the soil surface, delivers water at lower discharge rates of 0.6 to 3 L h⁻¹ and further reduces evaporation losses.

Drip irrigation systems achieve very high irrigation efficiencies, typically ranging from 90% to 95%, making them highly suitable for water-scarce environments and high-value crops such as vegetables, orchards and horticultural crops. Additionally, drip irrigation facilitates fertigation, where fertilizers are applied directly through the irrigation system, improving nutrient use efficiency and reducing environmental pollution.

Benefits of Precision Water Management (PWM)

Precision Water Management (PWM) provides significant agronomic, economic and environmental advantages by optimizing irrigation practices based on spatial and temporal variability within agricultural fields. By integrating advanced technologies such as soil moisture sensors, remote sensing, Geographic Information Systems (GIS), Global Positioning Systems (GPS) and automated irrigation systems, PWM ensures efficient utilization of water resources while maintaining high crop productivity.

1. Improved water use efficiency (WUE): PWM enables accurate scheduling and site-specific application of irrigation water according to crop water requirements and soil moisture status. This reduces non-productive water losses through deep percolation, runoff and evaporation, thereby improving overall water use efficiency.

2. Enhanced crop productivity: By maintaining optimal soil moisture within the crop root zone, precision irrigation promotes uniform plant growth, improved nutrient uptake and higher crop yields. Proper water management also reduces plant stress during critical growth stages, resulting in increased marketable yield and crop quality.

3. Reduction in input costs: Precision irrigation minimizes excessive use of water, fertilizers and energy associated with pumping and irrigation operations. Optimized input application reduces operational costs while maintaining or increasing productivity.

4. Increased economic returns: Through improved yield performance and reduced resource wastage, PWM enhances farm profitability and resource-use efficiency. Site-specific irrigation management allows farmers to allocate water strategically based on crop demand and field variability.

5. Reduced nutrient losses and leaching: Accurate water application prevents excessive irrigation that can lead to nutrient leaching below the root zone, particularly nitrogen and other mobile nutrients. This improves fertilizer use efficiency and reduces environmental contamination.

6. Environmental sustainability: Precision irrigation contributes to sustainable water resource management by conserving irrigation water, reducing groundwater depletion and minimizing nutrient runoff into surrounding ecosystems.

7. Water saving potential: Several studies have demonstrated that precision irrigation systems can achieve 8–20% water savings over conventional irrigation practices without compromising crop yield (Smith *et al.*, 2010). Additionally, PWM supports deficit irrigation strategies, where controlled water application optimizes crop productivity under limited water availability.

8. Adaptability to cropping systems: Precision irrigation systems are highly adaptable for a wide range of crops and diverse cropping systems, allowing flexible irrigation management tailored to crop type, growth stage and field variability.

Overall, precision water management represents a scientifically driven approach to irrigation, integrating data, technology and site-specific management to enhance water productivity, economic efficiency and environmental sustainability in modern agriculture.

Case Studies related to Precision Water Management

1. Precision Irrigation in Cotton (Turkey)

Attila Yazar *et al.* (2001) evaluated the performance of Low Energy Precision Application (LEPA) and drip irrigation systems for cotton production under semi-arid conditions in Turkey. The study demonstrated that both systems significantly improved irrigation water use efficiency (IWUE) by delivering water directly to the crop root zone and minimizing evaporation and runoff losses. Results indicated higher lint yield and better water productivity compared to conventional irrigation practices. The research highlighted the potential of precision irrigation technologies to enhance cotton production in water-limited environments.

2. Site-Specific Irrigation in Potatoes (USA)

King *et al.* (2006) investigated site-specific irrigation management using soil moisture sensors and spatial field data for potato cultivation in the United States. The study showed that variable irrigation scheduling based on soil and crop variability improved yield uniformity across the field and optimized water application. Compared with conventional uniform irrigation, the site-specific approach reduced water wastage while maintaining optimal soil moisture within the crop root zone. This resulted in improved water productivity and better crop growth performance.

3. Precision Irrigation in Slovakia

Jobby *et al.* (2011) assessed the effectiveness of precision irrigation techniques in potato production systems in Slovakia. By integrating soil moisture monitoring and automated irrigation scheduling, the study reported a significant reduction in irrigation water consumption and energy requirements. Precision irrigation enabled targeted water application according to crop demand, improving resource-use efficiency while maintaining stable yields. The findings emphasized the economic and environmental benefits of adopting precision irrigation technologies in European agriculture.

4. Drip Irrigation in Indian Sundarbans

Mahanta *et al.* (2019) evaluated the impact of drip irrigation systems in the saline coastal agro ecosystems of the Sundarbans region in West Bengal, India. The study found that drip irrigation reduced soil salinity accumulation by controlling excess water application and improving soil moisture distribution. This technology enhanced cropping intensity and crop productivity by enabling efficient water management in saline-prone soils. The results demonstrated the suitability of precision irrigation systems for improving agricultural sustainability in vulnerable coastal regions.

5. Variable Rate Irrigation in Corn (USA)

Sui *et al.* (2015) examined the application of Variable Rate Irrigation (VRI) technology in corn production systems in the United States. By adjusting irrigation rates according to spatial variability in soil properties, crop water demand and field topography, VRI significantly improved corn grain yield and water use efficiency compared with uniform irrigation practices. The study confirmed that integrating sensor-based monitoring and automated irrigation control can optimize water distribution, reduce resource wastage and enhance overall farm productivity.

Challenges and Future Prospects of Precision Water Management

Challenges

1. High initial investment

Adoption of precision water management systems requires substantial capital investment for technologies such as soil moisture sensors, automated irrigation controllers, remote sensing equipment, GPS-enabled devices and variable rate irrigation (VRI) systems, which can limit adoption, particularly among small and medium-scale farmers.

2. Technical complexity and skill requirements

Precision irrigation involves the integration of data acquisition systems, decision-support tools and automated irrigation infrastructure. Effective operation requires technical knowledge in sensor calibration, data interpretation and system maintenance, which may be challenging without proper training and technical support.

3. Limited awareness and adoption

In many agricultural regions, farmers have limited awareness of the economic and environmental benefits of precision irrigation technologies. Lack of extension services, demonstration farms and training programs can slow the adoption of advanced irrigation management practices.

4. Data management and infrastructure constraints

Precision water management generates large volumes of spatial and temporal data from sensors, weather stations and satellite imagery. Efficient data storage, processing and interpretation require reliable digital infrastructure, software platforms and skilled personnel.

Future Prospects

1. Advancements in sensor technology

Continuous improvements in low-cost soil moisture sensors, plant-based sensors and weather monitoring systems will enhance the accuracy of irrigation scheduling and reduce system costs.

2. Integration of artificial intelligence and machine learning

AI-driven decision support systems can analyze crop growth patterns, soil moisture dynamics and climatic data to provide predictive irrigation scheduling and optimize water application.

3. Internet of Things (IoT) and smart irrigation systems

IoT-enabled irrigation networks allow real-time monitoring and automated control of irrigation systems, improving water use efficiency and reducing manual intervention.

4. Satellite and remote sensing applications

High-resolution satellite imagery and UAV-based monitoring enable large-scale assessment of crop water stress, evapotranspiration and soil moisture variability, facilitating site-specific irrigation management.

5. Increased accessibility and affordability

As technologies mature and digital agriculture expands, the cost of precision irrigation tools is expected to decline, making precision water management more accessible to farmers worldwide and supporting sustainable agricultural water management.

Conclusion

Precision Water Management (PWM) is an essential component of modern precision agriculture aimed at addressing water scarcity, rising food demand and the need for sustainable resource use. Conventional irrigation methods often apply water uniformly across fields without considering spatial variability in soil properties, crop water requirements and climatic conditions, which leads to inefficient water use and reduced productivity. In contrast, PWM integrates advanced technologies such as soil and plant sensors, remote sensing, Geographic Information Systems (GIS), Global Positioning Systems (GPS), automated irrigation systems and decision-support tools to optimize irrigation scheduling and water application. The use of soil-based monitoring, plant-based sensing and weather data enables accurate evaluation of crop water requirements within the soil–plant–atmosphere continuum, allowing technologies like variable rate irrigation (VRI), drip irrigation and advanced sprinkler systems to deliver site-specific water application and improve irrigation efficiency.

These technologies enhance crop productivity, increase water use efficiency and reduce non-productive water losses while minimizing environmental impacts such as nutrient leaching and groundwater depletion. However, the adoption of precision water management is still constrained by factors including high initial investment, technical complexity, limited farmer awareness and challenges associated with data management. With rapid advancements in sensor technologies, artificial intelligence, Internet of Things (IoT) and satellite-based monitoring systems, precision irrigation tools are expected to become more accessible, accurate and affordable. Consequently, precision water management offers a scientifically advanced and sustainable approach to improving agricultural water productivity and supporting resilient, resource-efficient agricultural systems under increasing climate variability and water scarcity.

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SPIDERS AS POTENTIAL BIOLOGICAL PEST CONTROLLERS IN AGROECOSYSTEMS OF MAHARASHTRA: A REVIEW

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1. Introduction

In Maharashtra, agriculture is the backbone of the economy, yet it faces constant threats from a diverse pest complex in diverse agricultural fields. Most of the different types of crops face pest attacks such as Cotton, Soybean and gram. For years, farmers have leaned heavily on chemical sprays to manage pests. This has trapped many in a "pesticide treadmill," where chemicals backfire by causing new pest outbreaks, pests get immune to the pesticides, damaging the environment and burying growers in debt. A better, more natural solution lies in spiders (Order: Araneae), which provide a self-sustaining way to keep pest populations in check. As generalist predators, they are uniquely positioned to manage pests in Maharashtra's major crops, including cotton, soybean, rice, and sugarcane. Recent surveys in districts like Amravati, Akola, and Chandrapur have identified over 100 species of spiders actively preying on crop-destructive insects. The Vidarbha region of Maharashtra, characterized by its semi-arid climate and basaltic black cotton soil, serves as a critical landscape for studying the ecological services provided by arachnids. Spiders (Order: Araneae) are recognized as dominant, generalist predators that play a pivotal role in maintaining the biological equilibrium of agricultural fields by suppressing pest populations (Vairale, 2022). In the agroecosystems of districts like Amravati, Yavatmal, and Wardha, spiders are not merely incidental inhabitants but serve as sensitive bio-indicators of habitat health and pesticide pressure (Bade & Ade, 2017). Recent surveys have documented high species richness across this belt, with families such as Araneidae, Salticidae, and Lycosidae acting as the primary natural enemies of major crop pests like aphids, jassids, and lepidopteran larvae (Parkhi & Gaidhane, 2026; Chapke, 2012).

2. Significance of Spiders in Maharashtra's Context

The significance of spiders in farming of Maharashtra lies in their early-season colonization. In tropical and subtropical climates like ours, pests often have multiple generations. Spiders are present in the field from the day of sowing (or even before, in the bunds), providing a first line of defence that chemical sprays cannot match.

Economic Impact: For smallholder farmers in Marathwada and Vidarbha, reducing even two rounds of pesticide sprays can significantly increase the net profit margin of cotton and soybean.

Environmental Health: Protecting spider populations helps maintain the "beneficial-to-pest ratio," preventing the catastrophic outbreaks of Whitefly or Pink Bollworm seen in recent years.

3. Crop-Specific Roles and Major Species

Surveys in Maharashtra have highlighted specific spider-pest interactions across the state's key crops.

3.1. Cotton and Soybean (Vidarbha & Marathwada)

Cotton and soybean are the "cash-crop duo" of Central Maharashtra. Research in Amravati and Akola (Vairale, 2017) shows that the dominant families are Araneidae (Orb-weavers) and Salticidae (Jumping spiders).

Target Pests: Aphids, Jassids, Whiteflies, and young larvae of *Spodoptera litura* (Tobacco caterpillar).

Key Species: *Neoscona mokerjei* and *Argiope aemula*. These spiders weave intricate webs that trap flying adults of bollworms, preventing them from laying eggs.

Taxonomic and Functional Diversity

Taxonomic diversity in Maharashtra is remarkably high, with surveys in districts like Amravati, Akola, and Nanded recording between 50 to over 100 species in agroecosystems. To understand their impact, these species are categorized into Functional Guilds based on hunting strategies.

Table 1: Functional guild and hunting strategies.

Hunting Guild	Key Families in Maharashtra	Primary Pest Targets
Orb-Web Weavers	Araneidae (<i>Neoscona</i> , <i>Argiope</i>)	Flying moths, Cotton Bollworm adults, Dipterans.
Ground Hunters	Lycosidae (<i>Pardosa pseudoannulata</i>)	Rice Brown Planthoppers, soil-dwelling larvae.
Ambush Predators	Thomisidae (<i>Thomisus spectabilis</i>)	Flower-visiting pests, leaf miners.
Stalking Hunters	Salticidae (<i>Plexippus paykulli</i>), Oxyopidae	Jassids, Aphids, Whiteflies on foliage.

4. Literature Review: Regional & Global Perspectives

The efficacy of spiders is well-documented in regional literature, highlighting their potential as "bioindicators" and "biocontrol agents."

4.1. Case Studies in Maharashtra

Amravati & Akola (Vairale, 2022; Laharia et al., 2025): Research on soybean and pigeon pea (Tur) systems identified Salticidae and Araneidae as the most abundant families. Studies indicate that spider diversity peaks from August to November, coinciding with the critical vegetative and reproductive stages of Kharif crops.

Marathwada Region (Nanded): Recent investigations on university campuses and adjacent fields found that habitat heterogeneity (mixed cropping) significantly boosts spider richness. Species like *Oxyopes javanus* and *Neoscona mokerjei* were noted as dominant natural enemies of insect pests.

Chandrapur (Sindewahi Region): A 2024-25 survey of rice agroecosystems emphasized the role of Lycosidae (Wolf spiders). These ground-dwellers provide essential control for the Brown Planthopper, a major threat to Maharashtra's rice production.

4.2. Global Ecological Principles

The "Landscape of Fear": Research by Riechert & Bishop (1990) remains the gold standard, proving that increasing habitat complexity (e.g., mulching) can reduce crop damage by up to 98% due to both predation and the "scare effect" that deters pests from feeding.

Molecular Proof: Global studies using gut-content PCR analysis have confirmed that spiders consume significant quantities of aphids and hoppers even when pest densities are low, preventing the exponential growth that leads to outbreaks.

5. Predatory Potential and Efficiency

Family: Araneidae (Orb-weavers)

5.1 Predatory Strategy: Sit-and-wait aerial filtration.

Efficiency: Extremely high for flying pests (moths and flies). A single *Neoscona* web can intercept and kill up to 12–18 insects per 24 hours, often killing more than they consume—a phenomenon known as wasteful killing (Vairale, 2022).

5.2 Species-wise Highlights:

***Neoscona theisi* & *N. mukerjei*, *Olios lamarcki* and *N. bengalensis*:** These are the dominant species in Yavatmal's cotton and soybean fields. *N. theisi* is particularly efficient at catching adult moths of the American bollworm (*Helicoverpa armigera*) before they can lay eggs.

***Argiope pulchella* and *Argiope aemula*:** Larger webs; highly effective against Odonata and larger Lepidoptera in the Nagpur citrus and cotton belts.



Figure 1: *Argiope aemula*

6. Family: Salticidae (Jumping Spiders)

6.1 Predatory Strategy: Active stalking and pouncing using high-acuity vision.

Efficiency: High precision hunters for sucking pests. They exhibit a Type II Functional Response, meaning their kill rate increases rapidly with pest density until it levels off.

6.2 Species-wise Highlights:

Plexippus paykulli: A robust hunter in Vidarbha. Research shows it is the only common species capable of efficiently hunting thrips (*Thrips tabaci*) and jassid nymphs in cotton (Parkhi & Gaidhane, 2026).

Hasarius adansoni: Common in mixed-crop systems; known for consuming large quantities of mosquitoes and small flies that hover near the canopy.



Figure 2: *Plexippus paykuli*

7. Family: Lycosidae (Wolf Spiders)

7.1 Predatory Strategy: Ground-dwelling, high-speed chase hunters.

Efficiency: Vital for "soil-to-stem" pest control. They prevent ground-emerging pests from climbing into the crop canopy.

7.2 Species-wise Highlights:

Pardosa birmanica: The most abundant ground predator in Wardha. It shows a distinct preference for jassid nymphs (*Amrasca devastans*), consuming nearly 14–17 nymphs per day in laboratory trials (Bade & Ade, 2017). Similarly, *Pardosa sumatrana* is the abundant ground spider in agricultural fields of Yavatmal.

Lycosa tista: Larger and more aggressive; effectively suppresses soil-dwelling larvae and early-instar caterpillars that drop from the plant.



Figure 3: *Pardosa sumatrana*

8. Family: Oxyopidae (Lynx Spiders)

8.1 Predatory Strategy: Diurnal hunters that "wait and spring" on foliage.

Efficiency: High heat tolerance makes them the most active predators during the hot afternoon hours in Yavatmal and Akola, when other spiders retreat to the shade.

8.2 Species-wise Highlights:

***Oxyopes javanus* and *Oxyopes bermanicus*:** Documented as the most ecologically dominant hunter in Vidarbha's Kharif crops. It has an attack rate of 40–80% against plant-hoppers (Tahir & Butt, 2026).

***Peucetia viridana* (Green Lynx):** Perfectly camouflaged in cotton; specializes in catching adult flies and small moths.



Figure 4: *Oxyopes bermanicus*

Table 2: Summary of Predatory Potential by Guild

Hunting Guild	Family	Primary Target Pests	Predatory Potential (High/Med/Low)
Web-Builders	<i>Araneidae</i>	Moths, Whiteflies, Diptera	High (Mass interception)
Stalkers	<i>Salticidae</i>	Thrips, Jassids, Aphids	High (Precision hunting)
Foliage Hunters	<i>Oxyopidae</i>	Caterpillars, Plant-hoppers	Medium (High heat endurance)
Ground Hunters	<i>Lycosidae</i>	Jassid nymphs, Soil larvae	High (Boundary defense)

9. Challenges to Spider-Based Biocontrol

Despite their potential, spider populations in Maharashtra are under threat:

Chemical Interference: Broad-spectrum insecticides like Pyrethroids, common in cotton farming, are highly toxic to spiders.

Habitat Loss: The practice of clearing all weeds and "bund cleaning" removes the nesting sites spiders need during the off-season.

Climate Extremes: Increasing heatwaves in Vidarbha can desiccate spider egg sacs, leading to population crashes.

10. Management Recommendations for Maharashtra Farmers

To transform spiders into a reliable tool, a shift in "cultural practices" is required:

Organic farming is the best suitable method to increase spider abundance in the kharif and rabbi crops. Fruit farming is also a type of farming where the farm becomes an ideal habitat for cursorial spiders and which build webs.

Preservation of Bunds: Farmers should leave natural vegetation on the edges of fields to act as "spider nurseries."

Intercropping: Growing Pigeon Pea (Tur) with Soybean or Cotton increases structural diversity, allowing more spiders to anchor their webs.

Beetle Banks/Mulching: Providing straw mulch in orchards helps ground-dwelling Wolf spiders survive the hot summers.

Selective Spraying: Transitioning to Integrated Pest Management (IPM) where sprays are only used if the pest population exceeds the ETL, giving spiders a chance to do the work first.

Not burning the crop remains: Farmers often burn the crop remains in the field which not only burn the crop remains but also vanishes out the insects and spiders. By not burning these remains, farmers can use decomposers to make soil more fertile and productive.

C. Comparison of Regional Guild Abundance

Based on recent surveys in Vidarbha, the dominance of spider families varies slightly by district and primary crop:

Table 3: Comparison of Regional Guild Abundance

District	Primary Cropping Context	Dominant Family	Spider	Role in Ecosystem
Nagpur	Paddy & Horticulture	<i>Tetragnathidae</i> & <i>Araneidae</i>	/	Control of Diptera and leafhoppers near water-heavy zones.
Wardha	Cotton & Soy-intercrop	<i>Araneidae</i> (Orb-weavers)	/ <i>Lycosidae</i>	Catching flying moths and lepidopteran pests in vertical webs.
Yavatmal	High-density Cotton	<i>Salticidae</i> / <i>Oxyopidae</i> / <i>Araneidae</i>	/	Active stalking of jassids and aphids on foliage.

Conclusion

Spiders are the silent guardians of Maharashtra's fields. While they cannot replace pesticides entirely in the event of a massive plague, they are essential for preventing such plagues from starting. By integrating spider conservation into Maharashtra's state agricultural policies, farmers can move toward a more sustainable, "low-input" model of farming that protect both their yield and the environment.

Spiders as Bio-Indicators in Vidarbha's Agroecosystems

Regional Cropping Systems and Spider Dynamics

The Nagpur-Wardha-Yavatmal belt primarily follows a Kharif-dominant cycle. The specific structure of these crops determines the "guild" of spiders that will provide protection:

A. The Cotton-Soybean-Pigeon Pea Matrix

In **Yavatmal and Wardha**, the landscape is dominated by rain-fed cotton and soybean.

Monoculture vs. Intercropping: Research in the Wani and Arvi regions indicates that while monoculture cotton supports high numbers of *Oxyopidae* (lynx spiders), intercropping systems (Soybean + Pigeon Pea) support a broader diversity of orb-weavers and jumping spiders (Vairale, 2022).

Structural Continuity: In the Nagpur-Wardha stretch, the transition from the low-lying soybean canopy to the taller, perennial-like structure of pigeon pea (Tur) provides a "structural bridge." This allows spiders to avoid mass migration or mortality during the soybean harvest in late October (Bbrc, 2025).

B. Seasonal Population Shifts

The population dynamics in these districts are heavily synchronized with the monsoon.

Peak Abundance: Spider density in Yavatmal typically peaks in November, coinciding with the flowering and boll-development stages of cotton—the time when pest pressure from bollworms is highest (Bade & Ade, 2017).

The "February Crash": In districts like Nagpur, a sharp decline in spider populations is often noted in February due to the increasing dry heat and the removal of crop residues, which strips the spiders of their microhabitats (Chapke, 2012).

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AGRITEC INNOVATION IDENTIFIED BY GLOBAL RESEARCH AND DEVELOPMENT ON SERIC SECTOR

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Abstract

Environmental degradation of land and ecosystems has intensified due to pollution from modern agricultural practices, particularly the excessive use of chemical fertilizers and pesticides, making agriculture increasingly unsustainable. In this context, entrepreneurship plays a vital role in economic development, especially in addressing unemployment and leveraging emerging technologies. Beyond providing opportunities, entrepreneurs require strong institutional and technical support to succeed. Recent advances in nanotechnology offer an innovative solution through biopolymer-based delivery systems that enable controlled release of agrochemicals, minimizing environmental contamination. These nano-scale carriers enhance agricultural productivity while promoting sustainability. However, their real-world application raises potential toxicological and safety concerns that must be carefully evaluated. In sericulture, such technological interventions have transformed traditional practices, improving efficiency and output. Additionally, sericulture products and by-products are gaining importance in biotechnology, pharmaceutical, and biomedical sectors for developing high-value products. This creates significant opportunities for rural youth and unemployed women to engage in entrepreneurship, thereby improving livelihoods and contributing to socioeconomic development in India.

Keywords: Rearing, Innovation, Hybrid Silkworm, Chawki, Enterprise, Entrepreneurs and Silk-Industry.

1. Introduction:

Sericulture is a complex and multidisciplinary activity that integrates agriculture (mulberry cultivation), animal husbandry (silkworm rearing), and cottage industry (silk reeling and weaving). It is one of the oldest industries in the world and holds significant cultural, economic, and historical value, particularly in Asia. Silk originated in China over 4,000 years ago and later spread to countries such as India and Japan. Today, India ranks second in global silk production after China, while Japan has been a leader in adopting advanced silk technologies, despite a recent decline in output.

Traditional sericulture practices are eco-friendly but often labor-intensive and less productive. The sector plays an important role in rural employment and women's empowerment while supporting the textile and export industries. Technological advancements, including improved silkworm breeds, mechanized reeling, and disease management, have enhanced productivity and quality. However, India still lags behind China and Japan in large-scale technological adoption, highlighting the need for innovation and learning from global leaders.

This study seeks to offer concrete recommendations for improving India's sericulture technology and output, particularly in rural and tribal regions where the industry has a socioeconomic impact, by pinpointing gaps and opportunities for expansion. The diverse array of activities that make up the Indian silk industry include raising mulberry plants, producing disease-free layings, raising young (chawki) and late age silkworms for cocoon production, reeling cocoons (silk reeling) for yarn production, throwing (spinning, warp, and weft production), wet processing (dyeing and printing), weaving (fabric production), modern (computer aided) and traditional (textile designing) textile marketing, and more. The ancient industry of sericulture involves the rearing of silkworms in order to create raw silk. The role of technological advancements in silk manufacture will be covered in this chapter (Barber E. J. W, 1991). Mulberry production, silkworm rearing, disease control, and post-cocoon processing are the main areas of concentration. It displays a wide range of progress and degrees of acceptance. This chapter emphasizes how technological advancements in sericulture have the potential to promote both high-quality production and sustainability. The future of sericulture will be driven by ongoing innovation, adaptive laws, and cooperative initiatives. Research in agriculture is essential to maximize the renewable use of natural resources, increase crop yields, and reduce environmental impacts in order to satisfy the needs of feeding expanding global populations. According to predictions, food output will need to rise by 70% by 2050 in order to address the global hunger crisis (Chaudhuri, KN., 1978). Using solely conventional agricultural techniques would make this difficult. One aspect of the solution that will aid in sustainably expanding food production is the use of technology, creative ideas, and scientific reasoning in agriculture known as "agritech" to increase output. The 14 most popular agritech advancements posted on Connect, our online academia industry partnering network, by academic groups looking to advance their study, are listed in this chapter. It includes early-stage research initiatives, resources, and technologies that have attracted the most attention from the worldwide R&D community, which is actively utilizing our network to find novel discoveries for their pipelines. When you think of 'agritech,' the list might not be what you would expect because it mirrors recent industry trends. Even though our study touched on every facet of agricultural technology, the topics of most interest to R&D teams were crop genetics, crop protection, food output and sustainability, and soil health. Entrepreneurship, which is often achieved by establishing a firm that allows an individual or group to explore a unique business, is what is meant by the term "new entry" (Cheng, Y., 2009).

A comprehensive grasp of the opportunities that allow them to accomplish great things is necessary to be an entrepreneur. An entrepreneurial opportunity, sometimes referred to as a business opportunity, arises when new products, raw materials, services, organizational strategies, and methods are employed to sell a product for a price greater than its production cost (Das A., 2009). There is a great deal of entrepreneurial potential in the agriculture and industry industries, notably in developing nations like India, where agriculture and related farm industries contribute for 70% of the GDP (Francks, P., 2009). One example of such a fascinating industry is sericulture, sometimes referred to as "silk farming" It involves the industrial rearing of lepidopteron insects in order to manufacture silk and cocoons for commercial application. Both the mulberry and non-mulberry sectors are included in this category. Additionally, sericulture is known as the "Kalpavruksha" where everything is utilized from soil to fabric activities, giving it a great capacity to provide a wide range of commercial possibilities across basic to sophisticated fields such as the biomedical and pharmaceutical industries. The post-cocoon industry is also the hub of job possibilities, with 7. 6 million jobs related to the sericulture industries. (Good, I., 1995; Hansen, V., 2012) Consequently, the sericulture industry is seen as one of India's most well-established ones. Entrepreneurship in this industry is among the best, and its industrial output and byproducts have enormous potential for entrepreneurs throughout the nation. Young entrepreneurs from all around the world are drawn to start enterprises in this industry by the vast prospects offered by sericulture. Under this framework, we assess the most promising business prospects in the sericulture industry in order to found companies that have the potential to improve our nation and society.

2. Top Agritech Approaches for R&D

Agritech is a broad field of research and development that covers a variety of methods for enhancing agricultural and food production processes. Precision farming employs methods like sensors, drones, and data analytics to improve crop management, allowing farmers to react to circumstances in real time. Genetic engineering is also used in agriculture to change plant DNA in order to enhance characteristics like pest resistance or environmental stress tolerance. Additional methods in the agritech perspective include robotics, autonomous farming, intelligent irrigation systems, block chain technology, vertical farming, hydroponics, climate modeling, crop protection, and pest management. Moreover, it is well known that mulberry shoots left over from silkworm raising provide a great substrate for growing mushrooms on a large scale. Because mushrooms are considered as an alternative source of food, there is now a growing market for them to address the malnutrition problems that plague 113 million individuals in 53 nations throughout the world. (Kameda S, 1984) Given that silkworm farming generates around 15 MT of sericulture garbage (Liu X., 2010), mulberry shoots are a good place to start a mushroom production company. Mulberry shoot powder can produce substantial financial benefits for business owners who cultivate edible fungi such as oysters and buttons.

Additionally, since mulberry leaves are palatable and easy for herbivorous animals to digest, they are utilized as the main diet for ruminants in many nations, which enhances their nutritional condition. (Mukherjee, R., 1991) In addition, mulberry leaves are used by Angora rabbits as a dietary supplement to create their unique fleece. (Kuhn D, 2012) As a result, there may be untapped commercial potential in an integrated approach to utilizing mulberry and its byproducts. A comprehensive strategy for utilizing silkworm and mulberry litter for compost and biogas production provides an additional income stream for entrepreneurs (26). Grainages are often described as the “temple” and “backbone” of the sericulture industry, as they produce disease-free layings (silkworm eggs) on a large scale to meet the requirements of sericulturists. Silkworm eggshells and pupal cuticles contain chitin and chitosan with strong antibacterial properties, making them sustainable sources for applications in food and pharmaceutical industries. This presents a profitable opportunity for entrepreneurs.

Despite wide industrial uses of silkworm pupal oil—such as biodiesel production, cosmetics, soap, animal feed additives, and food processing—it remains underutilized. The oil contains about 75% unsaturated fatty acids, with alpha-linolenic acid (ALA) contributing nearly 34.27% (Hall, J. W., 1991). ALA offers health benefits including cholesterol reduction, improved memory, and antioxidant activity. Moreover, supercritical fluid extraction of mulberry silkworm pupal oil shows a cost-benefit ratio of 1.57 (Varadarajan, 1983), indicating strong commercial potential.

3. Methodology:

This study uses a qualitative comparative research design to analyze technological innovations in silk sericulture in India, China, and Japan, which allows for cross-national comparisons while preserving the contextual integrity of regional practices. Methods of Data Collection: Primary data was collected through field visits, expert interviews (where possible), and institutional reports; secondary data was collected from peer-reviewed journal articles, government and NGO reports (CSB, JICA, FAO), and technical manuals from sericulture training centers, and databases (PubMed, Science Direct, and AGRIS). The top 14 agritech innovations are listed based on a quantitative analysis of the data on our online partnering platform; connect, from the past year, which includes the number of introduction requests from companies to the teams behind each project, positive feedback from the companies reviewing them, and total chapter reads.

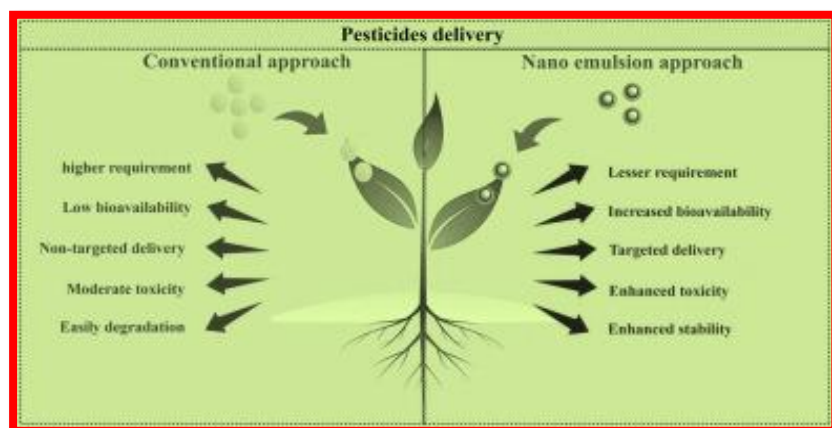
4. What are the top Agritech Innovations?

The history of silkworm farming for silk production (sericulture) is a long and significant one, especially in rural economies, and it has seen some innovations in recent years that have increased efficiency, sustainability, and quality of the silk. This review discusses some of the major advances in sericulture, including technology, genetics, sustainable farming practices, and the use of biotechnology to engineer silk proteins and transgenic silkworms for specialized

medical and industrial applications (Goto S, 2004). The use of biotechnology has opened new vistas for the sericulture industry, which has seen advances in engineering silk proteins and transgenic silkworms for specialized medical and industrial applications. In summary, these innovations have changed the industry to make it more efficient, sustainable, and economically viable, providing benefits to global silk markets and rural livelihoods.

a) Delivering agrochemicals sustainably using aqueous nano-dispersions

Farmers have traditionally used a lot of organic solvents and surfactants in their pesticide formulas to make the active ingredients dissolve better in water. This old way of making pesticides isn't good for the environment and can be pretty risky for people's health. So, to fix this, there's a new approach being developed that uses sustainable nano materials instead of those chemicals to help disperse agrochemicals.



Nano-emulsions mediated pesticides delivery insights for agricultural.

Conventional agrochemical formulations rely on significant quantities of surfactants and organic solvents to increase the water solubility of active ingredients (AI). This conventional method of pesticide and herbicide production employs organic solvents that are harmful to the environment, posing a serious threat to the health of agricultural ecosystems. As a result, in order to create a sustainable agricultural ecology, it is necessary to innovated aqueous agrochemical nano dispersions utilizing agricultural biomass or forest resources. Sustainable nano materials are now utilized as carriers or dispersing agents in current technology, which defines the composition and process for making aqueous nano-dispersion hydrophobic agrochemicals or agricultural active

components (AI) (Ma, J. , 2021). The nano dispersion is made by dissolving the water insoluble agrochemical in a polar or organic solvent and then combining it with a cellulose nano crystal (CNC) dispersion. Following the removal of the organic solvent, the result is either a concentrated dispersion or a wet table nano particle powder made by CNC-AI. The CNC-AI powder (or concentrated dispersion) is then simple to mix with water and use for pest management (Wang, X., 2019). Compared to the death rate of the target species, the current invention offers a far better level of effectiveness in controlling pests and parasites. The majority of pesticides and herbicides are now administered as emulsions, in which the hydrophobic pesticides or herbicides are dissolved in organic solvents like xylene before being diluted with water. Organic solvents present a significant risk to the environment and human health. To deliver hydrophobic pesticides or herbicides, recent competitors in this market sector still use organic compounds in part (such as a combination of emulsion and polymer particles). For water soluble applications, the University of Waterloo technology provides a unique, ecologically friendly, and efficient method for distributing hydrophobic active components. The method entails dissolving agrochemicals to create a nano particle powder, which may be readily dispersed in water for pest control, providing a sustainable, effective, and environmentally friendly alternative to conventional pesticide application techniques (Kumar R., 2018). This agritech technique may be helpful for businesses involved in treating seal lice in fish farms, controlling agricultural pests, and controlling insects and parasites in animals.

b) Enhancing photosynthesis to increase plant yields with GM and non-GM approaches

Since the photosynthetic process in crop plants is inefficient, scientists have long claimed that it is a good candidate for genetic modification (GM). Since the 1970s, it has been asserted that GM may enhance photosynthesis and thereby boost yield by as much as 100%. Despite the billions of pounds in funding and the numerous research paths that have been followed, no GM crop has been created that produces higher yields because of improved photosynthesis. The majorities of recorded successes have been on a modest scale and have not been duplicated on a practical scale (Zhang L, 2020). Recently, attention has shifted away from the sole focus on food production and toward the manufacturing of fuels, chemicals, and carbon capture from genetically modified plants and, increasingly, microorganisms. However, there has been no notable advancement once more, and there are questions about whether this strategy can be expanded enough to have a significant effect. The creators have boosted photosynthetic rates by 30% in *Arabidopsis thaliana* by suppressing specific genes, resulting in a 20% increase in seed production. The genes responsible for photosynthesis are extremely conserved, which means that they are quite similar across different plant species (Das S, 2021). The researchers have started experiments in which the same genes are silenced in tomato plants, and they hope that these experiments may be replicated in other important crop species. Their approach is adaptable since the plants may be

altered using a GM or non-GM method, which allows them to target a variety of markets. The team wants a license.

c) Maximizing the water uptake of soil

The cultivation of mulberry is a vital agricultural practice, especially in sericulture, where the yield and quality of mulberry leaves has a direct bearing on the production of silk. Effective irrigation and soil moisture management are two of the most important elements for a good harvest. In this blog, we'll examine different irrigation strategies and soil moisture retention methods that may enable farmers to maximize the output and quality of their mulberry leaves (Tanaka T, 2016). In mulberry cultivation, irrigation is crucial. Mulberry plants must have a steady water supply in order to create premium leaves, which are the main diet for silkworms. Mulberry plants can experience stunted growth, smaller leaves, and poor leaf quality in the absence of enough water. For this reason, effective irrigation techniques are essential for successful mulberry production (Gorgievski, M., 2016). In order to get the best results in mulberry farming, it is necessary to combine efficient irrigation techniques with strategies for conserving soil moisture. Farmers may maximize water use, maintain consistent soil moisture levels, and improve the growth and yield of mulberry plants by combining these strategies. The following are some strategies for incorporating these practices:

- **Choose the right irrigation method:** Select an irrigation method that suits your field conditions, water availability, and budget. Drip irrigation is highly recommended for its water efficiency and precise application.
- **Implement soil moisture conservation techniques:** Incorporate practices such as fall ploughing, compartmental bunding, mulching, and green manuring to enhance soil moisture retention and reduce water usage.
- **Monitor soil moisture levels:** Regularly check soil moisture levels using tools such as soil moisture sensors or tensiometers. This will help you determine when and how much to irrigate, ensuring optimal water application.
- **Adjust irrigation schedules:** Based on soil moisture levels and weather conditions, adjust your irrigation schedules to provide the right amount of water at the right time. Avoid over-irrigation, which can lead to water logging and nutrient leaching.
- **Maintain irrigation systems:** Regularly inspect and maintain your irrigation system to ensure it operates efficiently. Check for leaks, clogs, and other issues that may affect water distribution. Implementing effective irrigation and soil moisture conservation techniques offers numerous benefits for mulberry cultivation. Some of the key advantages include:
- **Improved water efficiency:** By using water-efficient irrigation methods and conserving soil moisture, farmers can reduce water usage and minimize wastage.

- **Enhanced plant growth:** Consistent soil moisture levels promote healthy mulberry plant growth, resulting in higher leaf yield and quality.
- **Reduced soil erosion:** Soil moisture conservation practices such as mulching and green manuring help to reduce soil erosion, maintaining soil structure and fertility.
- **Cost savings:** Efficient water usage and reduced irrigation frequency can lead to cost savings in terms of water and energy expenses.
- **Sustainable farming:** Integrating irrigation and soil moisture conservation practices promotes sustainable farming by conserving water resources and maintaining soil health.

Due to the high water requirements for soil irrigation, the agricultural industry accounts for 70% of the world's water consumption (Davidson, P., 2015). If no action is taken, the expansion of agriculture, population growth, and the accompanying competition for water are likely to put pressure on the world's food supplies and people. To increase the water absorption capacity of soil, use Bio-Enriched Soil Technologies (BEST). Their BEST method improves the soil by adding cactus mucilage, which enhances the capacity of soil systems to retain water and makes plants more readily available. By releasing extra molecules when needed, BEST regulates the storage and delivery of water and nutrients to the locations where they are most needed (Chauhan S. K., 2002). Even in harsh environments and places with limited resources, their technology may improve food production and biofuel-derived energy. The teams are looking for a development partner and licenses.

d) Modifying crops without creating GMOs

Mulberry (*Morus* spp.) is the primary food source for the silkworm (*Bombyx mori*), making it a cornerstone of sericulture and agricultural sustainability. However, increasing demand for higher productivity, along with challenges such as environmental stress, pests, and diseases, necessitates the development of improved mulberry cultivars. Biotechnology offers effective solutions to these challenges by enhancing both yield and quality. Modern approaches such as genetic engineering, molecular breeding, tissue culture, and biofertilizer application have significantly contributed to mulberry improvement while supporting sustainable agriculture and economic growth in the sericulture sector.

Mulberry breeding primarily focuses on increasing leaf yield, which contributes more than 38.2% to sericulture output (Chauhan, 2015). However, leaf production is a complex trait influenced by multiple factors, including plant height, branching pattern, leaf size, nodal length, and biomass (Dasari *et al.*, 2018). Conventional breeding has limited success due to high heterozygosity and inbreeding depression. Therefore, heterozygous parents are used to develop F1 hybrids, which are evaluated for desirable traits. However, this method restricts the incorporation of beneficial genes from wild relatives due to genetic drag.

Biotechnological interventions such as transgenesis and RNA interference provide targeted solutions by introducing or silencing specific genes without disturbing desirable trait

combinations (Wang *et al.*, 2013; Doi *et al.*, 2001). Molecular markers further enhance breeding efficiency by enabling marker-assisted selection (MAS), which helps identify superior genotypes independent of environmental influence. MAS has proven effective in selecting mulberry varieties with improved growth, disease resistance, and nutritional quality beneficial for silkworm development.

Genetic engineering has shown immense potential in improving mulberry traits. For instance, the incorporation of *Bacillus thuringiensis* (Bt) genes enhances pest resistance by enabling plants to produce insecticidal proteins, thereby reducing reliance on chemical pesticides. Similarly, drought tolerance has been improved through the expression of DREB (Dehydration-Responsive Element Binding) transcription factors, which enhance water retention and plant survival under stress conditions (Ghorpade *et al.*, 2022). Genetic modifications targeting growth regulators such as auxins and gibberellins have also resulted in faster growth rates and increased biomass production, ultimately boosting leaf yield (Kurt *et al.*, 2022; Tomas *et al.*, 2017).

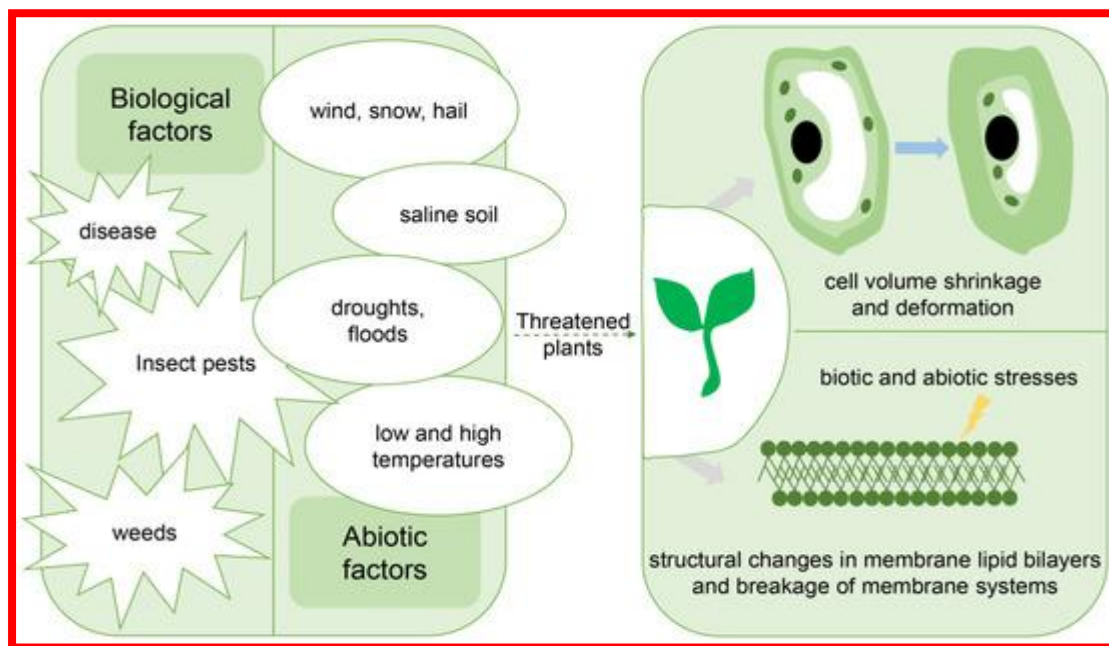
In addition to genetic approaches, tissue culture techniques facilitate rapid multiplication of disease-free planting material, while biofertilizers improve soil fertility and plant health in an eco-friendly manner. These advancements collectively reduce environmental impact, enhance plant resilience, and improve the nutritional quality of mulberry leaves.

The integration of biotechnology into mulberry cultivation is essential for overcoming existing limitations and ensuring sustainable sericulture. Future research should focus on advanced gene editing tools and eco-friendly innovations to further enhance productivity and resilience (Singhal *et al.*, 2010; Yuan & Zhao, 2017). Such advancements will not only strengthen the sericulture industry but also contribute to food security, rural employment, and environmental conservation.

e) Empowering cross-discipline research with bioinformatics architecture

By exploring the potential of symbiotic ecosystems, especially microbes like microalgae, in architectural and design applications, this chapter examines the contribution of architectural research in tackling current environmental, geopolitical, and socioeconomic problems. Microalgae biotechnology has the potential to be applied in a variety of ways in architecture and design, from small scale items to live systems on the outside of buildings to urban and rural environments, allowing for organized study. Before deploying microalgae-based systems in actual settings, it's important to take into account maintenance needs, environmental effects, and the possibility for improving public spaces and society across various dimensions in both the short-term and long-term when using these biotechnologies in architectural designs (Singh A, *et al.*, 2023). This work outlines a set of interdisciplinary studies and initiatives that include microbiology, architecture, and design, and it also suggests several experimental scenarios that integrate both human and non-human viewpoints. These projects showcase the possibility of combining microalgae culture with architectural uses through cooperative academic endeavors. The projects consist of Cultivated Environment, a compact microalgae culture device; Exchange

Instruments, a semi-closed culture system; Biotope, a permanent inside installation that makes use of microalgae; Synthesizing/Distancing, which deals with coexistence during international epidemics; Photosynthetic Landscape, a modular photo bio reactor system; and Cultivated Environment, a small-scale microalgae cultivation apparatus (Das *et al.*, 1997). The Chapter emphasizes the significance of controlled environments, upkeep, and interdisciplinary collaboration while demonstrating the potential of these systems.

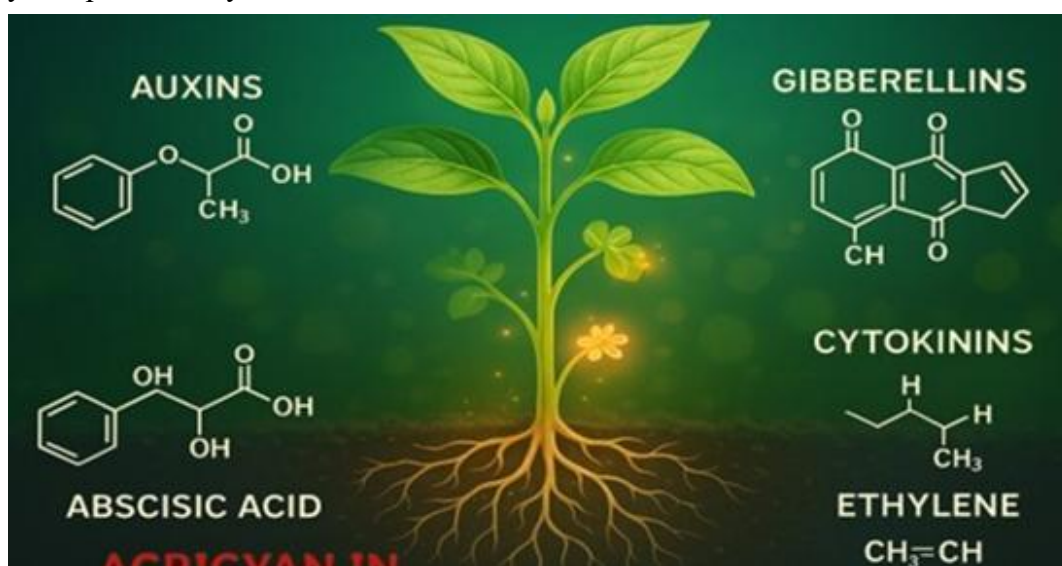


Bioinformatics architecture of mulberry

f) A diverse library of synthetic genetic regulators for mulberry plants

The mulberry (*Morus* spp.) is a crucial plant species for the silk industry. However, conventional breeding techniques have drawbacks when it comes to improving important characteristics like leaf production, stress tolerance, and disease resistance. Genetic transformation has become a potent instrument for mulberry improvement, allowing for precise changes to improve agronomic characteristics. This review covers recent developments in genetic transformation techniques, such as CRISPR/Cas genome editing, biolistic methods, and Agro bacterium-mediated transformation, which have greatly enhanced the accuracy and effectiveness of genetic changes in mulberry. The successful integration of particular genes, such as HVA1, osmotin, mAKR2A, MmSK, MaTCP, and MuGABA-T, into mulberry via genetic engineering has improved drought and salt tolerance, pest and disease resistance, biomass output, and secondary metabolite synthesis (Rohela G. K, *et al.*, 2020). The review also emphasizes the optimization of transformation protocols, such as improvements in tissue culture, regeneration systems, and selection marker strategies, which have increased the efficiency of transformation. Despite these improvements, difficulties still exist, including the low rate of transformation, dependence on genotype, and scarcity of genomic resources. We explore future directions, such as the use of synthetic biology, genome-wide association studies, and multi-omics approaches, to further

speed up genetic improvements in mulberry (Singh B., *et al.*, 1984). Furthermore, novel gene-editing techniques have a lot of potential for improving traits in a targeted and effective way. In order to improve the silkworm (*Bombyx mori*) performance, cocoon weight, and consistent silk production, genetic alterations in mulberry have been investigated with the goal of enhancing leaf quality as well as biotic and abiotic stress tolerance (Amelia I, *et al.*, 2020). This assessment offers useful information about the possibility of genetic transformation in mulberry by summarizing the most recent advancements and future possibilities. The improvements mentioned here are anticipated to aid in the genetic improvement of mulberry, ensuring its viability and productivity in the sericulture sector.



Mulberry plant Growth regulator

Transgenic plants, also known as genetically modified plants, have benefits over conventional plants, such as increased disease resistance, lower pesticide requirements, and better nutrition and flavor (Savithri G., Sujathamma P, 2013). The use of endogenous promoters, which restrict the degree to which gene expression may be changed, is nonetheless a feature of modern plant genetic engineering techniques and improving the interaction between plants and microbes in order to promote sustainable crop development. Sustainable crop output and global food security are seriously threatened by abiotic stresses like drought, salinity, and heavy metal toxicity. Modern cultivars, on the other hand, frequently lack the resilience required to endure environmental challenges, even if they perform well in ideal circumstances (Nelaballe V. K., *et al.*, 2014). The essential function of plant-associated microbial communities, such as arbuscular mycorrhizal fungi (AMF), endophytes, and plant growth-promoting rhizobacteria (PGPR), in promoting plant resilience to abiotic stresses and reestablishing soil health is becoming increasingly clear. The chapter examines how abiotic stressors and intensive agricultural practices affect rhizospheric microbial diversity and activity. Then, it investigates potential methods for restoring and creating advantageous microbial communities, such as sustainable farming methods, seed bio priming, selective microbial recruitment, nanotechnology, and

precision microbiome engineering (Sivaprasad V., *et al.*, 2015). Recent developments in microbial therapies that enhance plant development and production in challenging soils are summarized, with a focus on reducing the effects of stress through morpho physiological, biochemical, and molecular mechanisms. *Serendipita indica*'s broad-spectrum effectiveness in improving plant resilience under a variety of stress scenarios is demonstrated in a targeted case study. Lastly, there is a thorough assessment of the existing difficulties and knowledge gaps that prevent the widespread use of microbial technologies in diverse field settings. The review also outlines potential future research avenues for customizing microbial solutions to particular stress circumstances. Collectively, these findings establish microbiome-based methods as potent instruments for promoting soil health and crop resilience, laying the groundwork for a more environmentally friendly future for agriculture. Although promising microbial interventions in agriculture (Munikrishnappa, H. M., *et al.*, 2009) have a number of drawbacks that must be taken into account in order for them to be effectively implemented. The effectiveness of microbial inoculants is also greatly influenced by environmental variables. The effectiveness of these treatments is very location-specific since microbial interactions are influenced by soil pH, temperature, moisture content, and native microbial communities (Rao M. V., *et al.*, 2001). Additionally, changes in weather patterns can have an impact on microbial viability and activity, resulting in inconsistent outcomes due to climate variability. There are trade-offs between microbial interventions and conventional farming methods like organic farming in terms of complexity, expense, and environmental effect. Microbial solutions have the potential to increase sustainability by fostering plant health and lowering chemical inputs, but they may also necessitate more complex management and long-term monitoring, which may outweigh some of the advantages of conventional approaches. The introduction of manufactured microbes, such as genetically modified microorganisms (GMMs), faces regulatory obstacles as well as environmental hazards. From an ecological standpoint, these species have the potential to disrupt indigenous soil microbiomes, transmit unintentional genetic characteristics, or promote horizontal gene transfer, all of which raise issues like the development of antibiotic resistance. On the regulatory front, strict risk assessment methods, safety measures, and public concern frequently impede field trials and restrict their use in open settings (Chandrappa D., *et al.*, 2001). To overcome these obstacles, we need empirical validation, science-based regulatory frameworks, and complementary approaches like tiered risk evaluations, farmer education, and modular inoculants to assure safe and effective use.

g) Diversifying the nutrition and flavor of mulberry plant-based protein products

We looked at the amino acid makeup, physicochemical functional characteristics, extraction yield, and inhibitory effect on pancreatic lipase for seven different kinds of mulberry leaf glutelins. Each of the seven forms of mulberry leaf glutelins, each with seventeen amino acids, nine of which are necessary and eight of which are not, were extracted using a combination of

acid precipitation and alkali dissolution, along with ultrasonic-assisted extraction. These glutelins are a great source of protein, as evidenced by their well-balanced amino acid profiles (Umesh K. B, *et al.*, 2001). Additionally, FTIR analysis showed consistent amide I, II, and III bands across samples, with β -sheets and β -turns serving as the primary secondary structures. Despite having similar structures, the functional characteristics varied significantly. C4G displayed good water retention, foaming, and foam stability; DSG exhibited superior digestibility, emulsifying capacity, and lipase inhibition; and TSG had exceptional oil absorption and emulsifying capacity. These results imply that TSG and DSG may be used as dietary supplements, with TSG appropriate for oil-based systems and DSG for functional foods that reduce lipid levels. Furthermore, C4G may help food items retain more moisture. In summary, this research lays a theoretical framework for the use of mulberry leaf glutelin in food processing and functional food development, while also highlighting the need for more research in order to realize its full potential (Enomoto, S, 1987). Future research will concentrate on enhancing the effectiveness of glutelin purification and thoroughly investigating the connections between structure and function at the molecular level. Their approach, called Myshroom, is applicable to a wide variety of fungal species, allowing for the creation of a diverse array of mycoproteins with varying textures and tastes (Purushotam S, *et al.*, 2009). The growing method may also be utilized to increase the nutritional content of the mushroom crop, which means that it can be used to improve the variety of flavors and nutrients in plant-based dishes (Thakur J., Bali R. K., 2022). This novel technology's growth substrate is derived from food industry side streams, making this alternative to meat production a thrilling step toward a circular economy. The group is searching for collaborators to evaluate the functionality and application of the components across various sectors.

h) Removing pesticides from agricultural water run-off

Due to their overuse in contemporary agriculture, the quantity of pesticides in water has risen. The kind of pesticide and the effectiveness of the water treatment method determine which one is best for eliminating it. This chapter offers a thorough analysis and explanation of several chemical, physical, and biological methods for eliminating pesticides from water, including membrane technologies, membrane bioreactors, activated sludge, adsorption, and sophisticated oxidation processes. Both hybrid and single-treatment approaches are carefully explained and analyzed. The use of hybrid removal techniques provides promising prospects for creating novel methods for removing pesticides. To create a water treatment facility that targets the highest potential removal rate for various types of pesticides, a comprehensive analysis of influent composition and identification of the most effective removal strategy are essential. The decentralization of water treatment was also discussed, in which it is a crucial strategy for achieving superior effluent water quality at a lower cost (Kaul S., & Pandey R. K., 2014). Numerous affordable methods, including activated sludge and adsorption by agricultural

adsorbents, demonstrated significant efficacy in treating high concentrations of various pesticides. The use of pesticides necessitates a comprehensive scientific evaluation, as using the wrong treatment techniques can lead to the creation of more hazardous byproducts. Different pesticides have a different physical and chemical property, which explains why their environmental fate varies. Before any complete course of treatment can be administered, laboratory studies are required (Kallimani, C. S. *et al.*, 2016). The most important aspect of creating the most effective wastewater treatment procedure is to link the physical and chemical properties of the pollutant to its environmental fate, such as its solubility, molecular weight, water coefficient, sludge distribution coefficient, and reactivity with free radicals (Lamboni L, *et al.*, 2015). All of these will aid in selecting the best method or combination of methods for maximizing pesticide removal. In addition to being suitable for each nation's environmental circumstances, the treatment methods that are adopted should also be nationally appropriate in that they make use of the available resources (adsorbents, etc.), which will improve the treatment facility's cost-effectiveness.

i) Fungicidal targets for crop pathogens

Management plans for fungicide resistance require novel modes of action for fungicides. As potential molecular targets for fungicides, several commercial herbicide targets found in fungi that are not used by commercial fungicides are examined. The enzymes listed below are examples of acetyl CoA carboxylase, acetolactate synthase, 5-enolpyruvylshikimate-3-phosphate synthase, glutamine synthase, phytoene desaturase, protoporphyrinogen oxidase, long-chain fatty acid synthase, dihydropteroate synthase, hydroxyphenyl pyruvate dioxygenase, and Ser/Thr protein phosphatase (Rockwood D. N, *et al.*, 2011). Certain inhibitors of these herbicide targets seem to be promising leads for novel fungicides or effective fungicides. For instance, some dihydropteroate inhibitors and acetolactate synthase are effective fungicides. Some herbicides have been shown to provide indirect benefits to some crops by acting on fungal crop diseases. The total amount of pesticide used might be decreased by using a pesticide with both herbicide and fungicide action based on the same molecular target. The restrictions of such a product are examined (Holland C, *et al.*, 2019). Research in this field is a valuable element of global food security since fungal diseases can wreak havoc on agriculture, causing losses of 10–20% of crops and an annual economic loss of \$100–200 billion (US Department of Agriculture, 2022). Bio-agriculture is the third largest biotech industry sector in India, producing biofertilizer and biopesticides, which are driving the expansion of the Indian agri-biotech market. The farmer-centered and farmer-participatory Integrated Farming System Management (IFSM), Integrated Nutrient Management (INM), and Integrated Pest Management (IPM) programs, which seek to encourage environmentally friendly methods to achieve sustained productivity and optimize resource utilization in sericulture, include a summary of some of the industries this endeavor is

involved in, making the large-scale production of biofertilizer, biopesticides, and vermicomposting a potential startup.

j) A green alternative to the Haber-Bosch process

For more than a century, the Haber-Bosch method for producing ammonia has allowed humans to increase food output worldwide. It does, however, use a lot of electricity and emit a lot of CO₂. Consequently, creating decarbonization plans is essential in order to achieve the objective of net-zero carbon emissions by 2050. At this point, humanity cannot continue to endanger the preservation of the environment in order to create a sustainable society that depends on vital chemical processes and energy production. The team's technology employs non-thermal plasma-assisted catalytic reactions, which produce a nitrate-rich liquid that can be used as a fertilizer (Joy O. P, 2003). Since it makes use of renewable resources, this approach to producing nitrogen has a smaller environmental impact than traditional methods like the Haber-Bosch process. The group is looking for funding, licensing, and co-development.

k) Bio-derived and biodegradable slow-release fertilizers and flocculent agents

The manufacturing of these fertilizers may be expensive, and their efficacy might be affected by environmental variables like temperature and humidity. The rate at which these fertilizers release nutrients might also be influenced by the soil type and pH. In conclusion, slow-release fertilizers made from bio-polymers may revolutionize the agricultural sector by increasing crop production and reducing nutrient losses (Doss, S. G, *et al.*, 2011). Additional research is necessary, though, to optimize the output and efficiency of these fertilizers across a variety of agricultural environments and soil types. Additionally, the chapter examines how the release of nutrients from delayed-release fertilizers made with bio-polymers can be affected by factors like pH, temperature, and soil moisture. The authors also discuss the advantages and disadvantages of these fertilizers, as well as their potential application in precision agriculture and organic farming. In general, the study provides a comprehensive and educational overview of the current state of bio-polymer-based slow-release fertilizers and is a useful resource for researchers, scientists, and industry professionals working in this field (Singh V, Bukhari R., 2022). The benefits of utilizing bio-based polymers like starch, cellulose, chitosan, and alginate as a matrix for controlled release fertilizers are discussed. Nitrogen fertilizers are frequently encapsulated in water-soluble polymers by manufacturers in order to ensure a gradual release of the product over time and avoid early nitrogen loss. However, most encapsulations are only partially biodegradable and include microplastics.

l) Restoring plant-fungus symbiosis to enhance mulberry crop resilience

The effects of AMF on plant development and nutrient uptake are covered in this chapter, with a focus on difficult environmental situations. Additionally, we investigate the degree to which AMF enhances plant growth and resilience under stress. The majority of research articles have previously demonstrated the beneficial impact of AMF in promoting plant development under

harsh circumstances. Consequently, this study has coherently integrated the existing literature on the role of AMF in order to comprehend the symbiotic relationship between AMF and different plants when subjected to stressful conditions (Chugh R. M, *et al.*, 2022). The AMF has historically been viewed as a positive tool for facilitating the absorption of nutrients from the soil. Nevertheless, it has recently been shown that plants inoculated with AMF can successfully fight a variety of environmental signals, including salinity, drought, nutrient stress, alkali stress, cold stress, and extreme temperatures, and as a result, can help raise the yield per hectare of a wide range of crops and vegetables. By enhancing the absorption of phosphorus, nitrogen, zinc, and other nutrients, as well as the bioavailability of some key micronutrients, arbuscular mycorrhizal fungi (AMF) can improve nutrient uptake. By colonizing the soil, AMF can enhance its structure and increase the activity of beneficial bacteria, which in turn can make plants more resilient to drought and disease. As a result, boosting AMF colonization in the soil may help boost crop yield and productivity in the future.

m) Silk's Biomedical industry

Due to their versatility and biocompatibility, silk-based biomaterials have become increasingly important, making them a viable option for the future of medical technology. They can be manufactured and customized using a variety of processing techniques, including electro spinning, freeze drying, and 3D printing, to produce particular properties and structures, such as sponges, hydrogels, films, and scaffolds, which can be used in a variety of biomedical applications (Dandin, S. B, *et al.*, 1986). Through in vitro and in vivo investigations, the exceptional property of biocompatibility of silk-based biomaterials has been shown, and numerous studies have now documented the effective application of these materials across various medical specialties. In this chapter, we have extensively covered the various kinds of silk, their structural makeup, and biophysical characteristics (Awasthi, A. K. *et al.*, 2004). Furthermore, the existing review places emphasis on highlighting several biomedical uses of manufactured and engineered silk-based biomaterials that help treat particular illnesses and infections of the skin, eyes, teeth, bones, heart, nerves, and liver. Additionally, we have combined the progress made in silk-based biomaterials across the various biotechnological domains, including drug delivery, textiles, food packaging and coating, sensors, and cosmetics. The study in this area, meanwhile, is still growing, and in order for it to be utilized in a variety of biomedical applications, more important data with practical outcomes must be produced. In the area of regenerative medicine, silk-based biomaterials have become an intriguing and promising field of research and development (Banerjee, S. P, 1998). Silk is a one-of-a-kind polymer with exceptional mechanical strength that outperforms other biopolymers. The widespread use of silk-based biomaterials in a variety of biomedical and biotechnological fields has been significantly impacted by the historical clinical effectiveness of silk as a biomaterial.

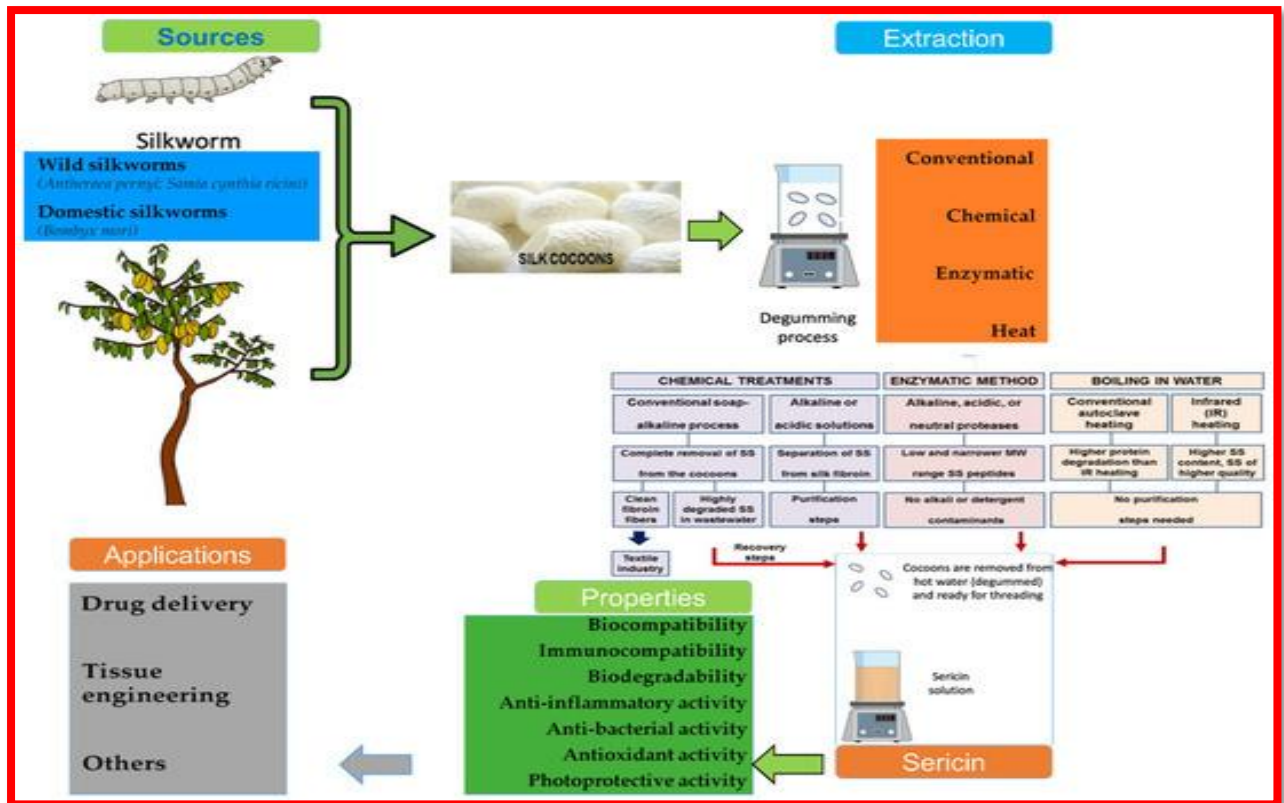


Fig: Silk’s sericin protein materials and application in food sector and biomedical industry

Many biomaterials have been made using various types of silk, such as mulberry silk, non-mulberry silk, and spider silk. These silk proteins may be made and regenerated into hydrogels, nano fibers, sponges, and films. Silk is a promising biomaterial for use in a variety of applications, including skin regeneration, ophthalmology, and dentistry, bone tissue engineering, hepatic, and neurological, due to its versatility in biocompatibility and process ability into different types of biomaterial, simplicity in sterilization, regulated breakdown, and surface chemistry for chemical modifications. Additionally, the progress of silk-based biomaterials in several domains of biotechnology, including cosmetics, textiles, drug delivery, food packaging and coating, sensors, and other industries, opens up new avenues for innovation that benefit humanity. In summary, silk-based biomaterials provide a strong foundation for advancing medical technology and enhancing patient outcomes (Bhau, B. S & Wakhlu, A. K, 2003). They are useful instruments for a wide range of biomedical applications due to their unique combination of biocompatibility, mechanical strength, and regulated breakdown. We may expect even more thrilling advancements and uses for silk-based biomaterials in the future as research in this area advances. Silk is mostly made up of sericin, or gum, and fibrin, or silk strand, which has a wide range of therapeutic and biological applications. Chemical or enzymatic processing is used to isolate independently. Sericin, according to Biasiolo M *et al.* (2004), has applications in biotechnology, such as supplementing culture media, as well as in biomedicine, for tissue engineering, wound healing, drug delivery, and anticancer activity. At the same time, using the reverse-engineered

approach, fibroin that was extracted is being used to create biomaterials like nanofibers, nanoparticles, nanocoating tubes, composite scaffolds, films, hydrogels, sponges, and microspheres (Collins, F. S, *et al.*, 1997). Many companies are developing and selling silk protein biomaterials because of their widespread use in the healthcare industry; some of these are being tested in clinical studies, while others are still in the research phase. Developments in biological science, engineering technology, and, most recently, and 3D printing are accelerating the application of silk fibroin matrices in a wide range of medical and pharmaceutical disciplines. Because of the newfound importance of silk protein, business owners may employ silk to produce a wide range of second-generation materials that are potentially useful and medically appropriate. On this subject, consider the silk items made by businesses for biomedical uses that are currently available in the Indian and international markets.

Conclusion

The technological advancements in silk sericulture in India, China, and Japan are thoroughly compared in this chapter. Each nation has been proven to have embraced a distinct set of innovations that are specific to its socioeconomic circumstances, regulatory environment, and market needs. The nation is now struggling with unemployment, notably in its rural and urban centers. The Indian government has responded by initiating six targeted initiatives: the Startup India Scheme, the Mudra Yojana Scheme, the Stand-Up India Scheme, the Atal Innovation Mission (AIM), the Electronic Development Fund (EDF), and the Pradhan Mantri Mudra Loan Yojana (PMMY). Thanks to the great advantage that these flagship programs provide, such as tax exemption, self-certification compliances, and a dedicated special mobile app for registration potential entrepreneurs may now establish their businesses from simple sericulture industry operations to biotechnological and biomedical industries to create high value silk protein based products. The sericulture industry is currently undergoing a transformation through the use of cutting-edge technology, automation, and supply chain management. As a result, there are many prospects for new business ventures, job creation, and economic development. Special programs like "Startup India" have paved the way for the creation of a new generation of entrepreneurs who can not only support themselves but also contribute to addressing India's unemployment issues.

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INFERENCE STATISTICS: FROM SAMPLE TO POPULATION INSIGHTS

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Statistical Inference: It is a branch of statistics which is concerned with using probability concepts to deal with uncertainty in the decision making.

Forms of statistical inference:

1. Hypothesis testing i.e. to test some hypothesis about parent population from which the sample is drawn;
2. Estimation i.e. to use the 'statistics' obtained from the sample as estimate of the unknown 'parameter' of the population from which the sample is drawn.

In both these problems, inferences can be drawn from the sample data.

Procedure of testing hypothesis:

1. Set up a hypothesis
2. Set up a suitable level of significance
3. Setting a test criterion
4. Doing computation
5. Making decision.

Hypothesis: Any tentative statement

Statistical hypothesis: Any statement regarding population parameter is known as statistical hypothesis.

Simple hypothesis: If the hypothesis specifies all the population parameter completely, it is known as simple hypothesis. E.g. In normal population, $\mu = \mu_0$ and $\sigma^2 = \sigma_0^2$.

Composite hypothesis: If in a hypothesis some of the parameters are unspecified then, it is known as composite hypothesis. E.g. Mean of the normal distribution is $\mu = \mu_0$ is a composite hypothesis because it does not tell anything about σ^2 .

Null hypothesis: Any statement which is to be nullified where no personnel biasness is there is called null hypothesis. E .g. To write $H_0: u=50$ means that we are to test the null hypothesis that the mean of the distribution is 50.

Alternate hypothesis: Any statement opposite to null hypothesis is called alternate hypothesis. (H_1) .E.g. $H_1: u \neq 50$ means that we are to test the alternate hypothesis that mean of the distribution is not 50.

Caution: Always remember when H_0 is rejected then, alternate hypothesis H_1 is accepted. Always remember when we accept H_1 , then, we say that there is no evidence against H_0 . Never use the word accepts or reject.

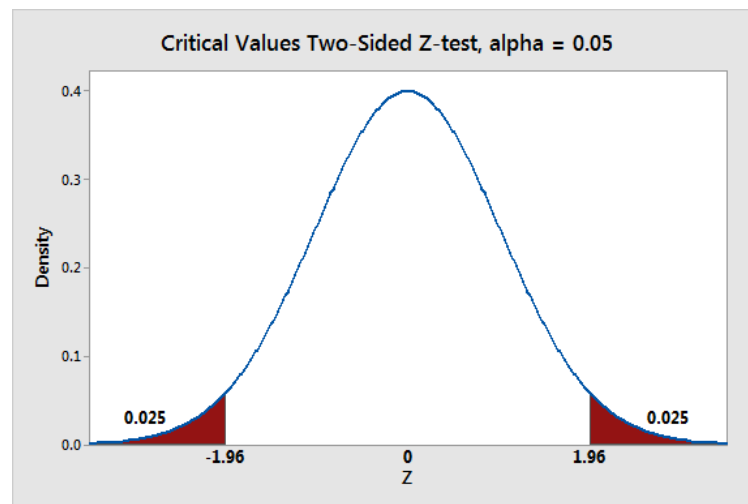
Test: A test of a statistical hypothesis is a procedure of deciding whether to reject or accept H_0 .

Coefficient of confidence: It mean with what degree of confidence, the estimate is correct or wrong. If the estimate is 90 % correct then, coefficient of confidence is 0.9 or 90 % and is denoted by $(1 - \alpha)$.

Level of significance (LOS): When the critical region is expressed in terms of probability, it is known as level of significance and is denoted by ' α '.

Critical region: Region of rejection is known as critical region. It is that region if our test statistics falls in it we reject our null hypothesis. It is expressed in terms of area or probability.

Test Statistics: It is any statistics which is used to test a thing. Test statistics are generally based on some probability distribution. Some of the common probability distributions which are used in hypothesis testing are Z, t, F and χ^2 etc. Choice of test statistics would depends upon the nature of the distribution and the size of the sample.

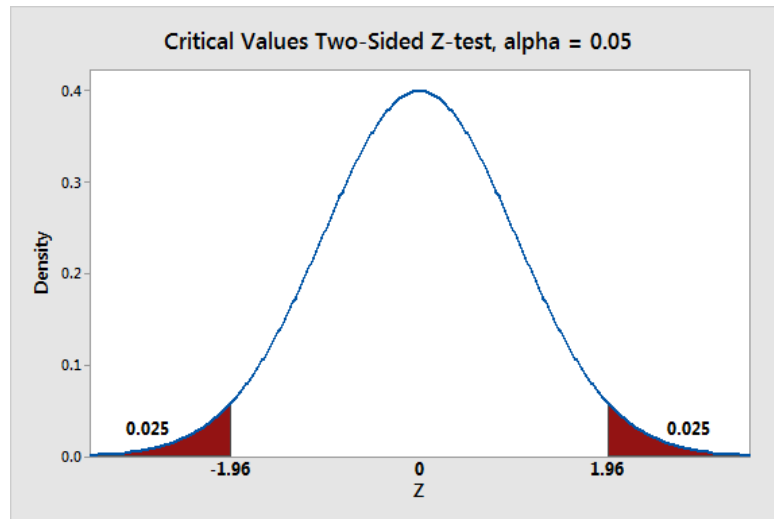


Note: Always remember probability lies between 0 and 1. Area under the normal curve is represented by probability and is equal to 1.

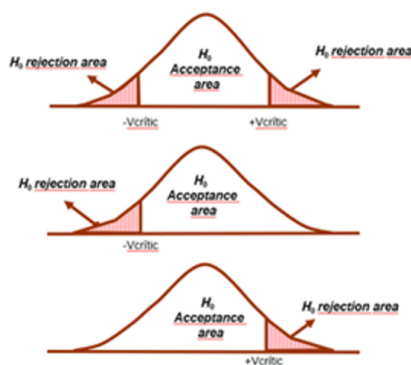
Confidence level and significance level: The confidence level or reliability is the expected percentage of times that the actual value fall within the stated precision limits. Thus, if we take a confidence level of 95 %, then, we mean that there are 95 chances in 100 (0.95 in 1) that the sample results represent the true condition of the population within a specified precision range against 5 chances in 100 (0.05 in 1) that it does not. Precision is the range within which the answer may vary and still be acceptable; confidence level indicates the likelihood that the answer will fall within the range, and the significance level indicates the likelihood that the answer will fall outside the range. One should always remember that if the confidence level is 95% then, the significance level will be $(100-95)$ i.e. 5 %; and if the confidence level is 99%, then the significance level is $(100-99)$ i.e. 1% and so on. We should also remember that the area of the normal curve within precision limits for the specified confidence level constitutes the acceptance region and the area of the curve outside these limits in either direction constitutes the rejection region.

One-tailed and two-tailed test: If the critical region (region of rejection) lies on both side of the tail then it is known as two-tailed test and if the critical region (CR) lies only one side of the tail then, it is known as one-tail test. E.g. Whenever $H_1: \bar{x} \neq u$, It is always advised to use two tail test because it is either $\bar{x} > u$ or $\bar{x} < u$.

If $H_1: \bar{x} > u$, it means that we are using only one side of this tail i.e. RHS. And if $H_1: \bar{x} < u$, it means we are using the LHS of the tail or one tail test.



“Two –tail test Diagram”



H_0 : sample mean = population mean
 H_a : sample mean \neq population mean

H_0 : sample mean \geq population mean
 H_a : sample mean $<$ population mean

H_0 : sample mean \leq population mean
 H_a : sample mean $>$ population mean

Type-1 error: When we are rejecting something whereas it is correct, it is known as Type -1 error. Type-1 error of rejecting null hypothesis when it is true is denoted by α .

α = Probability of Type-1 error = Probability of rejecting H_0 when H_0 is true.

Type-2 error: Type-2 error of accepting null hypothesis when it is not true is denoted by ‘ β ’.

β = Probability of type-2 error = Probability of accepting H_0 when H_0 is not true.

To conclude from the above, the following points should also be remembered:

1. A thing which is rejected at 1% LOS will always be rejected at 5% LOS and a thing which is rejected at 5% LOS may not be rejected at 1% LOS.
2. The probability of committing Type-1 error is known as level of significance (power of a test).
3. 5% LOS means that result may come to be true up to 95% and there are chances that 5% may go wrong.

4. Type-1 error is more dangerous in terms of money. Whereas Type-2 error is more dangerous in because of medicine. Both these error cannot be minimize simultaneously because they are interdependent. E.g. when Type-1 error is 90 % then, Type-2 error is 10%. It is not possible to reduce both types of error simultaneously. If we reduce the probability of Type-1 error from 0.05 to .01, we simultaneously increase the probability of Type-2 error. The value of α can be reduced only by increasing the value of β . Type-1 error is more serious for economic point of view. Fix Type-1 error, and then minimize Type-2 error.
5. Type-1 error is committed when we accept a wrong or incorrect hypothesis. i.e. Type-1 error is committed when we reject a correct or true hypothesis.
6. Region of rejection in terms of probability is known as level of significance (LOS). It gives us the probability of rejection of null hypothesis.
7. Type-1 and Type-2 error: To summarize, decision depending upon sample can be of two type and is given in the following table:

	Decision	
	Rejection H_0	Accept H_0
H_0 : True	Type-1 error	Correct decision
		(No error)
H_0 : False	Correct decision	Type-2 error
	(No error)	

Level of Significance: After setting up the hypothesis, the next step is to determine the level of significance at which the hypothesis would be tested. It means that we have to determine the level of confidence with which a particular hypothesis is accepted or rejected. The level of confidence will determine the probability of our being right (or wrong) in accepting or rejecting a hypothesis. Normally, the level of confidence set for most hypothesis testing is 5%. This mean that our decision of accepting or rejecting a hypothesis would be correct 95 times out of 100 and the chances of our going wrong are only 5 %. This further means that there is a 5 per cent chance of our rejecting a null hypothesis which is true or 5 per cent chances of our accepting an alternate hypothesis which is wrong. If we want a greater precision, the hypothesis can be tested at 1 % LOS in which case the chances of our going wrong are only 1%.

Procedure of hypothesis testing:

1. The first step is to set up a hypothesis. The hypothesis is a set of inferences that is drawn concerning the parameter of population.
2. After setting up the hypothesis, the next step is to determine the level of significance at which the hypothesis would be tested.
3. The third step in hypothesis testing is to decide the test statistics.
4. The last stage in hypothesis testing is to draw conclusions about accepting or rejecting a hypothesis.

Degree of freedom: If 'n' is the independent observations and 'k' the independent constraints then (n-k) is called the degree of freedom. E.g. 2,3,4,5 are the four independent observations. The total is 14. But, the constraint is there. Therefore, $df = 4 - 1 = 3$.

In other words, the number of unspecified parameters is known as degree of freedom. That is those parameters which are not stated in detail is called the degree of freedom.

Parameter: These are the constant of population which specify completely.

Statistics: It is a function of all the sample observation. Suppose, we have got only three observations, x_1, x_2, x_3 then

$$Y = x_1 - x_2 + x_3$$

$$Y_1 = x_1 + x_2 - x_3$$

These functions are nothing but sample statistics. Among these functions, the function which gives very close value of population parameters, that statistics is selected.

Functions of sample observation or estimating function: The best estimate would be one which fall nearest to the true value of the parameter to be estimated i.e. statistics whose distribution concentrate as closely as possible near the true value of the parameter is regarded as the best estimate.

Characteristics of a good estimator: i) unbiased; ii) consistent; iii) efficiency; iv) sufficiency; v) minimum variance; vi) invariance; vii) completeness. If all these qualities are there in the estimator, then we say it is an ideal estimator.

Amount of information (AI): $AI = 1 / \text{Variance}$

Efficiency of A over B: Amount of information of A / Amount of information B.

$= \text{Var. B} / \text{Var. A}$. Efficiency are also measured in terms of variance.

Test of a statistical hypothesis: A test of a statistical hypothesis is two action decision problems after the experimental sample value have been obtained. The two actions being the acceptance or rejection of the hypothesis under consideration.

Test of a Null hypothesis: For example,

Reject H_0 , when $X \geq 15$

Accept H_0 , when $X < 15$

This technique is called test of a null hypothesis. X is called test statistics. Let $X = 60$ i.e. it is > 15 , it means there is no evidence against H_1 (reject H_0).

Test of significance: We can find out the significance level of a variable by means of following statistics given below:

Z-statistics

t-statistics

F-statistics

X^2 -statistics

When performing any type of inferential statistics and any type of statistical testing, a value is generated based on the data (either t, F, Z, or X^2), and this value is being compared to some corresponding critical value (these critical values can be found by looking at the table in the back of any statistics textbook.) and this value is being compared to some corresponding critical value (t, F, Z, or X^2) in order to determine the statistical significance.

Z-statistics: Z is nothing but standard normal variate. Whenever large sample is there then we use Z-statistics also called large sample test.

$$Z = \frac{|\bar{x} - \mu|}{\sigma / \sqrt{n}}$$

Where, \bar{x} = sample mean; μ = population mean

σ = population standard deviation; n = sample size

Whether we use one-tail test or two-tail test, we must fix up H_0 & H_1 by looking into the problem before solution. If the calculated value of $Z \leq$ table value of Z at a desired LOS accept H_0 . On the other hand if the calculated value of Z is $>$ the table value of Z, reject H_0 .

Assumption of Z-statistics:

1. Parent population is normal
2. Sample is a simple random sample.
3. Sample size is large (>30).
4. Standard deviation of population is known.

Z –test for two samples:

For a single sample mean, the standardized normal variate (Z) is given by:

$$Z = \frac{|\bar{x} - \mu|}{\sigma / \sqrt{n}}$$

where

\bar{x} = sample mean, μ = population mean, σ = population standard deviation, n = sample size.

Thus,

$$Z = \frac{|\bar{x} - \mu|}{\text{S.E. of } \bar{x}}$$

Z-test for difference between two sample means

For two independent samples, the Z-value is:

$$Z = \frac{|\bar{x}_1 - \bar{x}_2|}{\text{S.E. of } (\bar{x}_1 - \bar{x}_2)}$$

The standard error of the difference between two means is:

$$Z = \frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}}$$

Case 1: Equal population variances ($\sigma_1^2 = \sigma_2^2 = \sigma^2$)

$$Z = \frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{\frac{\sigma^2}{n_1} + \frac{\sigma^2}{n_2}}}$$

This simplifies to:

$$Z = \frac{|\bar{x}_1 - \bar{x}_2|}{\sigma \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

Case 2: Equal sample sizes ($n_1 = n_2 = n$)

$$Z = \frac{|\bar{x}_1 - \bar{x}_2|}{\sigma \sqrt{\frac{1}{n} + \frac{1}{n}}}$$

Further simplifying:

$$Z = \frac{|\bar{x}_1 - \bar{x}_2|}{\sigma \sqrt{\frac{2}{n}}}$$

Final simplified form

$$Z = \frac{|\bar{x}_1 - \bar{x}_2|}{\sigma \sqrt{2/n}}$$

Inference: If $Z_{\text{calculated}} \leq Z_{\text{table}}$ at desired level of significance, accept H_0 . And If $Z_{\text{calculated}} > Z_{\text{table}}$ at desired level of significance, reject H_0 .

Additional information about Z-test:

Sometimes sample size is large; population is normal; samples are simple random sample; but standard deviation of the sample is unknown. In that case

$$Z = \frac{|\bar{x} - \mu|}{s/\sqrt{n}}$$

Where, s is estimate of variance =

$$\frac{1}{n-1} \sum ((x_1 - \bar{x}_2)^2)$$

For two sample,

$$Z = \frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} = \frac{|\bar{x}_1 - \bar{x}_2|}{\text{SE of } (\bar{x}_1 - \bar{x}_2)}$$

Where,

$$s_1^2 = \frac{1}{n_1 - 1} \sum ((x_{1i} - \bar{x}_1)^2)$$

Inference: If $Z_{\text{calculated}} \leq Z_{\text{table}}$ at desired level of significance, accept H_0 . And If $Z_{\text{calculated}} > Z_{\text{table}}$ at desired level of significance, reject H_0 .

Student's t –statistics: Student was the pen name of the scientist. t-distribution is used when sample size is 30 or less and the population standard deviation is unknown. It is also called as small sample test.

Assumptions of t-distribution:

1. Population is a normal population.
2. Sample is a simple random sample.
3. Sample size is small ($n \leq 30$).
4. Population standard deviation is unknown.

$$t_{(n-1) df} = \frac{|\bar{x} - \mu|}{\text{SE of } (\bar{x} - \mu)} = \frac{|\bar{x} - \mu|}{\text{SE of } \bar{x}} = \frac{|\bar{x} - \mu|}{s/\sqrt{n}}$$

\bar{x} = sample mean, μ = population mean

s = standard deviation of population, n = sample size

Where,

$$s^2 = \frac{1}{n-1} \sum ((x_i - \bar{x})^2)$$

t has got (n-1) degree of freedom.

Inference: If $t_{\text{calculated}} \leq t_{\text{table}}$ at desired level of significance and for a given number of degree of freedom, accept H_0 . And If $t_{\text{calculated}} > t_{\text{table}}$ at desired level of significance and for a given number of degree of freedom, reject H_0 .

Fisher's t-test or t-test for two samples:

Assumptions:

1. Population is normal.
2. Samples are simple random samples.
3. There is homogeneity of variances in two populations.
4. Sample sizes are small.
5. Standard deviations of the population are statistically same but unknown.

(Statistically same means $3=4$ i.e. here we put probability. Numerically same means $3=3$ i.e. they are exactly same.)

$$t_{(n_1+n_2-2)df} = \frac{|\bar{x}_1 - \bar{x}_2|}{\text{SE of } (\bar{x}_1 - \bar{x}_2)} = \frac{|\bar{x}_1 - \bar{x}_2|}{s \sqrt{1/n_1 + 1/n_2}}$$

Where, $s^2 = \frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1 + n_2 - 2}$

$$s_1^2 = \frac{1}{n_1-1} \sum ((\bar{x}_i - \bar{x}_1)^2) = \{ \sum x_i^2 - (\sum x_1)^2 / n \}$$

$$s_2^2 = \frac{1}{n_2-1} \sum ((\bar{x}_i - \bar{x}_2)^2) = \{ \sum x_i^2 - (\sum x_2)^2 / n \}$$

‘s²’ is known as pooled variance. Pooling is feasible only if the variances are homogeneous. Otherwise not. This test is used only when the variances are homogeneous. This ‘t’ is called Fisher’s t. Fisher is known as the father of statistics.

Inference: If $t_{\text{calculated}} > t_{\text{table}}$ at desired level of significance, the difference between the sample mean is said to be significant at 5% LOS. Otherwise, data are said to be consistent with the hypothesis.

Matched Paired t-test: When two samples are given indication of correlation and are not independent, then we use paired t-test. In other words, there is 1-1 correspondence between two values so as to minimize any differential effect due to different factors.

Where, d = difference between the paired value

$$t_{(n-1)df} = \frac{|\bar{d}|}{s / \sqrt{n}}$$

| \bar{d} | = mean of the difference
n = number of pairs
s = standard deviation of difference = $\frac{1}{n-1} \sum (d_i - \bar{d})^2$

or $s = \frac{1}{n-1} \{ \sum d_i^2 - (\sum d_i)^2 / n \}$

This paired “t” is based on (n-1) degree of freedom.

Inference: If $t_{\text{calculated}} \leq t_{\text{table}}$ for a desired level of significance at (n-1) df then, accept H₀. And If $t_{\text{calculated}} > t_{\text{table}}$ for a desired level of significance at (n-1) df then reject H₀.

Snedecor’s F-test:

$$F = e^{2Z} \text{ where, } Z \text{ is Fisher’s } Z.$$

This statistics is used to test the homogeneity of two variances.

$$F_{(n_1-1)(n_2-1)df} = s_1^2 / s_2^2 \text{ provided } s_1^2 > s_2^2$$

$$F_{(n_1-1)(n_2-1)df} = s_2^2 / s_1^2 \text{ provided } s_2^2 > s_1^2$$

F’ will be having two degree of freedom (n₁-1) and (n₂-1)

For (n₂-1)df, we see horizontal degree of freedom and for (n₂-1) df, we see vertical degree of freedom.

Inference: If $F_{\text{calculated}} \leq F_{\text{table}}$, accept H_0 and if $F_{\text{calculated}} > F_{\text{table}}$ value, then reject H_0 .

Assumptions: $H_0: \sigma_1^2 = \sigma_2^2$ i.e. variances are same.

$H_1: \sigma_1^2 \neq \sigma_2^2$ i.e. variances are not same. If $F_{\text{calculated}} < F_{\text{table}}$, accept H_0 i.e. variances are same.

Two samples have been drawn from two different population having same variance and same mean. Also, two samples have been drawn from two different population having same variance but different means.

If there are more than two samples, then we use ANOVA table for testing the homogeneity of variances. This is called Bartlett test for testing the homogeneity of variances for more than two samples.

In t-test, we test the means. In F-test we test the variances whether they are significant or not. If the variances are homogeneous, they can be pooled, otherwise not.

Fisher's and Behreem's 'd' test: For testing the difference in means when the variances are heterogeneous or when the variances are not same, then we use this test. In other words, if in the above F-test, H_1 is accepted, then we use this test.

$$\tan \theta = \frac{s_1 / \sqrt{n_1}}{s_2 / \sqrt{n_2}} = \frac{\text{SE of } \bar{x}_1}{\text{SE of } \bar{x}_2}$$

$$\theta = \tan^{-1} \left\{ \frac{s_1 / \sqrt{n_1}}{s_2 / \sqrt{n_2}} \right\}$$

Here, we have three parameters viz. (n_1-1) , (n_2-1) and θ . We use Fisher's and Yates's table.

1. Calculate θ (see natural tan table).

$$2. \quad d = \frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{s_1^2/n_1 + s_2^2/n_2}}$$

(Table value of d is seen from table no. 6 keeping in view (n_1-1) df & (n_2-1) df.)

Inference: If $d_{\text{calculated}} \leq d_{\text{table}}$, accept H_0 and if $d_{\text{calculated}} > d_{\text{table}}$, reject H_0 .

Approximate method:

Cochran and Cox 't' test: This is an approximate method to Fisher's and Behreem's d-test.

$$d = \frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{s_1^2/n_1 + s_2^2/n_2}}$$

$$\text{Where, } s_1^2 = \frac{1}{n_1-1} \sum ((\bar{x}_1 - \bar{x}_2)^2) \quad \text{And } s_2^2 = \frac{1}{n_2-1} \sum ((\bar{x}_1 - \bar{x}_2)^2)$$

$$t' = \frac{t_1 s_1^2/n_1 + t_2 s_2^2/n_2}{s_1^2/n_1 + s_2^2/n_2}$$

Where, $t_1 = t$ value at 5 % LOS for (n_1-1) df

$t_2 = t$ value at 5% LOS for (n_2-1) df

The value of t' at 5 % LOS is given approximately by the weighted mean of the two value of t i.e. t_1 & t_2 and the weights are the variances of means. Weighted mean is denoted by t' .

Inference: if t calculated \leq accept H_0 at 5% LOS and if t calculated $>$ t' , reject H_0 at 5% LOS.

Assumptions of Cochran and Cox t test and Fisher's and Behreem's d test:

1. Population is normal.
2. Samples are simple random sample but they are independent.
3. Samples sizes are small (≤ 30).
4. Variances of the population are heterogeneous (different) and unknown.

Note: 1. Z-test is used to test the significance of the correlation coefficient.

2. F-test also called variance ratio test as it is based on the ratio of the two variances.

Large estimate of variance

Small estimate of variance

$v_1 = n_1 - 1$ and $v_2 = n_2 - 1$

$v_1 =$ degree of freedom for samples having large variance.

$v_2 =$ degree of freedom for samples having smaller variance.

Assumptions of F –test:

1. Normality, i.e. the values in each group is normally distributed.
2. Homogeneity, i.e. variance within each group should be equal for all groups ($\sigma_1^2 = \sigma_2^2 = \dots = \sigma_n^2$).
3. Independence of error. It states that the error (variation of each value around its own group mean) should be independent for each other.

Remember: if the variances are homogeneous, use Fisher's' test for testing the means. And if the variances are not homogeneous, use Cochran and Cox't' test for testing the means.

Analysis of Variance: The analysis of variance frequently referred to by the contraction 'ANOVA' is a statistical technique specially designed to test whether the means of more than two quantitative populations are equal. This technique was developed by R.A. Fisher in 1920s.

Assumptions in the Analysis of Variance: The assumptions in the analysis of variance are the same as discussed in F-test, i.e.,

1. Normality;
2. Homogeneity; and

3. Independence of error.

Technique of the Analysis of Variance: For the sake of clarity the technique of the analysis of variance has been discussed separately for (a) one-way classification and (b) two-way classification.

One-way Classification: In one way classification, the data are classified according to only one criterion. The null hypothesis is:

$$H_0: u_1 = u_2 = u_3 = \dots \dots \dots u_k$$

$$H_1: u_1 \neq u_2 \neq u_3 \neq \dots \dots \dots \neq u_k$$

All the means are not equal i.e. the arithmetic means of populations from which the k samples are randomly drawn are equal to one another. The steps in carrying out the analysis are:

1. Calculate the variance between the samples.
2. Calculate the variance within the samples.
3. Calculate the ratio F as follows

Between column variance

$$F = \frac{\text{Between column variance}}{\text{Within column variance}}$$

Within column variance

Compare the calculated value of F with the table value of F for the degree of freedom at a certain critical level. If $F_{\text{calculated}} > F_{\text{table}}$, it is concluded that the difference in sample means is significant i.e. it could not have arisen due to the fluctuation of simple sampling. On the other hand, if $F_{\text{calculated}} \leq F_{\text{table}}$ that means the difference is not significant and has arisen due to fluctuations of simple sampling.

It is customary to summarize calculations for sum of squares, together with their number of degree of freedom and mean squares in a table, called the analysis of variance table, generally abbreviated ANOVA. The specimen of ANOVA table is given below:

Analysis of Variance (ANOVA) Table: One Way Classification Model:

Source of variation	SS(Sum of Square)	V (degree of freedom)	MS (Mean Square)	Variance ratio of F
Between samples	SSC	$v_1 = C-1$	$MSC = SSC / (c-1)$	MSC / MSE
Within samples	SSE	$v_2 = n-c$	$MSE = SSC / (n-c)$	
Total	SST	$n-1$		

Where, SST = Total sum of squares of variations

SSC = Sum of squares between samples (column)

SSE = Sum of squares within samples (rows)

MSC = Mean sum of squares between samples

MSE = Mean sum of squares within samples.

Coding: Coding refers to addition, subtraction, division and multiplication of data by a constant.

Analysis of Variance in Two Way Classification Model: In a two way classification, the data are classified according to two different criterion or factors. The procedure for analysis of variance is somewhat different than the one followed while dealing with the problems of one-way classification. In two-way classification, the analysis of variance table takes the following forms:

Source of variation	Sum of square	Degrees of freedom	Mean sum of squares	Ratio of F
Between samples	SSC	(c-1)	MSC = SSC/(c-1)	MSC/MSE
Between rows	SSR	(r-1)	MSR = SSR/ (r-1)	MSR/MSE
Residual or error	SSE	(c-1)(r-1)	MSE = SSE/(c-1)(r-1)	
Total	SST	n-1		

Where, SSC = Sum of squares between column

SSR = Sum of squares between rows

SSE = Sum of squares due to error

SST = Total sum of squares

c = Number of column

r = Number of rows

Remember: Z, t and F statistics are known as ‘parametric tests’ while X^2 is a ‘non-parametric test’.

Chi-square test: The X^2 test is one of the simplest and most widely used non-parametric tests in statistical work. It was first used by Karl Pearson in the year 1990s. the quantity X^2 describes the magnitude of the discrepancy between theory and observation. It is defined as:

$$\chi^2 = \sum (O-E)^2/E$$

Where, O = Observed frequencies and E = Expected frequencies

Steps: To determine the value of chi square, the steps required are:

1. Calculate the expected frequencies. In general the expected frequencies of any cell can be calculated from the following equation:

$$E = \frac{RT \times CT}{N}$$

Where, E = Expected frequency

RT = the row total for the row containing the cell.

CT= the column total for the column containing the cell.

N = the total number of observations.

2. Take the difference between the observed and expected frequencies and obtain the squares of these differences, i.e., obtain the value of $(O-E)^2$.
3. Divide the values of $(O-E)^2$ obtained in step 2 by the respective expected frequencies and obtain the total $\sum (O-E)^2/E$. This gives the value of χ^2 which can range from 0 to infinity. If χ^2 is zero it means that the observed and the expected frequencies completely coincide. The greater the discrepancy between the observed and the expected frequencies, greater shall be the value of χ^2 .
4. The calculated value of χ^2 is compared with the table value of χ^2 for given degree of freedom at a certain specified level of significance. If at the stated level (generally 5% level is selected), the calculated value of $\chi^2 >$ table value of χ^2 , the difference between theory and observation is considered to be significant, i. e. , it could not have arisen due to fluctuations of simple sampling. If on the other hand, the calculated value of χ^2 is $<$ table value of χ^2 , then the difference between theory and observation is not considered as significant, i.e., it is regarded as due to fluctuations of simple sampling and hence ignored.

Constants of χ^2 distribution:

1. The mean of the χ^2 distribution is equal to the number of degrees of freedom.
2. The variance of χ^2 distribution is twice the degrees of freedom
3. Total area under the curve in chi-square distribution is 1. Square of the standard normal variate is a χ^2 variate with 1 degree of freedom.

Applications and uses of χ^2 :

1. It is used as a test of significance whether a given sample has been taken from a population of specified variate.
2. It is used to test the homogeneity of sample variances. This test is called Bartlett test.
3. It is used as a test of goodness of fit, i.e., to test whether the sample has been taken from a specified population or not.
4. It is used to test the association of attributes.
5. It is extensively used in the analysis of genetics especially to test the genetic hypothesis and to test the linkage.

Contingency table: When the data are classified into ‘m’ rows representing ‘n’ classes according to one attribute and ‘n’ columns and ‘m’ classes according to the other attribute. There is an mxn classes. The resulting table is known as mxn contingency table. For example,

	Blind	Non-blind
Dumbness		
Non-dumbness		

This is a 2x2 contingency table because, one attribute is blind and the other is dumbness. In 2x2 contingency table, Yates's correction is always applied.

Yates's Correction: $\chi^2 (\text{corrected}) = \sum (|O-E| - 0.5)^2 / E$

Bivariate distribution: Those distribution having two variances, we call it as bivariate distribution.

Sampling distribution: A sampling distribution is an array of sample studies relating to a universe. If, for example, we wish to know the average income of industrial workers, we can have a large number of samples of individual workers and study their income. These samples which have been taken from the universe of individual workers would be a "Sampling distribution".

Conclusion: The introduction of inferential statistics marks the transition from merely describing a dataset (descriptive statistics) to making educated, probabilistic guesses about a larger population based on a smaller sample. It allows researchers to draw conclusions that go beyond the immediate data, enabling generalization and prediction. Key inferences drawn from the introduction of inferential statistics include:

1. Inferences can be drawn about a large population based on a representative sample, which is more cost-effective and faster than studying an entire population.
2. It allows us to determine if patterns observed in a sample represent real population trends or are merely due to chance.
3. Inferential statistics (through confidence intervals and p-values) accounts for sampling errors and acknowledges that sample data will not perfectly represent the population.
4. Researchers can accept or reject hypotheses about population parameters (like mean or variance) using tests such as t-tests, z-tests, and ANOVA.
5. It enables the identification of relationships between variables (e.g., via regression analysis) to predict future outcome.

In essence, inferential statistics transforms raw sample data into actionable knowledge and evidence-based decision-making.

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PROBABILITY AND RANDOM EXPERIMENTS: BASICS OF UNCERTAINTY

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Probability: In common parlance, the term probability refers to the chance of happening or not happening of an event. The moment we use the word chance, we indicate that there is an element of uncertainty about the statement that has been made or is being made. Thus, we say that (a) The probability of India winning a hockey match against Pakistan is poor, (b) or the chance that India will put a man on the moon are low.

Here, we are making statement about which we are not certain. There is an element of uncertainty associated with each of the above statements. We have not assigned any numerical value to these statements. The theory of probability provides a numerical measure of chance is called probability. It enables us to take decision under conditions of uncertainty with a calculated risk. E.g. if we throw a coin, the chance of getting head or tail is $1/2$ and if we throw a dice, the chance of getting 1 or 2 or 3 or 4 or 5 or 6 is $1/6$.

Random Experiment: It is an experiment which if conducted repeatedly under homogeneous conditions does not give the same result. The result may be any one of the various possible "outcomes". Here, the result is not unique (or the same every time). For instance, if a disc is thrown it would not always fall with no. 6 up. It would fall in any one of the six ways which are possible i.e. with any one of the six numbers on the disc.

Trial and Event: The performance of a random experiment is called trial and the outcome an event. Thus throwing of a disc would be called a trial and the result (falling with numbers 1, 2,3,4,5, or 6) an event.

Exhaustive Cases or Event: All possible outcomes of an event are known as exhaustive cases. In the throw of a disc the exhaustive cases are six as the disc has only six faces each marked with different numbers. However, if two disc are thrown, the exhaustive cases are 36 (6×6) as there are 36 ways in which the two disc can fall. Similarly, the number of exhaustive cases in the throw of two coin would be four (2×2) - HH, TT, HT, TH (if H stands for head and T for tail).

Mutual Exclusive Cases or Event: Two or more cases are said to be mutually exclusive if the happening of any one of them excludes the happening of all others in a single experiment. Thus in the throw of a disc, the event 5 & 6 are mutually exclusive, if the event 5 happens no other event is possible in the same experiment. Here, one and only one of the events can take place excluding all others.

Equally Likely Cases or Event: Two or more event is said to be equally likely if the chance of their happening is equal i.e. there is no preference of any one event over the other. Thus, in a

throw of a disc, the coming up of 1, 2, 3, 4, 5, or 6 is equally likely. Likewise, in the throw of a coin the coming up of head or tail is equally likely.

Independent Events: An event is said to be independent if it's happening is not affected by the happening of other events. Thus, in the throw of a disc repeatedly, the coming up of 5 on the first throw is independent of the coming up of 5 again in the second throw.

Dependent Events: If we are successively drawing cards from a pack (without replacement) the event would be dependent. The chance of getting a king in the first draw is $4/52$ (as there are four kings in a pack). If this card is not replaced before the second draw, the chance of getting a king is again $3/51$ as there are now only 51 cards left and they contain only 3 kings.

If however the card is replaced after the first draw, the event would remain independent. In each of the successive draws, the chance of getting a king would be $4/52$.

Favorable Cases: The numbers of outcomes which result in the happening of a desired event are called favorable cases. Thus in a single throw of a disc, the number of favorable cases of getting an odd number are three 1, 3, & 5. Similarly, in drawing a card from a pack, the cases favorable to getting a spade are 13 (as there are 13 spade card in the pack).

Mathematical or Classical or a "Priori" definition of Probability: If a random experiment results in N-exhaustive mutually exclusive and equally likely outcome (cases) out of which 'm' are favorable to the happening of an event 'A'. Then the probability of occurrence of 'A' usually denoted by P (A) is given by

$$P(A) = \frac{\text{Favorable number of cases to A}}{\text{Exhaustive number of cases}}$$

Or $P(A) = m/N$

Statistical / Empirical Probability:

$$P(A) = \lim_{N \rightarrow \infty} m / N$$

It means probability of happening of the limit.

Remember:

1. In statistics, probability of happening of 'A' is written as P (A) or simply (A).
2. Probability of not happening of the limit 'A' is written as P (\bar{A}).
3. Suppose, there are two events A& B. A+B means either A happens or B happens or both happen. Both happens means both simultaneously happen.
4. Probability always lies between 0-1. Never say probability is negative or positive.

Question: Suppose A & B are mutually exclusive events. Then A & B means what?

Solution: It means either A happens or B happens or it means if A happens then B is not happens. Here both happen are zero if they are independent.

Permutations and combination: The words permutation refers to the “arrangement” and combination refers to “group”. These terms are used in the calculation of probability. Some simple rules of Permutation and Combination are given below:

1. The permutation of ‘n’ dissimilar things taken all at a time is $n!$. Thus, if there are three letters A, B, & C, the total number of ways in which they can be arranged is $3! = 3 \times 2 \times 1 = 6$ i.e. ABC, ACB, BCA, CAB, BAC & CBA.
2. The permutation of ‘n’ dissimilar things taken ‘r’ at a time is ${}^n P_r$ or $n! / (n-r)!$. Thus, if we have to arrange any two letters out of three (A, B, & C), we can arrange them as ${}^3 P_2$ or $3! / (3-2)!$ Or $3 \times 2 \times 1 / 1 = 6$ ways i.e. AB, BA, BC, CB, CA, AC.
3. The number of permutations of n things when n_1 of them are of one kind and n_2 of another kind is given by $n! / (n_1! n_2!)$. Thus, if we have to find out the permutation of the letter of the word ‘FARIDABAD’ (where ‘A’ occurs three times and ‘D’ occurs two times), the answer would be $9! / 3! 2! = 9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1 / 3 \times 2 \times 1 \times 2 \times 1$.
4. The number of combination of ‘n’ different things taken ‘r’ at a time is given by ${}^n C_r$ or $n! / (r! (n-r)!)$. Thus, if we have to pick up two alphabets out of the three A, B, & C; we can pick up as ${}^3 C_2 = 3! / 2! (3-2)! = 3 \times 2 \times 1 / 2 \times 1 \times 1 = 3$ i.e. AB, AC, or BC. We had seen that the number of permutations in this case was 6 because each combination can be arranged in two ways as AB, BA, AC, CA, BC, and CB. Thus, the number of permutation is equal to the number of combinations multiplied by ‘r’. In other words, ${}^n P_r = {}^n C_r \times r$ or ${}^n C_r = {}^n P_r / r$

Remember: $5! = 5 \times 4 \times 3 \times 2 \times 1 = 120$; $0! = 1$; $1! = 1$

Question: There are three students. I want a combination of either A student or B student or C student. Then what is the probability of A.

Solution: Since, Probability = Favorable Cases / No. of Cases = $4 / 7$.

A + B + C

A, B, C

AB, BC, AC

ABC

${}^3 C_1$

${}^3 C_2$

${}^3 C_3$

Question: What is the probability of a random event?

Solution: $\frac{1}{2}$

Question: What is the probability of getting 53 Sunday in a leap year.

Solution: Leap year is always after 4 year in which 29 days are there in February month.

Leap Year = 366 days.

Probability = $366 / 7 = 52. (2 / 7) = 2/7$

Theorem of Probability: There are three theorems of probability. These are:

Theorem of addition

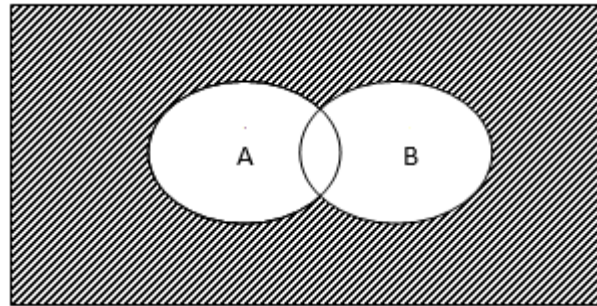
Theorem of multiplication

Baye’s theorem

Theorem of addition: The probability of happening of at least one of the several mutually exclusive events is the sum of the probability of each event. If E_1, E_2, E_3, E_4 are four mutually exclusive events then,

$$P(E_1+E_2+E_3+E_4) = P(E_1) + P(E_2) + P(E_3) + P(E_4)$$

Caution: The theorem of addition will not be applicable when the events are not mutually exclusive (when two or more event can take place together). The following diagram explains the nature of two events which are not mutually exclusive or are overlapping.



The addition formula in such cases then takes the following shapes:

$$P(A \text{ or } B) = P(A) + P(B) - P(AB)$$

If there are three such events then,

$$P(A \text{ or } B \text{ or } C) = P(A) + P(B) + P(C) - P(AB) - P(AC) - P(BC) + P(ABC).$$

Theorem of multiplication: If A, B are two events occur simultaneously then probability of simultaneously occurrence of two events A & B means

$$P(AB) = P(A) \cdot P(B/A)$$

(B/A) means event B happens when A has already occur.

Conditional occurrence of B = B/A when A has already occurred. This is called theorem of multiplication.

This can also be written as $P(AB) = P(B) \cdot P(A/B)$. It means conditional occurrence of A if B has already occurred.

Note: AB means simultaneously occurrence of both the event. ABC means simultaneously occurrence of all the three events.

Theoretical distribution: it is also known as distribution of count because of specific countable number.

Difference between theoretical distributions and frequency distribution: A distribution which is based on observation and experimentation is called frequency distribution. The variable in frequency distribution does not follow the exact law. E.g. if we throw a coin, the distribution of head or a distribution of tail is a frequency distribution. While, theoretical distribution is based on probability distribution. In theoretical distribution, variables follow an exact mathematical law.

Distribution: It shows the trends on which the variables taking different values.

Variable: A thing which takes any value.

Variate: When a variable takes a certain value at certain probability, it is known as variate. Other name given to variate is random variable, stochastic variable, chance variable.

Probability distribution: How the probability values are falling in a particular pattern.

Probability model: Specific value of probability distribution is called probability model. E.g. model may be a set which is taken from a particular trial. In model, we chose a particular distribution.

Types of theoretical distribution: Two

Theoretical discrete distribution,

Theoretical continuous distribution.

Theoretical discrete distribution: These include

Bernoulli's distribution, ii) Binomial distribution, iii) Poisson distribution, iv) Negative binomial distribution

Theoretical continuous distribution: Normal distribution

Remark: For every distribution, we can calculate mean, variance, skewness and kurtosis because these are helpful in making comparison.

Why we study distribution? We study distributions for comparison and interpretation of data.

Continuous random variable: A random variable X is said to be continuous if it can take all the possible values between certain limit.

Discrete random variable: A random variable X is said to be discrete if it can take a specific value.

Probability density function: Whenever the variate is continuous, the probability function is known as probability density function (p.d.f). It will generate probability between two limits.

Probability mass function: Whenever the variate is discrete, the probability function is known as probability mass function (p.m.f). It will generate probability at a particular point.

Bernoulli's Distribution: A random variable X is said to be a Bernoulli's variate if it takes the value of head as $X=1$ (successful event) with probability 'p' and takes the value of tail as $X=0$ (failure event) with probability 'q' then, this distribution is called Bernoulli's distribution. Bernoulli's distribution takes the value of 0 and 1. For example, germination of seed follows Bernoulli's distribution.

Conditions of Bernoulli's distribution: There are four conditions of Bernoulli's distribution. These are: 1. each trial has independent event. 2. Probability of successful event is 'p'. 3. Probability of failure event is 'q'. 4. An experiment is performed under the same conditions for a fixed number of trial.

Why should we study Theoretical distribution? We study theoretical distribution because these parameters are known to us and are helpful for us in comparison. We study Bernoulli's distribution for comparison and interpretation.

Remark: For every distribution, we can calculate mean, variance, skewness and kurtosis because these are helpful in comparison.

Binomial Distribution: It is again a discrete type of theoretical distribution and is more advanced than the Bernoulli's distribution. Here, 'Bi' means two and 'Nomial' means expression. The expansion of binomial expression is known as Binomial distribution.

If a coin is tossed once, there are two outcomes, namely head or tail. The probability of obtaining head i.e. $p = 1/2$ and the probability of obtaining tail i.e. $q = 1/2$. Thus, $(q+p) = 1$. These are the terms of the binomial $(q+p)$. The general form of binomial distribution thus is given by

$$P(r) = {}^n C_r q^{n-r} p^r \text{ -----(1)}$$

Where, p = probability of success in a single trial.

$q = 1-p$; n = number of trial; and r = number of success in 'n' trial.

Equation (1) is called the probability mass function of the binomial distribution. N and p are known as the parameters of the binomial distribution. 'n' is also known as degree of binomial distribution.

Properties of Binomial Distribution: 1. Shape and location of binomial distribution changes as 'p' changes for a given 'n'.

2. The mode of binomial distribution is equal to the value of x which has higher probability.

3. As 'n' increases for a fixed 'p', the binomial distribution moves to the right, flattens and spread out.

4. If 'n' is large and if neither 'p' nor 'q' is too close to zero, the binomial distribution can be closely approximated by a normal distribution with standard variate given by

$$Z = \frac{X - np}{\sqrt{npq}}$$

The approximation becomes better with increasing 'n'.

1. Mean of the binomial distribution is equal to 'np'.
2. Variance of the binomial distribution is equal to 'npq'.
3. Mean is always greater than variance in binomial distribution.
4. Coefficient of skewness of binomial distribution is given by ' β_1 ' and is equal to $(q-p)^2 / npq$.
5. Coefficient of kurtosis of binomial distribution is given by ' β_2 ' and is equal to $3 + (1-6pq) / npq$.

Importance of Binomial Distribution:

1. The outcome of each trial in the process is characterized as one of the two types of possible outcomes. In other words, they are attributes.
2. The possibility of outcome of any trial does not change and is independent of the result of previous trial.
3. Sum of the independent binomial variate is not a binomial variate. In other words, binomial distribution does not possess the additive or reproductive properties.

Poisson distribution: The Poisson distribution is defined as

$$P(r) = e^{-m} m^r / r! \text{ ----- (1)}$$

Where, $r = 0, 1, 2, 3, \dots$

$$E = 2.7183 \text{ (base of natural log)}$$

m = mean of the Poisson distribution i.e. ‘ np ’ or the average number of occurrences of an event. ‘ m ’ is also known as the parameter of the distribution and is always greater than zero.

This is the probability mass function or the probability model of Poisson distribution because it will generate a population of probability for different values of ‘ r ’. It is a discrete theoretical distribution with a single parameter ‘ m ’. As ‘ m ’ increases, the distribution shifts to the right. All the Poisson distribution is skewed to the right. This is the reason why Poisson distribution has been called the “probability distribution of rare events”. The probability tends to be high for small number of occurrence.

Postulates of Poisson distribution: Successful event occur in time obeying the following the following points.

1. The number of time the success occurs in any interval of time is independent of the number of the occurrence of the successes in any other disjoint time interval.
2. The chances of two or more occurrences happening simultaneously can be assumed to be zero.
3. The average number of occurrence per unit of time is constant and it does not change with time.
4. When average number of successes are known per unit of space than we use Poisson distribution.

Poisson distribution as a limiting case of Binomial distribution: Poisson distribution is a limiting case of Binomial distribution under the following conditions:

1. Number of trial i.e. ‘ n ’ is independently large i.e. $n \rightarrow \infty$
2. ‘ p ’ the constant probability of success for each trial is independently small i.e. $p \rightarrow 0$
3. ‘ np ’ = m (say) is finite. Thus $p = m/n$ and $q = 1 - m/n$. where ‘ m ’ is a positive real number.
4. The Poisson distribution is a good approximation of the Binomial distribution when $n \geq 20$ and $p \leq 0.5$

If the above conditions hold well, we can substitute the mean of the Binomial distribution (np) in place of the mean of the Poisson distribution (m) so that the formula becomes

$$P(r) = e^{-np} (np)^r / r!$$

Other Characteristics of Poisson distribution:

1. Mean and variance of the Poisson distribution are same i.e. ‘ m ’.
2. Coefficient of skewness of Poisson distribution $\beta_1 = 1 / \sqrt{m}$.
3. Coefficient of Kurtosis of Poisson distribution $\beta_2 = 1/m$.

4. Poisson distribution is always a skewed distribution and its standard deviation is \sqrt{m} and standard Poisson variate = $x - m / \sqrt{m}$.
5. Sum of the independent Poisson variate is also a Poisson variate.

Negative Binomial Distribution: The equality of the mean and variance is an important characteristic of the Poisson distribution, whereas for Binomial distribution mean is always greater than variance. But, occasionally, observable phenomenon gives rise to empirical discrete distributions which shows a variance larger than mean. Some of the commonest examples of such behavior are the frequency distribution of plant density obtained by quadrant sampling when the clustering of plants makes the simple Poisson model inapplicable. In such a case, negative Binomial distribution provides an excellent model because this distribution has a variance larger than mean. For example, death of insect, number of insects bite lead to a negative binomial distribution and the distribution also arises in inverse sampling from a binomial population or as a weighted average of Poisson distribution. Poisson distribution as a limiting case of Negative Binomial distribution.

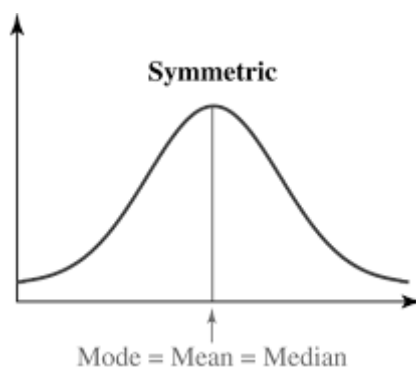
Normal Distribution: A random variable X is said to have a normal distribution with parameter u (called mean) and σ^2 (called variance) if its density function is given by the probability law:

$$f(x; u, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{x-u}{\sigma}\right)^2\right\}$$

$$\text{or } f(x; u, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-1/2(x-u)^2/2\sigma^2}, \quad -\infty < x < \infty \text{ \& } -\infty < u < \infty, \sigma > 0$$

Chief characteristics of the normal distribution and the normal probability curve:

1. The curve is bell shaped and symmetrical about the line $x = u$
2. Mean, median and mode of the distribution coincide
3. As x increases numerically, f(x) decreases rapidly, the maximum probability occurring at a point $x = u$ and is given by
4. $[p(x)]_{\max} = 1/\sigma\sqrt{2\pi}$
5. Coefficient of skewness(β_1) is equal to zero and coefficient of kurtosis (β_2) is equal to 3
6. Since f(x) being the probability, can never be negative. No portion of the curve lies below x-axis.
7. X-axis is asymptotic to the curve
8. Linear combination of independent normal variate is also normal.



Normal Probability Curve

8. The point of inflection of the curve are given by

$$[x = u + r, f(x) = \{1 / \sigma\sqrt{2\pi}\} e^{-1/2}]$$

9. Mean deviation about mean is given by

$$\sqrt{2/\pi} \cdot \sigma = 4/5 \cdot \sigma \text{ (approx.)}$$

$$10. \text{Q.D.} = (Q_3 - Q_1)/2 \approx (1/2) \sigma$$

11. In normal distribution, the sample size is large.

12. Normal distribution is a particular case or a limiting case of Binomial distribution when $n \rightarrow \infty$ and neither p nor q is very small.

Area property:

$$P(u - \sigma < X < u + \sigma) = 0.6826$$

$$P(u - 2\sigma < X < u + 2\sigma) = 0.9544$$

$$P(u - 3\sigma < X < u + 3\sigma) = 0.9973$$

The table gives the area under the normal probability curve for some important values of standard normal variate Z.

Distance from the mean ordinates in terms of $\pm \sigma$	Area under the curve
$Z = \pm 0.745$	50% = 0.50
$Z = \pm 0.196$	95% = 0.95
$Z = \pm 0.2.58$	99% = 0.99

Note: In normal distribution, we have probability density function (pdf). Probability density function will generate probability value between two limits. Probability mass function (pmf) will generate probability at a particular point. Any distribution when its size is very large then, it becomes normal distribution. Normal distribution is also called the normal probability distribution or symmetrical distribution or distribution of error happens to be the most useful theoretical distribution for continuous variable. In normal distribution, sample size is large. The whole data are uniformly distributed for normal distribution. Sometimes, the data are not uniformly distributed for normal distribution then; we transform the data into normal form. There

are different transformations by which we transform the data into normal form. These transformations are:

Under-root transformation,

Arc-sine transformation,

$\sqrt{(x + 1/4)}$ transformation.

We use transformation just to convert the data into normal form. With the help of scattered diagram, the shape of the curve go on changes as the value of σ either increase or decrease (σ = error). We choose smaller value of σ for normal distribution.

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SUSTAINABLE AGRICULTURAL PRACTICES FOR A FOOD SECURE INDIA

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Abstract

Herbal drugs and vegetarian diet food have gained attention after the outbreak of COVID-19. People are exploring healthy ways of living and adopting traditional way of living. With changing climate conditions, we need to find ways of sustainable agriculture. Present article discusses how our neglected crops like millets and heirloom plants are not only good for health but also good choices for sustainable agriculture. GI tagging helps in increasing reach and economical value of such crops. Importance of mushrooms for supplementing protein in vegetarian diet and medicinal plants for the production of herbal drugs are also discussed. The need of the hour is to lean towards traditional ways of living and sustainable agriculture for food security and a healthy life.

Keywords: Millets, Pseudo-Cereals, Heirloom Crops, Landraces, Traditional Varieties, Native Crops, Heritage Crops, Medicinal Plants, Mushrooms.

Introduction

Zero hunger and food security is the second sustainable developmental goal adopted by United nations in 2015 (Mishra 2025 a,b ; United Nations 2026). Due to changing climatic conditions and global warming, we need plants which can tolerate high temperature and can grow in water scarcity. Millets and Heirloom plants are suitable choices for such conditions and a sustainable agriculture. Millets are short duration resilient C4 plants which have more photosynthetic efficiency than C3 plants, grow well on acidic to alkaline soil. They are drought and thermo-tolerant and do not require much care. Recognising the high potential of millets, United nations declared year 2023 as “International year of Millets” (Mishra 2025a).

Heirloom plants are our neglected heritage crops which are vanishing gradually However, they are hardy and highly nutritious and well suited to local climatic conditions. Before the introduction of high yielding hybrid varieties, they were cultivated widely in India. They thrive well in water scarcity and are tolerant to many abiotic stresses. Revival of their cultivation at large scale can aid in food security of India (Mishra 2025b).

After the COVID pandemic of 2019, people are switching to vegetable diets for their protein requirements and herbal medicines to combat diseases. Mushrooms have emerged an alternative source of protein and new medicinal plants are being explored for herbal drugs. In the present article, a brief account of mushrooms and an important medicinal plant *Trichopus zeylanicus* (Arogyapacha) is also discussed with reference to sustainable living practices.

Millets

Milletts are small seeded plants with coarse grains belonging to the family of Poaceae. They are rich sources of macronutrients and micronutrients. Milletts have low glycaemic index, gluten-free and are rich sources of protein, vitamins and minerals and can be grown in summers as well as winter season. Milletts are classified on the basis of their grain size as as large or major milletts and small or minor milletts. Jowar (*Sorghum vulgare*, Sorghum), Bajra (*Pennisetum typhoides*, Pearl Millet) and Ragi (*Eleusine coracana*, Finger Millet) are examples of **large or major milletts**. Kutki (*Urochloa ramosa*, Little Millet), Sama (*Echinochloa esculenta*, Barnyard Millet) and Hari Kagni (*Panicum miliare*, Browntop millet) are examples of **small or minor milletts**.

Milletts are hardy crops

Milletts can be grown in soils of low fertility and have low water requirements. Pearl millet (Bajra) requires a 20 cm rainfall compared to rice which requires an average rainfall of 120–140 cm (Mishra, 2025a). Milletts takes less time to grow compared to our staple crops wheat and rice. For example Barnyard millet (Sama) takes 45–70 days to grow while rice takes around 120–140 days. Another advantage is that they have minimal requirements of fertilizers and pesticides . They can be stored for periods as long as 10-12 years (Kumar *et al.*, 2018).

Milletts are called as 'mota anaaj' or poor man's food and grain made of milletts may not be as delicious as wheat or rice. However, there are immense benefits of milletts. Their protein concentration is comparable to wheat, rice and maize along with having high fibre content and low glycaemic index (ISTI, 2026). Low glycaemic index results in reduced spike of glucose after consuming milletts, which leads to reduced risk of diabetes and cardiovascular diseases (Kumar *et al* 2018). Releases of sugars slowly in body increases the happy hormone 'dopamine' levels and enhances mood and energy (Mishra, 2025a).

Pseudo-cereals

Another class of cereals called pseudo-cereals have seeds resembling cereals. However, they are dicotyledonous plants and do not belong to cereal family Poaceae. They have nutritional content similar to cereals and does not require much water and fertilisers for growing. *Ramdana* or *chaulai*, (*Amaranthus caudatus*) and buckwheat (*Kuttu*, *Fagopyrum esculentum*) are examples of pseudocereals. These can be easily grown like milletts and can be grown on marginal lands also (Nagar *et al.*, 2022).

Heirloom cultivars are resilient heritage crops

Heirloom plants are open pollinated, non-hybrid, desi or folk varieties of plants, found in specific geographical region. The seeds of these desi cultivars are passed from one generation to other and hold heritage value. These crops, can be grown with minimal requirements of fertilizers and even without fertilizers and have immense health benefits. These crops are suitable choices not only for sustainable agriculture but also for conserving our biodiversity. To combat global

warming and changing climatic conditions, revival of cultivation of these crops at large scale is need of the hour.

During green revolution, high yielding hybrid varieties of crops were introduced in India. However, their cultivation require lot of water, fertilizers and pesticides. Their demand gradually increased due to government subsidies on them. This started monoculture of hybrid varieties of wheat and rice. Gradually heirloom cultivars faced lot of competition from them and started vanishing (Chorol *et al.*, 2018, Dwivedi *et al.*, 2019).

Heirloom cultivars are highly nutritious and they have high levels of vitamins and nutrients. For food security for poor farmers, these desi landraces should be included in food and agriculture policy of India (Ray *et al.*, 2021).

Some important Heirloom plants of India



Figure 1: Some heirloom rice growing regions of India (Photo credit : Pinterest , Slurp

<https://in.pinterest.com/pin/586875395208535366/>)



Figure 2: Map showing regions of India rich in heirloom crops (Photo Credit: Pinterest <https://in.pinterest.com/pin/947867052815828255/>)

India is a treasure trove of heirloom plants. It's Sub-Himalayan Terai region is rich in heirloom rice cultivars (Mondal *et al.*, 2021). They have unique and delicious taste and are very colourful as well as resistant to pests and diseases. *Bhutmuri*, rice cultivar grown in West Bengal is rich in iron and B complex vitamins. Consumption of starch from rice of this cultivar cures peripartum anaemia in women. It helps in restoration of blood in anaemic women and after childbirth (Mondal *et al.*, 2021, Mishra 2025b). Cultivar *Bardhaman Sitabhog* grown in Bengal has a unique sweet taste. Cultivar *Dudh-sar* enhances milk production in lactating mothers. However, these local landraces are not much in demand due to monopoly of hybrid varieties. They are grown by only a few poor farmers and are on the verge of extinction. These heirloom cultivars are immensely beneficial due to their nutritional benefits. Some heirloom rice growing regions of India are shown in figure 1. There are lot of heirloom vegetables also/ *Gya-labuk* is heirloom radish and *nyungma* is heirloom turnip grown in Ladakh. They have long shelf life and can withstand harsh cold conditions (Chorol *et al.*, 2018). They have a shelf life of more than five to

six months and local people store them for winter. India has a rich diversity of such landraces shown in figure 2.

GI tags enhance the economic potential of heirloom crops

Geographical indication tag or GI tag refers to the place of origin of a product. GI tags are markers of authentic products. This tag indicates quality and uniqueness of the product of a specific geographic area (Bisoyi, 2024). It protects the rights of growers by preventing delinquency of product and consumer can identify the authentic products by GI tags. Department for Promotion of Industry and Internal Trade, Ministry of Commerce and Industry awards GIs in India. GI tags have proved to be economic catalysts. It enhances the economic potential of heritage crops and empower farmers and local communities. It brings fame and attention of the local products to a global level. It makes a brand identity of the product, helps in enhancing its price and finally making a stronger economy of the country. Since GI tagged agricultural products mostly come from rural areas, these generate income, create employment opportunities, reduce poverty and boost economy in these otherwise underprivileged areas. India has a rich diversity of GI tagged agriculturally important products (Table 1). In the year 2023, Department of posts, Government of India illustrated importance of these produces by releasing stamps on some GI tagged fruits (Figure 3).



Figure 3: Stamps released by Department of Posts, Government of India on GI tagged heirloom fruits (Photo credit: Philacy <https://philacy.com/product/miniature-sheet/13-2-2023-geographical-indications-agricultural-goods-miniature-sheet>)

Heirloom plants are more tolerant to abiotic stresses like drought, cold etc. and also resistant to disease and pest compared to hybrid varieties. Government of India should come up with policies so that these are cultivated widely and help in sustainable agriculture.

Table 1: Some popular GI tagged agricultural products from different parts of India (Source: Wikipedia)

S.No.	State	GI tagged products
1	Arunachal Pradesh	Arunachal Orange
2	Bihar	Mithila Makhana
3	Himachal Pradesh	Kangra Tea
4	Jammu and Kashmir	Kashmir Saffron
5	Karnataka, Kerala, Tamil Nadu	Malabar Pepper
6	Manipur	Black Rice
7	Rajasthan	Bikaneri Bhujia
8	Sikkim	Sikkim Large Cardamom
9	Tamil Nadu	Tall Coconut
10	West Bengal	Dargeeling Tea
11	Odisha	Kala Jeera Rice

Cultivation of medicinal plants for sustainable herbal drugs

People are exploring plants as herbal remedies for many diseases after COVID pandemic. Herbal drugs are believed to have lesser side effects than allopathic medicines. Using plants for curing diseases is an age old practice and still considered healthy. Many new plants are being explored and *Trichopus zeylanicus* (Arogyapacha) growing in Kerala is one of them. The Kani Tribe of Kerala consumes leaves of *Trichopus zeylanicus* (Arogyapacha) to remain healthy and young. It gives instant energy and source of anti-fatigue drug “Jeevani”. It has antidiabetic as well as anticancer properties also (Biju *et al.*, 2019). Local tribal helped in the discovery of Arogyapach. After this discovery, it was cultivated in more than 20 hectares of land for the production of this drug (Down to Earth, 2012). These conservation strategies are examples where local people not only help in conservation of plant but also help in sustainable production of herbal drugs.

Such medicinal plants should be cultivated at large scale by encouraging local communities to grow them. Local people can sell them to pharmacy companies and generate money by selling them. Biodiversity conservation and sustainable agricultural practices grow hand in hand this way.

Mushroom Cultivation

The nine essential amino acids necessary for growth and development can not be made in human body and is obtained from diet. Milk, Meat and poultry obtained from animals are the sources of

these essential amino acids. Generally, people take animal meat and their products to fulfil the requirements of essential amino acids. However, all the essential amino acids are present in edible mushrooms. They can serve as an alternative and complete protein source in vegetarian diet (Ayimbila 2023, Bach *et al.*, 2017, Liu *et al.*, 2025). Mushrooms can be grown easily on agricultural wastes like paddy and wheat straw. Marginal Farmers with meagre means and small lands can cultivate mushrooms on agricultural wastes like paddy straw. They can grow them throughout the year and sell them to increase their income (Chand and Singh 2022). Mushroom cultivation can also help in controlling air pollution as it utilises waste and reduces stubble burning. Sustainable vegetarian food diets are eco-friendly and helps in nutrition as well as food security.

Use of bio fertilizers and traditional remedies for insects and pests for sustainable agriculture

Modern fertilizers increase productivity in short terms but also come with long term adverse effects on ecology. Bio fertilizers are good substitute or supplements to achieve more sustainable, eco friendly, easily available and economically viable option (Ghimirey 2024; Daniel 2022). Nitrogen-fixing bacteria like *Rhizobium*, *Azotobacter*, *Azospirillum* increases fertility and productivity of soil. It also improves physical and chemical properties of soil. Sustainable agriculture can be achieved with biofertilizers (Ghimirey 2024). Similarly, organic farming practised with vermicomposting enhance soil fertility Blouin (2019). Traditional ways to tackle pests and insects are sustainable ways of living and reduces soil pollution. Sprinkling neem water, turmeric water on plants to remove pests are age old practices. Using compost and manures can increase fertility of soil and combat pollution also. Such agricultural practices will help us in achieving our goal of sustainable agricultural.

Conclusion

Cultivating Millets, heirloom crops greatly support United Nations Sustainable Development goals and sustainable agriculture. Growing mushrooms and medicinal plants are also ways of good agricultural practices. These practices help in conserving biodiversity and can help in combating air and soil pollution. This sustainable practice along with growing medicinal plants also helps in elevating economical and social condition of rural areas.

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ADVANCES IN SUSTAINABLE AGRICULTURE IN INDIA: ROLE OF AGRITECH, PRECISION FARMING TECHNIQUES AND GOVERNMENT INITIATIVES DRIVING SUSTAINABILITY

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Introduction

Sustainable agriculture integrates environmental health, economic profitability and social equity to produce food while conserving natural resources. Its main focus is on improving soil fertility, reducing chemical use, conserving water and fostering biodiversity to ensure long-term viability. Sustainable agriculture in India is advancing rapidly through Climate-resilient crop varieties, digital technology and government backed organic farming, aiming to reduce chemical reliance and improve water efficiency.

Key advancements include 109 new climate-resilient crop varieties, wide adoption of natural farming, drone-enabled surveillance and IoT-driven precision irrigation systems like drip and sprinkler systems that reduce water use by 25-85%.

Key Advancements in Sustainable Agriculture

Climate-Resilient Crops & Research: India has introduced drought-tolerant and flood-resistant paddy and heat-tolerant wheat to combat climate change, with 109 new, high-yielding and climate-resilient crop varieties developed to ensure food security.

Agri-Tech and Precision Farming: includes applications of the following-

Drones & Iot: Drones & IOT drive sustainable agriculture by enabling precision farming, which reduces resource waste and environmental impact. Drones provide aerial imaging for crop monitoring, health assessment and targeted spraying.

Drones identify areas requiring pesticides or nutrients, enabling precise application only where needed rather than blanket spraying, which protects the surrounding environment and reduced costs.

Through the 'NAMO Drone Didi' scheme and the Kisan Drone Scheme (2022) the government aims to boost productivity and provide employment. ICAR reported demonstrations covering about 41,010 hectares benefitting over 450,000 farmers

IoT sensors offer real-time data on soil moisture, nutrients and weather optimizing water and chemical use. IoT sensors monitor soil nutrients and moisture in real-time, allowing for precise, automated irrigation and fertilizer application to reduced waste.

The combination of drone data and IoT sensors enables faster, data-driven decisions that reduce the overall ecological footprint, such as optimizing water usage and reducing fertilizer runoff.

The *key challenges* of Agricultural drones involves high initial cost, training gaps, regulatory barriers and that of IoTs suffer from poor rural internet connectivity, high maintenance costs.

AI & Machine Learning: AI & Machine Learning drive sustainable agriculture by optimizing resource use, reducing chemical inputs, and enhancing predictive capabilities. These technologies enable precision farming via sensors, drones and satellites to monitor crop health, reduce water waste and detect disease early, resulting in higher yields.

AI algorithms analyze sensor and satellite data to determine the exact needs of crops, optimizing water, fertilizer and pesticide application. This prevents overuse, reduces costs and minimizes pollution.

Computer vision and Machine learning enable early identification of crop disease and pest infestations before they spread. This allows for targeted, localized intervention rather than broad-spectrum spraying.

Agri Stack: It is a digital public infrastructure developed by the Ministry of Agriculture and Farmers Welfare, advances sustainable agriculture by Integrating GPS-tagged land records, real-time satellite data and soil health information.

It enables precision farming, accurate input subsidies, and tailored, data-driven advisories to farmers, promoting ecologically and financially sustainable practices. Through real-time monitoring of crop conditions and pest outbreaks, farmers can implement targeted interventions, minimize the overuse of chemicals and adopt eco-friendly, sustainable techniques.

By directly connecting farmers to markets and mandis, Agristack reduces post-harvest losses and improves price discovery, supporting the economic viability of farming.

AgriStack promotes a, “*build once-use in multiple schemes*” approach, which helps in efficient, data-driven policy planning for a more resilient agricultural sector.

A government initiative building an ecosystem for digital services, including a Digital Crop Survey across 400+ districts to aid in precision agriculture.

Natural and organic farming expansion: The government is pushing to transition over one crore farmers to natural farming, supporting the setup of 10,000 bio-input resource centres.

“Sikkim is recognized as India’s first 100% organic state”

Madya Pradesh leads in total organic area, contributing significantly to national organic production.

Maharastra features extensive certified areas with strong producer organizations

Gujarat is well known for substantial organic clusters and high farmer adoption rates

Rajasthan focuses on dryland organic farming, focusing on crop rotation and water saving methods.

Karnataka known for growing organic coffee and horticultural crop varieties.

Water management Technologies: sustainable water management in agriculture focuses on increasing water use efficiency to maximize crop yield while minimizing wastage and

environmental impact. Key practices include adopting precision irrigation, rainwater harvesting, soil moisture management, and treating/reusing waste water.

- Implementing techniques like composting increases soil organic matter, improving water retention and reducing evaporation.
- Capturing rain water through ponds or tanks for agricultural use reduces reliance on groundwater, ensuring supply during dry periods.
- Employing sensors to monitor soil moisture and automating irrigation schedules allows for real-time adjustments based on exact plant needs.
- Reducing water loss by using technology like laser land leveling improves irrigation efficiency
- Rotating crops and choosing drought-resistant varieties based on available water resources reduces demand.

Adoption of direct seeded rice, laser land leveling and drip irrigation to minimize water wastage and increase efficiency.

Comparison over the years from 2017-2025

Feature	2017	2025
Irrigation	Time-based automation	Real-time AI-based,
Water monitoring	Manual checks and basic sensors	IoT-enabled real time AI dashboards
Leak Detection	Visual inspection	UAV/RoboticThermal detection
Crop choice	Traditional crops	Drought-resistant
Water source	Fresh groundwater	Treated & Recycled water

Soil Health Initiatives: Promotion of biochar and soil microbial communities to improve soil carbon and structural health, alongside traditional, low-cost organic methods.

Government initiatives Driving Sustainability

National Mission for Sustainable Agriculture (NMSA): This was launched in 2014-15. This is a key component of India’s National Action Plan on Climate Change (NAPCC).

NAPCC aimed at making agriculture productive, sustainable and climate-resilient. It promotes location-specific integrated farming, soil health management and efficient water use.

“More Crop per Drop”

The mission focuses on transforming Indian agriculture into a climate-resilient production system through enhanced resource conservation and technology adoption.

Promotes organic farming, soil health management, and efficient water use.

Rashtriya Krishi Vikas Yojana(RKVY-RAFTAAR): focuses on agricultural research, innovation and infrastructure.

RKVY: The scheme offers financial support for technological upgrades, infrastructure development, and natural farming practices, with over Rs.1,100 crore approved for initiatives in states like Haryana as of March 2026.

Key objectives and impact:

Funding Mechanism: RKVY operates with a 60:40 fund sharing ratio between the central and state governments.

State flexibility: States have the autonomy to plan and execute projects aligned with local agro-climate conditions.

Infrastructure Enhancement: Support for pre- and post-harvest infrastructure, such as modern irrigation and agricultural machinery to increase agricultural productivity.

Support for Allied sectors: RKVY includes horticulture, fisheries and apiculture, supporting a broader, sustainable agricultural system.

For e.g., a Rs. crore action plan for 2026-2027 in Haryana focuses heavily on sustainable practices, including Rs.15 crore for natural farming and Rs.250 crores for crop residue management.

Key RKVY initiatives for sustainable agriculture include:

Natural farming: It is a chemical-free, regenerative agricultural system that works with nature

- to enhance soil fertility
- promote biodiversity
- Lower production costs

It relies on low-cost bio-inputs rather than synthetic fertilizers/pesticides.

- Fosters sustainable livelihoods
- Healthy ecosystems
- Nutritious food production.
- Total exclusion of chemical fertilizers
- Minimal soil disturbance
- 365 days a year with living plants
- Encourages livestock integration

NMNF (Natural Mission on Natural Farming) is current being expanded in India to cover large areas of farmland, providing financial incentives for farmers to adopt the above methods and establish bio-input resource centers.

Soil health Management: Sustainable soil management for agriculture involves maintaining soil health, increasing organic matter and reducing erosion to support long-term productivity and ecosystem services. Core strategies for sustainable soil management includes-

- Using compost, green manure to boost soil structure, water retention
- Using techniques like terracing, windbreaks and buffer strips to protect topsoil
- Applying fertilizers based on soil test
- Using cover crops to prevent erosion and increase bio-diversity
- Foster beneficial microorganisms and insects to improve soil nutrient cycling

The above practices help transition agriculture toward a more sustainable system, reducing environmental damage and ensuring long-term food security.

Merging Soil Health cards into RKVY to manage nutrient levels through integrated nutrient management.

Rainfed Area Development: This plays a major role in food production contributing significantly to food requirements in country like India. They are crucial for agricultural biodiversity. It is an agricultural region where farming relies entirely on natural rainfall rather than artificial irrigation. They often feature dryland or rain dependent farming with low rainfall of less than 750mm. this is usually fit for growing low-water-consuming crops.

Organic farming Promotion: Supporting organic farming through programs like the Paramparagat Krishi Vikas Yojana (PKVY)

Agroforestry & Crop diversification: Agroforestry is the deliberate integration of woody perennials like trees/shrubs with agricultural crops and livestock. Crop diversification strategies include planting different crops such as legumes and cereals simultaneously (intercropping).

- Varying the timing of planting and harvesting such as through sequential cropping
- Diverse systems like home gardens in south India and popular-based agroforestry in punjab, Haryana and Uttar Pradesh are prominent examples.
- Promoting Climate-smart agriculture and crop diversification for enhanced resilience.

Crop Residue management: This involves utilizing agricultural leftovers straw, stover through retaining, incorporating, baling, removal to enhance soil health and prevent pollution.

- Key practice includes using machinery like Happy seeders and zero-till drills to improve soil carbon structure and nutrient cycling while reducing erosion.
- funding machinery to prevent stubble burning, reducing pollution while improving soil fertility.

On-Farm Water Management: It primarily aim to improve water use efficiency, increase coverage of assured irrigation and enhance farm productivity through precision irrigation like drop and sprinkler systems, which is now under the ***“Per Drop More Crop” component of PMKSY.***

Command Area Development & Water Management aims to bridge the gap between irrigation potential created and utilized, promoting pressurized pipe networks to stop water loss.

The government is focusing on modernizing the Command Area Development Program 2025-2026 for better efficiency.

Climate Change Adaptation: It involves adjusting farming practices to withstand increased temperatures, erratic rainfall, and extreme weather. Key techniques involve

- Planting stress –tolerant crop varieties
- Optimizing water use through drip irrigation
- Improving soil health and diversifying farming systems

- Protecting animals from heat stress through better ventilation, cooling systems
- implements initiatives like the National Initiative for Climate Resilient Agriculture (NICRA) to develop drought-and pest-resistant crops.

Sub-Mission on Agro-Forestry (SMAF): It was launched in 2016-17 under the National Mission for Sustainable Agriculture. It promotes planting trees on farmlands to increase income, provide climate resilience and secure raw materials for industries.

- The scheme focuses on boundary and block plantations offering financial incentives for planting multipurpose tree species.
- Currently active in over 20 States/UTs that have liberalized transit regulations for timber
- The policy supports India's commitment to restoring 26 million hectares of degraded land by integrating trees with agricultural systems, promoting both environmental sustainability and rural livelihoods.

This aims to increase tree coverage on farmland to enhance carbon sequestration and provide additional income.

Mission for Integrated Development of Horticulture (MIDH): This centrally sponsored scheme was launched in 2014-15 to holistically develop India's horticulture sector, covering fruits, vegetables, spices, flowers, etc.

- The mission emphasizes production of quality planting material, area expansion, rejuvenating old orchards and post-harvest management over 52000 hectares have been brought under organic farming for horticultural crops.
- To enhance horticulture production, improve nutritional security, increase income and create employment particularly for the rural youth.
- Key activities include setting up facilities to produce quality-certified planting materials
- Promoting tools for efficient horticulture farming
- Infrastructure development such as packing houses, cold storage and marketing

Future focus

The shift is towards integrating Ai-driven technologies with traditional sustainable practice like agroforestry to enhance ecological health and economic security for farmers, aiming for long-term food security despite climate challenges.

Conclusion

Sustainable agriculture is a vital, long-term solution for feeding a growing global population while protecting the environment, preserving biodiversity and ensuring economic viability for farmers.

**PLANT-DERIVED BIOACTIVES IN AGRICULTURE:
FUNDAMENTALS, CLASSIFICATION, MECHANISMS,
APPLICATIONS, AND FUTURE PROSPECTS**

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Abstract

The investigation of plant-derived bioactive molecules as substitutes for synthetic agrochemicals has intensified due to the growing demand for sustainable agriculture methods. Flavonoids, alkaloids, terpenoids, and phenolic compounds are examples of phytochemicals that are important for plant defense and growth control. These organic substances are useful tools in contemporary agriculture because of their antibacterial, insecticidal, antioxidant, and growth-promoting qualities. Their stability, bioavailability, and field efficacy have all been enhanced by recent developments in extraction methods, formulation approaches, and nano-delivery systems. Additionally, by improving soil health and lowering environmental pollution, the incorporation of phytochemicals into agricultural systems supports global sustainability objectives. The classification, mechanisms of action, agricultural uses, and prospects for the future of phytochemicals are highlighted in this chapter, with a focus on their potential for crop protection, plant growth promotion, and sustainable farming systems.

Keywords: Phytochemicals, Bioactives, Sustainable Agriculture, Biopesticides, Plant Growth Regulators, Natural Products.

1. Introduction

The desire to minimize environmental harm while ensuring food security is driving a change in agriculture. Soil degradation, biodiversity loss, and pest and pathogen resistance are all consequences of overuse of synthetic fertilizers and pesticides. Plant-based bioactive substances have become viable substitutes in this regard.

Plants naturally produce secondary metabolites called phytochemicals as part of their defense mechanisms. These compounds include flavonoids, alkaloids, tannins, terpenoids, and glycosides, which possess diverse biological activities. Their eco-friendliness and lower toxicity when compared to synthetic chemicals have drawn attention to their use in agriculture. According to recent research, phytochemicals can improve crop resilience and successfully manage plant diseases by triggering defense signaling pathways like the salicylic acid and jasmonic acid pathways. Additionally, these substances break down quickly in the environment, lessening their long-term ecological influence. Phytochemicals are now important elements of

integrated agricultural systems due to the increased interest in sustainable agriculture. Their use enhances agricultural yield, promotes organic farming, and aids in environmental preservation.

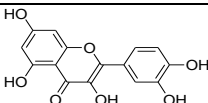
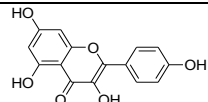
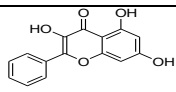
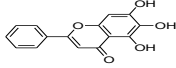
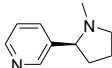
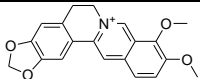
2. Classification of Phytochemicals

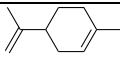
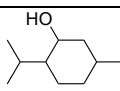
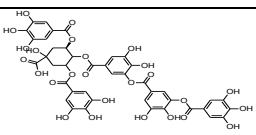
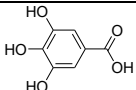
Based on their biological activity and chemical structure, phytochemicals are broadly categorized. Phytochemicals have a variety of bioactivities that support ecological balance and plant viability. Numerous agricultural applications are made possible by their structural variety. The classification of plant chemicals is shown in Table 1. The chemical structure of few phytochemicals is presented in Table 2.

Table 1: Major Classes of Phytochemicals and Their Agricultural Roles

Class	Examples	Source Plants	Agricultural Function
Flavonoids	Quercetin, Kaempferol, Galangin, Baicalein	Onion, Tea, Citrus	Antioxidant, disease resistance
Alkaloids	Nicotine, Berberine	Tobacco, Berberis	Insecticidal, antimicrobial
Terpenoids	Limonene, Menthol	Citrus, Mint	Pest repellent, antifungal
Phenolics	Tannins, Gallic Acid	Tea, Grapes	Antimicrobial, soil health
Saponins	Glycyrrhizin	Licorice	Antifungal, insect deterrent

Table 2: Chemical Structure of Selected Phytochemicals

Sr. No.	Phytochemical Name	Chemical Structure
1	Quercetin	
2	Kaempferol	
3	Galangin	
4	Baicalein	
5	Nicotine	
6	Berberine	

7	Limonene	
8	Menthol	
9	Tannins	
10	Gallic Acid	

3. Mechanisms of Action

Through a variety of interrelated mechanisms, phytochemicals affect plant health, defense, and productivity. By interacting with microbial systems, plant signaling pathways, and physiological processes, these naturally occurring substances help plants resist biotic and abiotic stressors. They are very useful in sustainable farming systems because of their multipurpose nature.

3.1 Antimicrobial Activity

The antibacterial activity of phytochemicals against a variety of plant diseases, including as bacteria, fungus, and viruses, is one of their most important functions. These substances work in a variety of ways. Numerous phytochemicals damage microbial cell membranes, causing vital intracellular components to seep out and ultimately resulting in cell death. For example, phenolic chemicals and essential oils change the permeability of membranes and cause lipid bilayers to become unstable. Phytochemicals not only disrupt membranes but also block important enzymatic pathways that are essential for bacteria survival. They restrict the growth of pathogens by interfering with metabolic enzymes involved in respiration and energy production. Additionally, some substances bind to nucleic acids to prevent transcription and DNA replication. These effects are especially well-known for alkaloids and terpenoids.

3.2 Induction of Plant Defense

Phytochemicals are crucial for stimulating the plant's innate immune system in addition to their direct antimicrobial activities. They increase resistance to infections by activating defensive signaling pathways. Systemic acquired resistance (SAR) and induced systemic resistance (ISR) are two important mechanisms at play.

SAR is usually linked to the build-up of signaling chemicals like salicylic acid, which cause pathogenesis-related proteins to be expressed. These proteins offer durable defense against a variety of infections. However, ISR involves signaling chemicals like ethylene and jasmonic acid and is mediated by beneficial bacteria. By acting as elicitors, phytochemicals increase the plant's defensive ability and activate these pathways. As a result, more defense enzymes are produced,

cell walls get lignified, and antibacterial chemicals are synthesized. In addition to shielding plants from current dangers, this kind of induced resistance also gets them ready for stressful situations in the future.

3.3 Insecticidal and Repellent Effects

Numerous phytochemicals are effective substitutes for synthetic pesticides because they have inherent insecticidal and repelling qualities. Through a variety of processes, these substances affect the physiology, behavior, and survival of insects. Some phytochemicals affect insects' neural systems by disrupting neurotransmission. Alkaloids, for instance, can cause paralysis and even death by interfering with ion channels. Others reduce crop damage by acting as antifeedants and influencing feeding behavior. Insects are often discouraged from approaching treated plants by terpenoids and essential oils. Furthermore, many phytochemicals impede insect growth and development by interfering with their hormonal systems. Molting, reproduction, and lifecycle completion are all hampered as a result. One common issue with synthetic pesticides is the development of resistance, which is less likely to occur with such comprehensive activities.

3.4 Growth Promotion

In addition to their defensive functions, phytochemicals aid in the growth and development of plants. Numerous bioactives originating from plants have hormone-like properties that impact physiological processes such cell division, elongation, and differentiation. By increasing water absorption and stimulating metabolic processes, these substances improve seed germination. Additionally, they promote root growth, which improves anchoring and increases water and nutrient absorption. Improved root architecture contributes to increased plant vigor and stress tolerance. By boosting chlorophyll content and maximizing energy use, phytochemicals further enhance photosynthetic efficiency. Certain substances help mobilize nutrients in the soil, increasing plants' access to vital components. When taken as a whole, these impacts lead to increased crop quality and yield.

4. Applications in Agriculture

Phytochemicals have several uses in contemporary agricultural operations due to their varied biological activity. Their use minimizes environmental impact while preserving productivity, which is in line with the objectives of sustainable farming.

4.1 Biopesticides

Because of their natural origin and lack of harm to the environment, phytochemicals are rapidly being developed into biopesticides. They break down quickly in the environment, unlike synthetic pesticides, which lowers the possibility of residue building up in soil and water. These substances offer efficient defense against a range of insect pests and plant diseases. Long-term efficacy is ensured by their intricate mechanisms of action, which prevent pests from developing resistance. Furthermore, their selective toxicity guarantees that beneficial creatures like soil microorganisms and pollinators are not severely harmed.

4.2 Biofertilizers and Biostimulants

Plant-based bioactives are essential for improving plant nutrition and soil fertility. They promote nutrient availability and cycling by increasing microbial activity in the rhizosphere when combined with biofertilizers. By improving plant metabolism and stress tolerance, phytochemicals also function as biostimulants. They enhance the efficiency of nutrient uptake and promote plant growth in challenging environments like salt, drought, and temperature swings. Over time, this leads to improved soil health and crop output.

4.3 Weed Management

Allelopathic qualities allow some phytochemicals to prevent rival plant species from growing. Through volatilization, leaf litter, or root exudates, these organic substances are discharged into the soil. Allelopathic substances reduce competition for nutrients, water, and light by interfering with weed root formation and seed germination. This promotes ecologically acceptable weed control techniques and offers a sustainable substitute for conventional pesticides.

4.4 Post-Harvest Preservation

In agriculture, post-harvest losses are a significant concern, especially in developing nations. The shelf life of agricultural products is significantly increased by phytochemicals with antibacterial and antioxidant qualities. During storage, these substances lessen oxidative damage and stop microbiological deterioration. Fruits and vegetables can be preserved in quality and freshness by applying natural coatings and phytochemical-containing formulations. This improves food safety while simultaneously lowering losses.

5. Advanced Technologies in Phytochemical Utilization

The use of cutting-edge technologies has greatly increased the efficacy of phytochemicals in agricultural applications. These developments solve issues with bioavailability, stability, and solubility. A possible method for distributing phytochemicals in a regulated and targeted way is nanoformulation. When bioactive substances are encapsulated in nanoparticles, they become more stable, are shielded from environmental deterioration, and are released over time. An effective technique for producing high-purity phytochemicals without the use of hazardous solvents is supercritical fluid extraction, which has drawn interest. This method increases extraction yield while maintaining the chemicals' biological activity. Another cutting-edge technique that increases extraction efficiency by breaking down plant cell walls and promoting solvent penetration is ultrasound-assisted extraction. These advanced techniques not only improve the quality of phytochemicals but also support environmentally sustainable processing.

6. Role in Sustainable Agriculture

Because they can lessen their negative effects on the environment while preserving agricultural productivity, phytochemicals are an essential part of sustainable agriculture. There are several ecological and financial advantages to incorporating them into farming operations. Utilizing plant-based bioactives minimizes contamination of soil and water by reducing reliance on

artificial agrochemicals. This helps to preserve biodiversity and enhance ecosystem health. Additionally, beneficial soil bacteria are supported by phytochemicals, which improve soil fertility and structure. Phytochemical-based eco-friendly pest management techniques lower the dangers of chemical residues and the emergence of resistance. Their function in sustainable agriculture is further strengthened by their compatibility with organic agricultural methods. Adopting phytochemical-based strategies offers a practical solution to achieve long-term agricultural sustainability in the face of global issues like resource depletion and climate change. These natural substances support resilient and productive farming systems by encouraging effective resource use and lowering environmental stress.

7. Challenges and Limitations

Despite their advantages, phytochemicals face several limitations:

- Variability in composition
- Limited stability under field conditions
- High production costs
- Regulatory challenges

Standardization and formulation improvements are required for large-scale adoption.

8. Future Prospects

The future of phytochemicals in agriculture lies in:

- Integration with precision farming
- Development of nano-based delivery systems
- Genetic engineering for enhanced production
- Utilization of agro-waste for phytochemical extraction

Advances in phytochemical research are expected to revolutionize sustainable agriculture and crop protection strategies.

Table 3: Applications of Phytochemicals in Agriculture

Application Area	Phytochemical Role	Example
Crop Protection	Antimicrobial, insecticidal	Neem-based compounds
Growth Promotion	Hormonal regulation	Auxin-like compounds
Soil Health	Microbial stimulation	Phenolic compounds
Post-harvest	Antioxidant activity	Flavonoids
Weed Control	Allelopathy	Terpenoids

Conclusion

Modern agriculture can be made more ecologically friendly and sustainable by using phytochemicals and plant-based bioactives. Because of their many uses, they can be used to preserve crops, promote growth, and improve soil health. These chemicals are becoming more and more feasible for widespread agricultural application thanks to developments in extraction

and formulation technology. Long-term sustainability can be enhanced and reliance on synthetic chemicals can be greatly decreased by incorporating phytochemicals into farming systems.

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CLIMATE SMART SOIL AND WATER CONSERVATION STRATEGIES FOR SUSTAINABLE AGRICULTURE

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Abstract

Climate change has emerged as one of the most critical challenges facing global agriculture, fundamentally altering the balance of soil and water resources that sustain crop production. Increasing variability in rainfall patterns, including delayed monsoons, intense short duration rainfall, and prolonged dry spells, directly affects soil moisture availability and groundwater recharge. Rising temperatures further accelerate evapotranspiration, leading to rapid depletion of soil water and increased irrigation demand. These climatic stresses contribute to soil erosion, nutrient leaching, salinity buildup, and declining soil organic matter, ultimately reducing soil fertility and crop productivity. In addition, unsustainable farming practices such as excessive tillage, overuse of chemical fertilizers, and inefficient irrigation systems intensify resource degradation, especially in developing regions where agriculture is largely rain-dependent.

Climate-smart soil and water conservation strategies provide a comprehensive and adaptive approach to address these challenges by integrating sustainable practices that enhance productivity while preserving environmental integrity. These strategies emphasize improving soil health, increasing water-use efficiency, and strengthening resilience against climate-induced stresses through practices such as conservation tillage, cover cropping, rainwater harvesting, efficient irrigation, and agroforestry. Beyond improving farm productivity and income, these approaches contribute to long-term sustainability by enhancing ecosystem services, promoting biodiversity, and increasing carbon sequestration. Ultimately, the adoption of climate-smart conservation practices plays a vital role in ensuring food security, environmental stability, and resilient agricultural systems in the face of ongoing climate change^{[1][2][3]}.

1. Introduction

Agriculture is fundamentally dependent on soil and water resources, making their conservation essential for sustainable production systems. In recent decades, climate change has disrupted traditional farming practices by altering rainfall distribution and increasing temperature extremes. These changes have resulted in reduced soil moisture, increased evapotranspiration, and declining crop yields. Soil degradation, including erosion and loss of organic matter, further aggravates the problem. Climate-Smart Agriculture (CSA) has been introduced as an integrated approach that aims to increase productivity, improve resilience, and reduce environmental

impact. Within this framework, soil and water conservation play a central role by maintaining ecosystem balance and ensuring efficient use of resources^{[1][2]}.

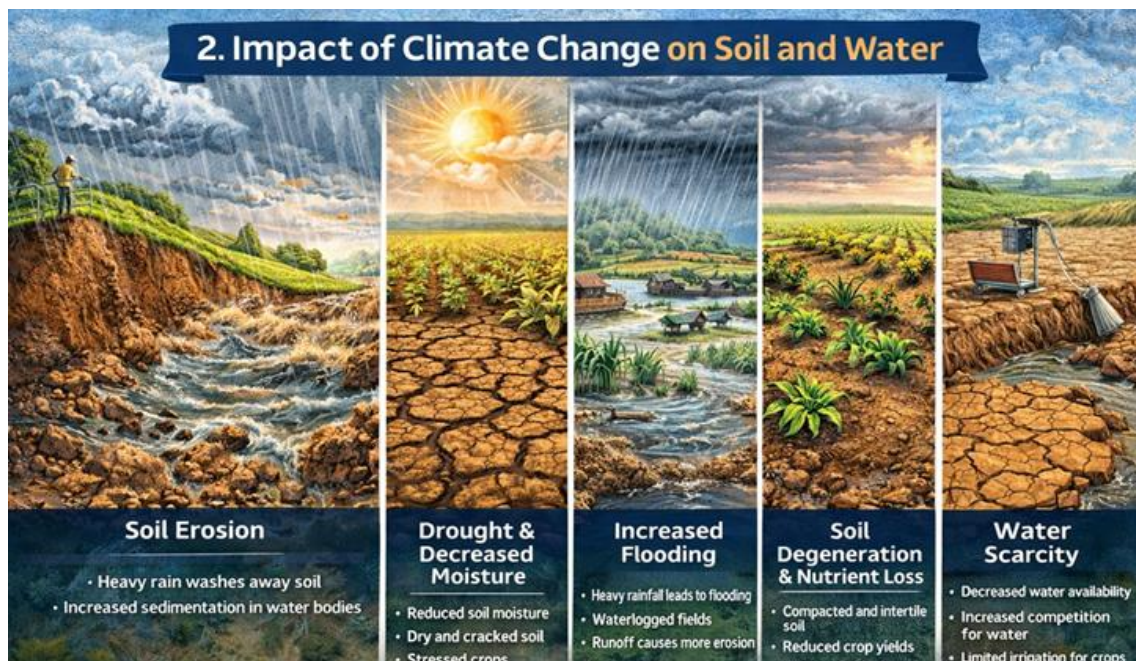
2. Impact of Climate Change on Soil and Water

2.1 Soil Degradation

Soil degradation is one of the most visible consequences of climate change, particularly in areas experiencing intense rainfall or prolonged dry periods. Heavy rainfall events increase surface runoff, which carries away the nutrient-rich topsoil layer essential for crop growth. At the same time, higher temperatures accelerate the decomposition of organic matter, reducing soil fertility and weakening soil structure. As a result, soils become less capable of retaining water and nutrients, leading to reduced agricultural productivity. Over time, degraded soils may become unsuitable for cultivation, threatening food security and farmer livelihoods^{[5][6]}.

2.2 Water Scarcity

Water scarcity is becoming increasingly common due to erratic rainfall and over-extraction of groundwater for irrigation. In many regions, rainfall is concentrated in short periods, leading to runoff rather than infiltration. This reduces groundwater recharge and creates water shortages during critical crop growth stages. Additionally, rising temperatures increase evaporation rates, further reducing available water. Without proper water management strategies, farmers face difficulties in maintaining crop yields, especially during dry seasons^{[4][9]}.



2.3 Extreme Weather Events

The frequency and intensity of extreme weather events such as floods and droughts have increased significantly due to climate change. Floods can destroy crops, erode soil, and wash away essential nutrients, while droughts lead to severe moisture stress and crop failure. These unpredictable events make farming more risky and require adaptive strategies that enhance resilience and reduce vulnerability^[5].

3. Soil Conservation Strategies

3.1 Conservation Tillage

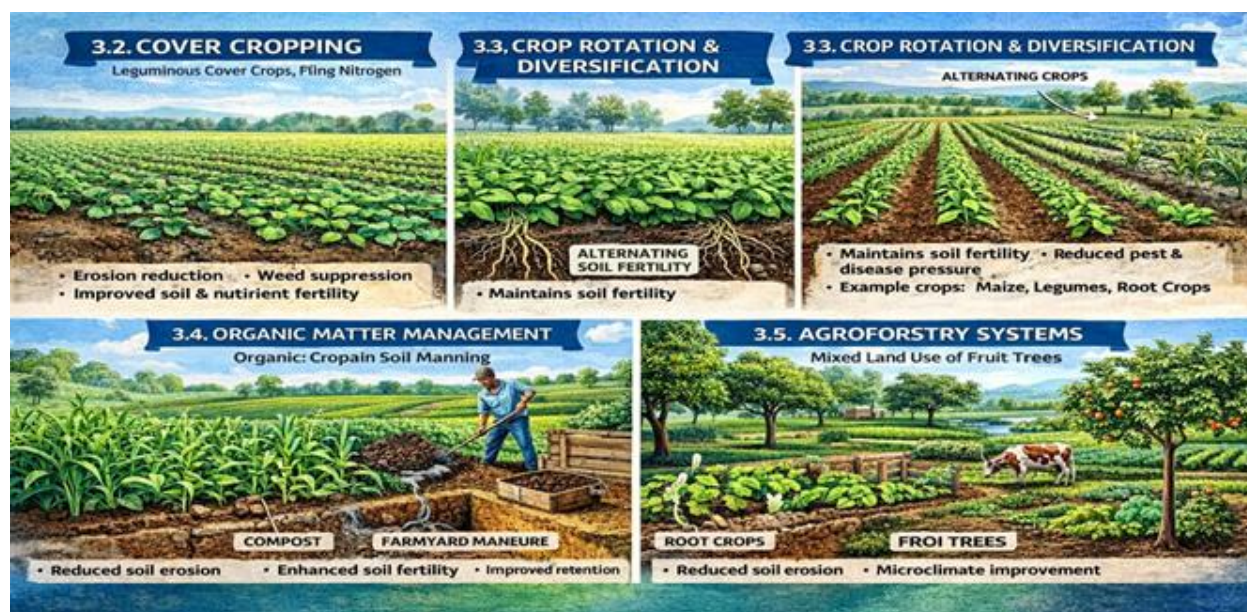
Conservation tillage involves reducing the intensity of soil disturbance during land preparation. Traditional plowing exposes soil to erosion and accelerate moisture loss, whereas conservation tillage preserves soil structure and organic matter. By leaving crop residues on the field, this practice protects the soil surface from wind and water erosion. It also enhances microbial activity and improves soil porosity, allowing better water infiltration. Over time, conservation tillage contributes to improved soil health and increased crop productivity^[7].

3.2 Cover Cropping

Cover cropping is the practice of growing specific crops during off-season periods to protect and enrich the soil. These crops act as a protective layer, reducing erosion caused by wind and rain. They also suppress weed growth and improve soil fertility by adding organic matter. Leguminous cover crops have the added advantage of fixing atmospheric nitrogen, which enhances soil nutrient content. This practice is particularly beneficial in maintaining soil health during periods when the land would otherwise remain bare^{[1][6]}.

3.3 Crop Rotation and Diversification

Crop rotation involves growing different crops in a planned sequence over time, which helps maintain soil fertility and reduce pest and disease buildup. Monocropping often leads to nutrient depletion and increased pest infestation, whereas diversified cropping systems promote ecological balance. Different crops have varying nutrient requirements and rooting patterns, which help improve soil structure and nutrient availability. This strategy enhances system resilience and reduces dependency on chemical inputs^{[1][7]}.



3.4 Organic Matter Management

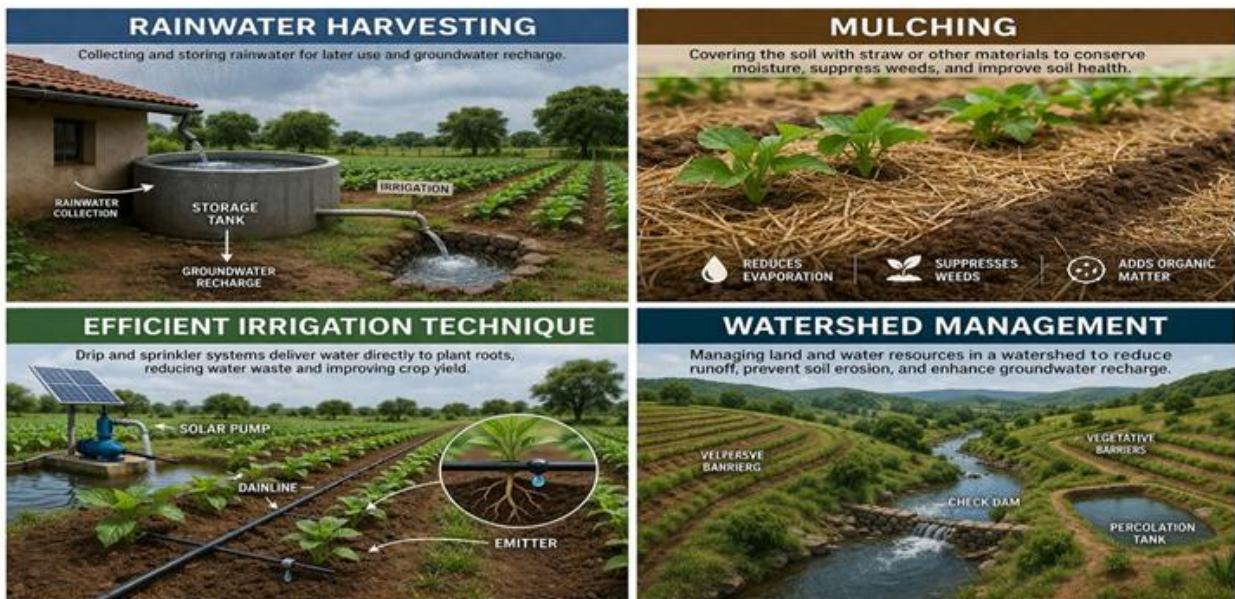
The addition of organic materials such as compost, farmyard manure, and crop residues plays a crucial role in improving soil quality. Organic matter enhances soil structure, increases water-

holding capacity, and supports beneficial microorganisms. It also improves nutrient availability by increasing the soil's capacity to retain essential elements. Regular application of organic inputs ensures long-term soil fertility and sustainability^{[6][10]}.

3.5 Agroforestry Systems

Agroforestry integrates trees with crops and livestock, creating a more diverse and sustainable farming system. Trees help reduce soil erosion by stabilizing the soil with their root systems. They also improve microclimatic conditions by providing shade and reducing temperature extremes. Additionally, agroforestry systems contribute to carbon sequestration, helping mitigate climate change while providing additional income sources such as fruits, timber, and fodder^{[1][10]}.

4. Water Conservation Strategies



4.1 Rainwater Harvesting

Rainwater harvesting involves collecting and storing rainwater for agricultural use. Structures such as farm ponds, check dams, and percolation tanks help capture runoff and increase groundwater recharge. This stored water can be used during dry periods, ensuring a reliable water supply for crops. Effective rainwater harvesting reduces dependency on external water sources and enhances farm resilience^[9].

4.2 Efficient Irrigation Techniques

Efficient irrigation systems such as drip and sprinkler irrigation optimize water use by delivering water directly to the crop root zone. Drip irrigation minimizes water loss due to evaporation and runoff, making it highly suitable for water-scarce regions. Sprinkler systems provide uniform water distribution, especially on uneven terrain. These technologies not only conserve water but also improve crop yields and reduce labor requirements^[9].

4.3 Mulching

Mulching involves covering the soil surface with materials such as straw, leaves, or plastic sheets. This practice reduces evaporation, maintains soil moisture, and regulates soil

temperature. Mulching also suppresses weed growth, reducing competition for nutrients and water. Organic mulches gradually decompose, adding nutrients to the soil and improving its structure^[6].

4.4 Watershed Management

Watershed management is a comprehensive approach to managing land and water resources within a defined area. It includes practices such as contour bunding, terracing, and vegetative barriers to reduce runoff and soil erosion. By improving water infiltration and groundwater recharge, watershed management enhances water availability and agricultural productivity. Community participation is essential for the success of watershed programs^[9].

5. Integrated Climate-Smart Approaches

Integrating multiple soil and water conservation strategies provides synergistic benefits and enhances overall system efficiency. For example, combining conservation tillage with mulching improves soil moisture retention, while integrating drip irrigation with organic farming optimizes resource use. Agroforestry systems combined with watershed management create a sustainable and resilient agricultural landscape. Such integrated approaches ensure better adaptation to climate variability and improve long-term sustainability^{[2][8]}.

6. Challenges in Implementation

Despite their advantages, climate-smart conservation practices face several challenges. High initial costs, particularly for technologies like drip irrigation, can discourage adoption among small-scale farmers. Limited technical knowledge and lack of awareness further hinder implementation. Additionally, fragmented landholdings and inadequate policy support can restrict the widespread adoption of these practices^[1].

7. Opportunities and Future Scope

There are significant opportunities to promote climate-smart agriculture through government initiatives, technological advancements, and capacity-building programs. Subsidies for micro-irrigation, training programs for farmers, and the use of digital technologies such as remote sensing and precision agriculture can enhance adoption. Development of climate-resilient crop varieties and improved extension services will further strengthen sustainable agricultural systems^{[2][8]}.

8. Policy and Institutional Support

Effective implementation of climate-smart soil and water conservation strategies requires strong policy backing and institutional support. Governments play a crucial role by designing policies that promote sustainable farming practices through subsidies, incentives, and regulatory frameworks. For example, financial assistance for micro-irrigation systems such as drip and sprinkler irrigation encourages farmers to adopt water-efficient technologies. Additionally, watershed development programs supported by public institutions help in large-scale conservation of land and water resources. Institutional mechanisms like agricultural extension

services are essential for transferring knowledge and technologies to farmers. Without proper policy support, even the most effective conservation strategies may fail to achieve widespread adoption^{[1][3]}.

9. Role of Technology and Innovation

Modern technologies are transforming soil and water conservation practices by improving efficiency and precision. Tools such as remote sensing, Geographic Information Systems (GIS), and drones enable monitoring of soil moisture, crop health, and water usage in real time. Precision agriculture techniques allow farmers to apply water and nutrients in optimal quantities, reducing wastage and environmental impact. Mobile-based applications and digital platforms provide weather forecasts, irrigation scheduling, and advisory services, helping farmers make informed decisions. These innovations not only enhance productivity but also make conservation practices more practical and scalable^[6].

10. Economic Benefits of Conservation Practices

Adoption of soil and water conservation strategies offers significant economic advantages to farmers. Although some practices require initial investment, they lead to long-term cost savings by reducing input requirements such as water, fertilizers, and pesticides. Improved soil health results in higher crop yields and better quality produce, increasing farm income. Efficient water management reduces the risk of crop failure during drought conditions, ensuring stable returns. Furthermore, practices like agroforestry provide additional sources of income through timber, fruits, and other by-products. Thus, conservation strategies are not only environmentally sustainable but also economically viable^[9].

11. Social and Community Participation

Community involvement is a key factor in the success of conservation initiatives, especially in watershed management programs. Collective action enables efficient use of shared resources such as water bodies and grazing lands. Farmer groups, cooperatives, and self-help groups play an important role in spreading awareness and encouraging adoption of sustainable practices. Participatory approaches ensure that local knowledge and traditional practices are integrated with modern techniques. This not only improves effectiveness but also promotes a sense of ownership among farmers, leading to long-term sustainability^[1].

12. Capacity Building and Farmer Education

Lack of awareness and technical knowledge is one of the major barriers to the adoption of climate-smart practices. Capacity-building programs such as training workshops, field demonstrations, and farmer field schools are essential to educate farmers about the benefits and implementation methods of conservation strategies. Extension services and agricultural institutions should focus on practical, hands-on training to improve farmer skills. Educated and informed farmers are more likely to adopt innovative practices and adapt to changing climatic conditions effectively^{[1][2]}.

13. Case Studies and Field Applications

Real-world examples demonstrate the effectiveness of climate-smart soil and water conservation strategies. In semi-arid regions, the construction of farm ponds and adoption of drip irrigation have significantly improved water availability and crop yields. Similarly, watershed management programs in rural areas have led to increased groundwater levels and improved agricultural productivity. In regions practicing agroforestry, farmers have reported better income stability due to diversified outputs. These case studies highlight that integrated approaches can successfully address climate challenges when implemented properly^{[8][9]}.

14. Environmental Benefits and Sustainability

Climate-smart conservation practices contribute significantly to environmental protection. By reducing soil erosion and improving soil organic matter, these practices enhance soil biodiversity and ecosystem health. Efficient water use reduces pressure on groundwater resources and prevents depletion. Agroforestry and organic matter management help in carbon sequestration, thereby mitigating climate change. Overall, these strategies support sustainable land use and ensure the preservation of natural resources for future generations^{[6][10]}.

15. Monitoring and Evaluation of Conservation Practices

Regular monitoring and evaluation are essential to assess the effectiveness of conservation strategies. Indicators such as soil moisture levels, crop yield, groundwater levels, and soil organic carbon can be used to measure success. Advanced tools like remote sensing and data analytics help in tracking changes over time. Continuous evaluation allows for timely modifications and improvements in management practices, ensuring optimal outcomes^[8].

16. Future Directions in Climate-Smart Agriculture

The future of sustainable agriculture lies in the integration of traditional knowledge with advanced technologies. Innovations such as artificial intelligence, machine learning, and climate modeling will further enhance decision-making in agriculture. Development of drought-resistant and climate-resilient crop varieties will play a key role in adapting to changing conditions. Strengthening policy frameworks and increasing investment in research and development will be crucial for scaling climate-smart practices globally^[2].

Conclusion

Climate-smart soil and water conservation strategies are essential for ensuring sustainable agriculture in the face of climate change. These practices not only protect natural resources but also enhance productivity and resilience. By adopting integrated approaches and leveraging technological innovations, farmers can overcome environmental challenges and achieve long-term agricultural sustainability. Effective policy support and farmer participation will be crucial in scaling these practices for future food security^{[1][2][3]}.

Summary

Climate-smart soil and water conservation strategies go beyond resource protection by integrating environmental, economic, and social dimensions. With proper policy support, technological innovation, and community participation, these practices can transform agricultural systems into resilient and sustainable models. Expanding awareness, improving access to resources, and strengthening institutional frameworks will be key to achieving long-term success^{[1][2]}.

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CIRCULAR ECONOMY APPROACHES IN AGRI-WASTE UTILIZATION: A COMPREHENSIVE REVIEW

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Abstract

The intensification of global agricultural practices has significantly increased the generation of agricultural waste, including crop residues, livestock manure, and agro-industrial by-products. Traditional linear economic models have proven inefficient in managing these wastes, leading to environmental degradation and resource depletion. The circular economy (CE) framework offers a sustainable alternative by emphasizing waste minimization, resource recovery, and closed-loop systems. This review critically examines circular economy approaches in agri-waste utilization, including composting, bio-energy production, bio-refineries, nutrient recycling, and industrial applications. Additionally, the integration of emerging technologies such as artificial intelligence (AI), block-chain, and the Internet of Things (IoT) is discussed. Environmental, economic, and policy implications are also analyzed. The findings suggest that CE approaches can significantly enhance sustainability in agriculture, though challenges related to infrastructure, policy, and awareness remain.

Keywords: Circular Economy, Agricultural Waste, Sustainability, Biomass Valorization, Bio-Economy.

1. Introduction

Agriculture remains one of the most essential sectors supporting global livelihoods, food security, and economic stability. However, alongside its benefits, it generates vast quantities of agricultural waste, including crop residues, livestock manure, and agro-industrial by-products. With the global population projected to exceed 9 billion by 2050, agricultural production is expected to increase significantly, which will further amplify waste generation challenges [1], [2]. Improper disposal methods such as open-field burning, dumping, and land filling are widely practiced, especially in developing countries, leading to serious environmental consequences including air pollution, greenhouse gas emissions, and soil degradation [1]. The inefficiency of traditional waste management practices is largely attributed to the dominance of linear economic systems, where resources are extracted, used, and discarded without consideration for reuse or recycling [3]. This model is increasingly unsustainable due to resource depletion, environmental degradation, and rising production costs. In contrast, the circular economy (CE) framework offers a regenerative approach that seeks to close resource loops by promoting reuse, recycling, and recovery of materials [4].

In agricultural systems, CE emphasizes converting waste into valuable resources such as bio-energy, organic fertilizers, and industrial raw materials. This transformation not only reduces environmental impacts but also creates economic opportunities for farmers and industries [5]. For instance, crop residues that were previously burned can now be used for bio-energy production or soil amendments, thereby contributing to both energy security and soil health. Furthermore, agricultural waste contains significant amounts of organic matter, nutrients, and bioactive compounds that can be harnessed for value-added applications. Advances in biotechnology and engineering have made it possible to convert these wastes into bio-fuels, bio-plastics, and other sustainable products [6]. Despite the growing interest in circular agriculture, several challenges hinder its widespread adoption. These include lack of infrastructure, limited awareness among farmers, financial constraints, and policy gaps. Additionally, integrating circular economy principles into existing agricultural systems requires coordinated efforts across multiple stakeholders, including governments, industries, and research institutions [7].

This review aims to provide a comprehensive understanding of circular economy approaches in agri-waste utilization. It explores various technologies, environmental and economic benefits, and challenges associated with CE implementation. The study also highlights the role of emerging technologies and policy frameworks in facilitating the transition toward sustainable agricultural systems.

2. Conceptual Framework of Circular Economy in Agriculture

2.1 Definition and Scope

The circular economy is a systemic approach designed to eliminate waste and promote the continual use of resources. It represents a shift from the conventional linear model to a regenerative system that prioritizes sustainability and resource efficiency [4]. In the context of agriculture, CE encompasses practices that enable the reuse and recycling of biological materials, ensuring that nutrients and organic matter are returned to the soil or repurposed for other applications.

The scope of CE in agriculture extends beyond waste management to include sustainable production, efficient supply chains, and responsible consumption patterns. It integrates principles of ecology, economics, and technology to create a holistic system where waste is minimized and resources are utilized optimally [5]. Moreover, CE in agriculture aligns with global sustainability goals, including climate change mitigation, biodiversity conservation, and food security. By reducing reliance on synthetic inputs and promoting natural cycles, circular agriculture contributes to long-term environmental sustainability [6].

2.2 Principles of Circular Economy

The circular economy framework is built upon the 4R principles—Reduce, Reuse, Recycle, and Recover—which serve as guiding strategies for sustainable resource management. The “Reduce” principle focuses on minimizing resource consumption and waste generation through efficient

production practices. In agriculture, this can be achieved through precision farming techniques that optimize the use of water, fertilizers, and pesticides [8]. The “Reuse” principle involves utilizing agricultural by-products without significant processing. For example, crop residues can be used as animal feed or mulching material. The “Recycle” principle emphasizes converting waste into new products, such as compost or bio-fertilizers, thereby closing nutrient loops [9]. The circular economy in agriculture operates through interconnected resource loops, as illustrated in Fig. 1.



Figure 1: Circular Economy in Agriculture

The “Recover” principle focuses on extracting energy or valuable compounds from waste materials. Technologies such as anaerobic digestion and pyrolysis enable the conversion of organic waste into biogas and bio-char, respectively [10]. These principles collectively contribute to resource efficiency, environmental protection, and economic sustainability.

2.3 Circular Economy in Agri-Food Systems

The integration of CE into agri-food systems requires a comprehensive approach that considers the entire value chain, from production to consumption. Circular agri-food systems aim to minimize waste generation, enhance resource efficiency, and promote sustainable consumption patterns [6]. At the production stage, circular practices include crop diversification, integrated farming systems, and efficient resource management. During processing and distribution, waste reduction strategies such as improved storage, packaging, and transportation are implemented. At the consumption stage, food waste can be reduced through awareness campaigns and efficient supply chain management [11]. Additionally, circular agri-food systems emphasize the importance of collaboration among stakeholders, including farmers, industries, policymakers, and consumers. This collaborative approach ensures the successful implementation of CE principles across the entire supply chain.

3. Types and Characteristics of Agricultural Waste

3.1 Crop Residues

Crop residues constitute a major portion of agricultural waste and include materials such as straw, husks, stalks, and leaves. These residues are generated during harvesting and processing of crops. Traditionally, crop residues have been considered waste and are often burned, leading to air pollution and loss of valuable nutrients [1]. However, crop residues are rich in lignocellulosic biomass, which can be utilized for various applications such as bio-energy production, composting, and industrial processing. Advances in technology have enabled the efficient conversion of these residues into bio-fuels and other value-added products [7].

3.2 Livestock Waste

Livestock waste, including manure and slurry, is another significant source of agricultural waste. It contains essential nutrients such as nitrogen, phosphorus, and potassium, which can be recycled into agricultural systems [8]. Improper management of livestock waste can lead to environmental issues such as water pollution and greenhouse gas emissions. However, when managed properly, it can be converted into biogas, organic fertilizers, and soil conditioners, contributing to sustainable agriculture [12].

3.3 Agro-Industrial Waste

Agro-industrial waste includes by-products generated during the processing of agricultural products. Examples include sugarcane bagasse, fruit peels, and oilseed cakes. These wastes contain valuable compounds such as fibers, proteins, and bioactive molecules [9]. These materials can be utilized for the production of bio-fuels, bio-plastics, and pharmaceuticals. The valorization of agro-industrial waste not only reduces environmental pollution but also creates economic opportunities [13].

3.4 Characteristics of Agri-Waste

Agricultural waste is characterized by its biodegradability, renewability, and nutrient-rich composition. These properties make it suitable for circular economy applications. Additionally, agri-waste has high moisture content and variability in composition, which can influence its suitability for different applications. Understanding these characteristics is essential for selecting appropriate waste management strategies [10].

4. Circular Economy Approaches in Agri-Waste Utilization

4.1 Composting and Vermi composting

Composting is one of the most widely used methods for managing agricultural waste. It involves the biological decomposition of organic materials into nutrient-rich compost. Vermi composting, which utilizes earthworms, enhances this process by improving nutrient availability and microbial activity [11]. These methods contribute to soil health by improving soil structure, increasing water retention, and enhancing nutrient availability. They also reduce the need for chemical fertilizers, thereby minimizing environmental pollution.

4.2 Bio-energy Production

Bio-gas Production - Anaerobic digestion converts organic waste into biogas, which can be used for cooking, heating, and electricity generation. This process also produces digestate, which can be used as fertilizer [12].

Bio-ethanol Production – Ligno-cellulosic biomass is converted into bio-ethanol through enzymatic hydrolysis and fermentation. This provides a renewable alternative to fossil fuels [13].

BIO-CHAR PRODUCTION – BIO-CHAR IS PRODUCED THROUGH PYROLYSIS AND IS USED AS A SOIL AMENDMENT. IT IMPROVES SOIL FERTILITY AND SEQUESTERS CARBON, CONTRIBUTING TO CLIMATE CHANGE MITIGATION [14].

4.3 Bio-refinery and Biomass Valorization

Bio-refineries integrate multiple processes to convert biomass into fuels, chemicals, and materials. This approach maximizes resource utilization and minimizes waste.

Bio-refineries are considered a key component of the circular bio-economy, enabling the production of high-value products from agricultural residues [15].

4.4 Nutrient Recycling

Nutrient recycling involves returning organic matter to the soil through compost, manure, and digestate application. This process enhances soil fertility and reduces reliance on synthetic fertilizers [16]. It also promotes sustainable nutrient management and reduces environmental impacts associated with fertilizer production and use.

4.5 Industrial Applications

Agricultural waste is increasingly used in industrial applications such as bio-plastics, construction materials, and packaging. These applications reduce dependency on non-renewable resources and contribute to sustainable development [17]. Various conversion pathways of agricultural waste into value-added products are summarized in Fig. 2.

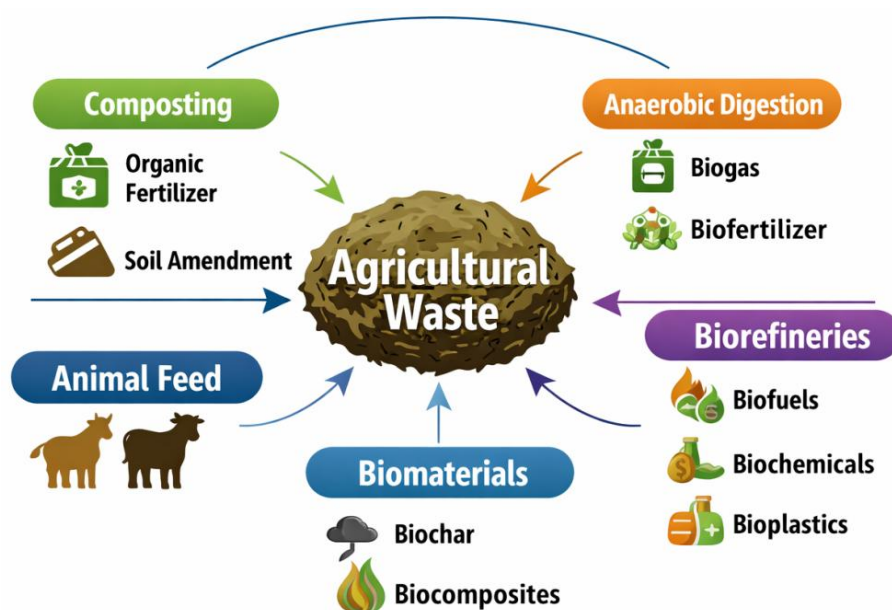


Figure 2: Agro-Waste valorization Pathways

5. Role of Emerging Technologies in Circular Agriculture

The integration of advanced technologies into agricultural systems has significantly accelerated the adoption of circular economy principles. Emerging technologies such as artificial intelligence (AI), block chain, the Internet of Things (IoT), and big data analytics are transforming traditional agricultural practices into more efficient, data-driven, and sustainable systems. These technologies play a crucial role in optimizing resource use, minimizing waste generation, and enhancing the recovery and reuse of agricultural by-products [18]. Artificial intelligence has become a powerful tool in circular agriculture by enabling predictive modeling, decision support systems, and automation. AI-based algorithms can analyze large datasets related to crop production, soil health, and waste generation, allowing farmers to make informed decisions about resource allocation and waste management. For example, AI-driven systems can optimize composting processes by monitoring temperature, moisture, and microbial activity, thereby improving efficiency and reducing processing time [18].

The Internet of Things (IoT) facilitates real-time monitoring of agricultural operations through interconnected sensors and devices. IoT-enabled systems can track parameters such as soil moisture, nutrient levels, and environmental conditions, enable precise application of inputs and reducing waste generation. Additionally, IoT devices can be used to monitor waste streams and ensure efficient collection, segregation, and processing of agricultural residues [20]. Block chain technology enhances transparency and traceability in agricultural supply chains. By providing a decentralized and secure platform for data sharing, block chain enables stakeholders to track the movement of agricultural products and waste materials throughout the supply chain. This improves accountability and supports the implementation of circular practices, such as recycling and reuse of materials [19].

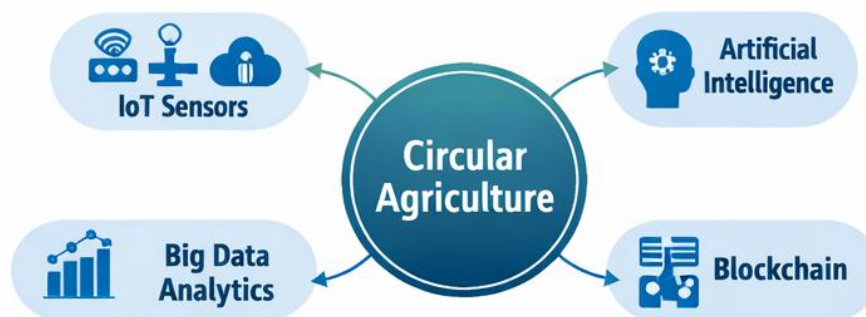


Figure 3: Technologies in Circular Agriculture

Big data analytics further complements these technologies by enabling the analysis of complex datasets to identify patterns and trends in resource use and waste generation. This information can be used to develop strategies for improving efficiency and reducing environmental impacts. Despite their potential, the adoption of these technologies is limited by factors such as high costs, lack of technical expertise, and inadequate infrastructure, particularly in developing countries. Therefore, capacity building and investment in digital infrastructure are essential for leveraging

the full potential of emerging technologies in circular agriculture. The integration of advanced technologies supporting circular agriculture systems is depicted in Fig. 3.

6. Environmental Impacts of Circular Economy in Agriculture

The adoption of circular economy approaches in agriculture has significant environmental benefits, particularly in reducing pollution and conserving natural resources. One of the primary advantages is the reduction of greenhouse gas (GHG) emissions. Traditional agricultural practices, such as open burning of crop residues and improper manure management, contribute substantially to emissions of carbon dioxide, methane, and nitrous oxide. Circular practices, such as composting and anaerobic digestion, mitigate these emissions by converting waste into useful products [21].

Circular economy approaches also contribute to improved soil health. The application of organic amendments such as compost and bio-char enhances soil structure, increases water retention, and promotes microbial activity. These improvements lead to better crop productivity and resilience to environmental stressors such as drought and soil erosion. Water conservation is another important environmental benefit. Circular systems reduce water pollution by preventing the leaching of nutrients and contaminants into water bodies. For example, proper management of livestock waste prevents the contamination of groundwater and surface water resources.

Furthermore, CE practices promote biodiversity by reducing the reliance on chemical inputs and encouraging the use of organic and natural farming methods. This creates a more balanced ecosystem and supports the conservation of beneficial organisms. However, certain environmental risks must also be considered. For instance, the use of contaminated waste materials in composting can introduce pollutants such as heavy metals and micro plastics into the soil. Therefore, proper quality control measures are essential to ensure the safety and effectiveness of circular practices. Overall, the environmental benefits of CE in agriculture outweigh the potential risks, making it a key strategy for achieving sustainable development and climate change mitigation.

7. Economic and Social Impacts

Circular economy approaches in agri-waste utilization offer significant economic and social benefits. From an economic perspective, the conversion of agricultural waste into value-added products creates new revenue streams for farmers and industries. For example, the production of bio-energy, organic fertilizers, and bio-plastics from agricultural residues can generate additional income and reduce dependency on external inputs [5]. Cost savings are another important economic benefit. By recycling nutrients and reusing materials, farmers can reduce their expenditure on chemical fertilizers, pesticides, and energy. This improves the overall profitability and sustainability of agricultural operations.

The circular economy also stimulates the development of new industries and markets, particularly in rural areas. Waste processing facilities, biogas plants, and bio-refineries create

employment opportunities and contribute to rural development. This helps in reducing migration to urban areas and supports local economies. From a social perspective, CE approaches improve the livelihoods of farmers and rural communities. Access to affordable energy and fertilizers enhances agricultural productivity and food security. Additionally, circular practices promote community participation and knowledge sharing, fostering social cohesion and resilience.

Education and awareness play a crucial role in maximizing the social benefits of CE. Training programs and extension services can help farmers adopt sustainable practices and utilize agricultural waste effectively. Despite these benefits, challenges such as market uncertainties, lack of financial support, and limited access to technology can hinder the economic viability of circular practices. Addressing these challenges requires coordinated efforts from governments, industries, and research institutions.

8. Challenges and Barriers to Implementation

The transition from linear to circular agricultural systems is associated with several challenges and barriers. One of the major challenges is the lack of infrastructure for waste collection, segregation, and processing. In many regions, especially in developing countries, agricultural waste management systems are poorly developed, making it difficult to implement circular practices [22]. Financial constraints also pose a significant barrier. The initial investment required for technologies such as biogas plants, composting facilities, and bio-refineries can be high, making them inaccessible to smallholder farmers. Limited access to credit and financial incentives further exacerbates this issue.

Another challenge is the lack of awareness and technical knowledge among farmers and stakeholders. Many farmers are not aware of the potential benefits of circular economy practices or lack the skills required to implement them effectively. Policy and regulatory barriers also hinder the adoption of CE. In some cases, existing policies do not adequately support circular practices or may even discourage them. For example, subsidies for chemical fertilizers can reduce the incentive to adopt organic alternatives.

Technological limitations, such as inefficiencies in waste conversion processes and lack of scalability, also pose challenges. Additionally, the variability in the composition of agricultural waste can affect the efficiency of processing technologies. To overcome these barriers, it is essential to develop supportive policies, provide financial incentives, and invest in research and development. Collaboration among stakeholders is also crucial for creating an enabling environment for circular agriculture.

9. Policy Framework and Global Initiatives

Policy frameworks play a critical role in promoting the adoption of circular economy practices in agriculture. Governments and international organizations have recognized the importance of CE in achieving sustainable development goals and have implemented various policies and initiatives to support its adoption [23]. At the national level, policies related to waste

management, renewable energy, and sustainable agriculture can facilitate the transition to circular systems. For example, subsidies and incentives for biogas production and organic farming encourage farmers to adopt circular practices.

International organizations such as the Food and Agriculture Organization (FAO), the United Nations Environment Programme (UNEP), and the World Bank have developed guidelines and programs to promote sustainable agricultural practices and circular economy principles [24], [25]. The European Union has been a leader in promoting CE through its Circular Economy Action Plan, which includes measures to improve resource efficiency and reduce waste across various sectors, including agriculture. Public-private partnerships also play a crucial role in implementing circular economy initiatives. Collaboration between governments, industries, and research institutions can facilitate the development and deployment of innovative technologies and solutions. Despite these efforts, there is a need for more comprehensive and integrated policies that address the specific challenges of circular agriculture. Policy coherence and coordination among different sectors are essential for achieving effective implementation.

Conclusion

Circular economy approaches in agri-waste utilization provide a sustainable solution to the challenges associated with agricultural waste management. By transforming waste into valuable resources, CE enhances environmental sustainability, economic viability, and social well-being. The adoption of circular practices such as composting, bio-energy production, bio-refineries, and nutrient recycling can significantly reduce environmental impacts and improve resource efficiency. Additionally, the integration of emerging technologies such as AI, IoT, and block chain further enhances the effectiveness of these approaches. However, the successful implementation of circular economy practices requires overcoming several challenges, including infrastructure limitations, financial constraints, and policy barriers. Addressing these challenges requires coordinated efforts from governments, industries, and research institutions. In conclusion, the transition to a circular economy in agriculture is essential for achieving sustainable development and ensuring food security for future generations. Continued research, innovation, and policy support are crucial for realizing the full potential of circular agriculture.

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MICROBIAL DIVERSITY AND NUTRIENT TRANSFORMATION IN AGRICULTURAL ECOSYSTEMS

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Abstract

Sustainable agriculture is a holistic farming system primarily aims to ensure that native assets are somewhat depleted, representing a forthcoming period that can be sustained through improvement in crop growing practices. The attention lies in integrating technological novelty with ecological stewardship to enrich both quality and productivity while safeguarding the planet's resources. The constant activities of microorganisms have appeared as a novel strategy, as they significantly contribute to soil health, sustainable farming methods, crop yields, soil fertility, betterment of nutrient absorption, production of growth hormones, and protection against stressors and pathogens. Tiny creatures like mycota, archaeal species, bacteria, and actinomycetes play very crucial intermediary roles in biodegradation, biogeochemical cycling, and phytostimulation. This review highlights evolution in bio-inspired manufacturing technologies such as the CRISPR-Cas9 gene editing tool, AI-driven pest management systems, and Nano fertilizers. It also discusses application techniques along with future perspectives and challenges.

Keywords: Sustainable Agriculture, Ecological Stewardship, Native Assets, Crop Yield, Soil Fertility, Growth Hormones, Tiny Creatures, Phytostimulation, AI-Inspired Manufacturing Technologies, CRISPR-Cas9, Nanofertilizers.

Introduction

Microbial population is of significant influence on agricultural ecosystem modification, while making its contribution significantly with soil health, sustainable farming, and crop productivity. These unseen organisms like bacteria, fungi, archaea and actinomycetes are a significant factor in soil nutrient cycle, organic matter decomposition and the overall growth of plants [1]. The mycorrhiza fungi in ecosystems attach plant roots as important partners, enhancing water and nutrient absorption and protecting against the soil borne pathogens [2]. Soil is a web of microorganisms growing and communicating with each other and plants. The diversity of microbial life includes: nitrogen fixation (*Rhizobium*), phosphorus solubilisation (*Pseudomonas*) and organic matter decomposition. Mutualistic relationship with plant roots and Mycorrhiza fungi to augment nutrient uptake and water absorption. Organic decay and antimicrobial

production of actinomycetes that inhibit plant pathogens. Algae play very important role in solar energy conversion and then break down, which adds to the structure and fertility of soil [3].

The interrelationship between this microflora provides the dynamic environment which can support plant development and soil vitality. By processes such as mineralisation is the conversion of organic compound into inorganic matter for example ammonium, phosphate, nitrate through the microbial decomposition, nutrient release, nitrification ammonification and mineral conversion. Immobilisation is nothing but the assimilation means incorporation of nutrient into microbial biomass through lacking nutrient away and holding nutrient in unavailable form or microbial uptake form soil solution where bacteria, fungi and archaea collaborate as one in the nitrogen transformation pathways, partitioning complex organic compounds into simpler molecules [4]. Microorganisms, such as *Bacillus* (for example *subtilis*) are reliable to fix the atmospheric nitrogen into more reactive form I.e., Ammonia in the presence of oxygen sensitive nitrogenase enzyme. *Pseudomonas* species (like *P. aeruginosa*) basically they have ability to grow in both oxygen rich and oxygen poor environments. They are also responsible to convert nitrates back into nitrogen gas in low oxygen soil. Some species of pseudomonas responsible for the degradation of hydrocarbon and iron cycling that is nothing but the siderophore production. This both genera are responsible to split organic nitrogen which are present in dead plants and certain animals into the ammonia that process is known as fossilisation. They both are also secrete organic acids such as gluconic acid and citric acid. They produce phosphatase enzyme, which play crucial role in breaking organic phosphorus from the spoiled organic matter and then releasing free form of phosphate ions that plants easily uptake and also degrade biological waste and exchange necessary nutrients like N, P and S via soil environments.

Soil nitrogen cycling is the most essential soil metabolic pathway of nutrient cycling. Bacteria that bind nitrogen such as Symbiotic Specialist *Rhizobium* and Free-living bacterium which are found in neutral to alkaline soil that is *Azotobacter* were said to have metamorphosed atmospheric nitrogen into ammonia, a metamorphosis of such atmospheric nitrogen into ammonia due to biological nitrogen fixation via Nitrogen fixing bacteria [5]. Nitrifying bacteria like *Nitrosomonas* responsible for ammonium oxidation and it basically uptake ammonia from the fixers and convert into nitrite. *Nitrobacter* (nitrite oxidation) takes nitrite produced by nitrosomonas and then it converts into nitrate simply oxidize ammonia (NH₃) into nitrates and nitrites, N₂ forms of which would comprise most of nitrogen assimilated by plants and thus, its most fundamental forms of nitrogen. Nitrate is converted to nitrogen by the denitrifying bacteria such as *Pseudomonas denitrificans*. Phosphate solubilizing microbe such as *Penicillium* such as (*P. bilaii* or *P. oxalicum*) disperse phosphate through the secretion of organic acids, also responsible to produce antibiotic penicillin which the cell walls synthesis inhibitor. *Pseudomonas* that generates organic acid that solubilize non-miscible phosphorus compounds, so phosphorus is

bioavailable to plants [6]. Similarly, Arbuscular Mycorrhizal fungi establish interplay with plant roots, boost phosphorus absorption by increasing the root surface area through the fungal hyphae. Fungi not only serve as the sole means for increasing phosphorus, but they also greatly contribute their role in plant resilience to abiotic stresses. Sulfur oxidising bacteria, like *Thiobacillus*, gram-negative rod-shaped bacteria, oxidise elemental sulfur or sulfides into sulfate digestible by plants [7]. They are obligate aerobes and chemolithoautotrophic microbes meaning that they get their energy from inorganic sulfur containing molecules and their carbon source from carbon dioxide. They are surviving in such an environment where sulfur is present in soil, marine as well as freshwater environments and even in acid mine drainage. There is one species that is *Acidothiobacillus ferrooxidans* which are acid loving bacteria that can oxidize both sulfur and iron. They play an important role in wastewater treatment, bio leaching, soil fertility and impact on environments. Even other nutrient cycles, e.g., potassium, calcium and iron, can be remade by microorganisms, produce organic acids such as citric acid, iron cycling and enzymes and thus can help resolve them for these compounds. Biotransformation is where all this happens for maintaining soil well being and environmentally sound farming or climate smart agriculture practices to flow. In automated agriculture with the help of microbial inoculant and bio control agent increase the productivity of crops [8]. Such as *Trichoderma*, *Bacillus* and *Pseudomonas* promote the formation of microbial plant growth by large scale fertilization and plant nutrient mobilisation and produce micro-organisms stimulating IAA and GA, which boost plant growth [9]. They function as ecologically appropriate substitutions to chemical fertilizers by decreasing environmental pollution and increasing climate-smart farming techniques. Biopesticides derived from microbes like BT and *Beauveria bassiana*, to aid the efforts to control pests and diseases, while maintaining healthy organisms and the ecosystems are also beneficial [10]. Through microbial and plant biocontrol consortium microbial cooperation provides a means of bioremediation also avoiding the application of chemical pesticides. To eliminate pathogens, *Trichoderma* and *Bacillus subtilis* employ strategies such as antibiosis, competition and inducing systemic resistance in plants. These biocontrol agents not only protect the crops but also help safeguard the environment by reducing the harm of chemical pesticides to non-target organisms and to ecosystems. And then some microbes can counterbalance toxic material in the soil like heavy metals. The function of microorganisms is not only in the soil health and productivity of crops, they are also crucial to climate smart agriculture. Anaerobic microbes in biogas generation systems reduce agriculture emissions. Such microbial based methods can be incorporated into an agricultural system for sustainable farming and not only will the environment be healthier but also the economic viability of farm and agricultural producers can be secured in the future [11]. Plant Growth-Promoting Rhizobacteria (PGPR) are a beneficial group of rhizosphere microorganisms also known as Biofertilizer bacteria, biocontrol agents and endophytic bacteria which are able to trigger the growth of plants directly or indirectly and thereby inhabit plant roots

and increase the growth of plant by advancing nutrient uptake where microorganisms absorb the substances from its environments to its growth and maintenance. fundamentally there are some related process or methods for the uptake that we might be used such as active transport means movement of nutrient against a concentration gradient primarily from low to high concentrations by using certain energy. Next method is nothing but the diffusion that is movement of nutrient along the concentration gradients viz., from high to low concentrations without using energy and last method is osmotrophy where specific nutrient plays an important role to absorb the dissolved organic compounds. Also, the microorganisms play crucial role in the production of growth hormones and protection against stress and pathogens. They are becoming increasingly critical for sustainable agriculture in other words chemical free farming, particularly for regions oriented towards the climate shocks specifically drought and salinity. They reside close to plant roots as part of the rhizomicrobiome. The examples are *Azospirillum*, *Bacillus*, *Pseudomonas*, *Rhizobium*, *Enterobacter*. Microbes solubilize phosphorus, fix nitrogen and mobilize micronutrients. Beneficial microbes outcompete pathogens or provoke plant immune responses [12]. PGPR promote plant growth through multiple pathways:

Direct Mechanisms:

- **Nitrogen Fixation:** Conversion of atmospheric nitrogen into usable forms.
- **Phosphate Solubilization:** Liberation of bound phosphorus from minerals.
- **Production of Phytohormones:** Synthesis of auxins/cytokinins/gibberellins stimulating both root/sprout development.

Indirect Mechanisms:

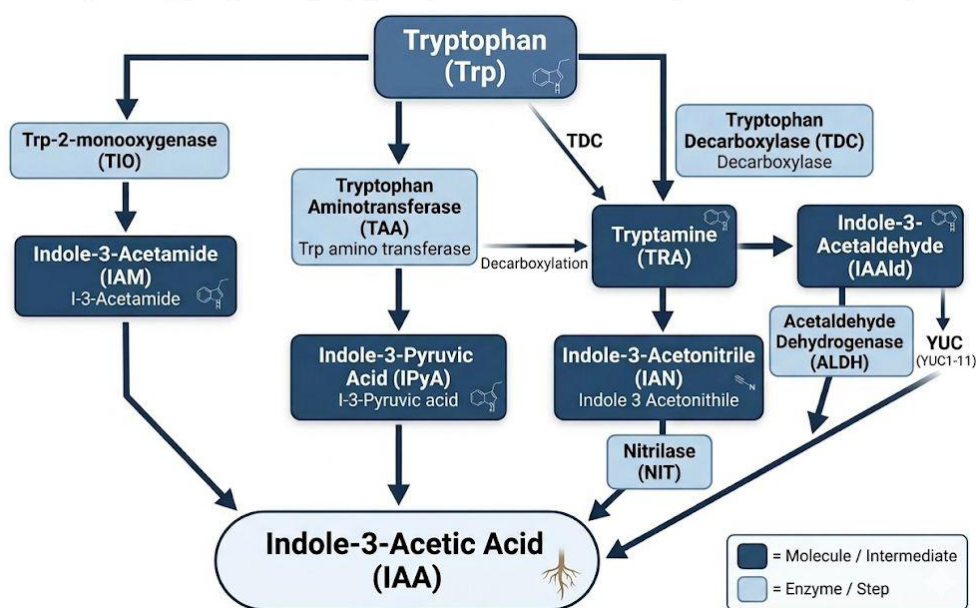
- **Biocontrol:** Generation of antibiotics/lytic enzymes competing for nutrients.
- **Induced Systemic Resistance (ISR):** Facilitation triggering defence pathways enhancing disease resistance.
- **Stress Tolerance Enhancement:** helping crops withstand drought/salinity/heavy metals availability leading towards better overall root architecture promoting water/nutrient uptake efficiency during adverse conditions reducing competition amongst different crops planted nearby each other thus optimizing yield potentials substantially over time too!

Microbial plant growth promoting substances are bioactive compounds produced by beneficial micro-organisms (bacteria, fungi and actinomycetes) that enhance plant growth directly (by supplying nutrients and hormones) or indirectly (by protecting against pathogens). They act as eco-friendly substitutes for chemical fertilizers and pesticides. Phytohormones are natural chemical or long-distance messengers produced in very small amounts by plants that regulate growth, development, reproduction and response to stress. The movement of hormones from the site of synthesis to the target site can be either directional (polar) movement or non-directional (non-polar) movement. The directional/upward movement is classified into acropetal movement,

meaning the motion of substances from base to apex, that is from root to shoot tip or older to younger tissues, and basipetal/downward movement of substances from apex to base region, that is from shoot to root tip or younger to older tissues [16].

Auxin, initially discovered plant hormone. It facilitates plant cell elongation and initiation of roots. Also involved in phototropism and gravitropism. Charles Darwin (1880) was discovered the term phototropism. It is also referred to as Indole 3 acetic acid (IAA). The Precursor molecule is tryptophan. Movement basipetal. Transport through phloem tissues. Indole 3 acetic acid (IAA) is found in all plants, but related compounds in plants have auxin activities. Peas contains 4 chloro Indole 3 acetic acid. Mustard and corn contain indole 3 butyric acid (IBA) [17]. The bulk of synthetic auxins are classified as herbicides in horticulture and agriculture. For instance: 2,4-dichlorophenoxyacetic acid and 2-methoxy-3,6-dichlorobenzoic acid. Sites of auxin biosynthesis include shoot apical meristem (primary sites of auxin synthesis), young leaves (auxin produced in leaf primordial), developing fruits/seeds (high auxin levels during development).

Multiple Tryptophan (Trp)-Dependent IAA Biosynthesis Pathways



Gibberellins play a fundamental role in many growth processes in plants such as stem elongation, seed germination, seed initiation, sex determination, and flowering. They are essential for seed dormancy breaking, fruit development and help alleviate genetic dwarfism and promote ovary enlargement and parthenocarpy. Gibberellins favor long-day plants (LDP) that bloom but inhibit short-day plants (SDP) with their movement accomplished via the phloem. This is in the family of diterpenoid acids and growth hormones that form the foundation of plant systems. *Gibberella fujikuroi*, a fungus that causes excessive elongation in rice plants, produces this compound [18] and, in Japan, it causes a condition called bakanae disease or "foolish seedlings". Gibberellins also promote stem development in dwarf and rosette forms. Gibberellins

regulate the transition between juvenile and adult plant phase life. The juvenile leaf appears simple, reproductive features lacking as well as GA signaling being lower. On the contrary, the adult life-phase is defined by complicated leaf structures, reproductive capacity and enhanced signaling via both gibberellins and auxins. These hormones are also applied to accelerate malting processes and enhance sugarcane yields. Gibberellins are all gibberellins and all have a basic structural common denominator; a gibbane ring from cyclohexane and four lactone rings. Differences among them are primarily due to small variations in the presence and structural arrangement of hydroxyl (OH), methyl (CH₃), and carboxyl (COOH) groups at different carbon atoms on the gibbane backbone. Isopentenyl diphosphate (IPP) is the precursor molecule for gibberellin synthesis. As diterpenes with 19- to 20-carbon chains, more than 136 types have been recorded (GA1 to GA136); among these, common bioactive forms include, but were not limited to, GA1, GA3 (the first one in historical records) and GA4 and GA7, which can facilitate elongation in apple fruits. Gibberellin was first detected by Kurosawa in *Fusarium moniliformae* (*Gibberella fujikuroi*), resulting in foolish seedling disease in rice. As the originator of this pathway was through the growth and isolation of gibberellin with GA3, Yabuta and Sumiki were key researchers. The sites of synthesis that produce these hormones include the shoot apical meristem, young leaves, developing seeds, embryos, flower buds, fruits, plastids, endoplasmic reticulum (ER), and cytosol; regions of rapid growth are the locations of highest concentration of gibberellins. Gibberellin is synthesized by the terpenoid pathway—also known as the isoprenoid pathway (which is an important metabolic pathway found not only in plants but in fungi and some bacteria, generating terpenoids that are made from isoprene units, C₅H₈). Beginning in plastids, after which it eventually ends in cytosol and ER. The main constituents are IPP together with its isomer dimethylallyl diphosphate (DMAPP). Inside plants there are two main pathways: the mevalonate pathway occurring in cytosol and the methylerythritol phosphate pathway occurring within plant plastids. The byproducts generated by these pathways may include several terpenes, monoterpenes (C₁₀), sesquiterpenes (C₁₅), diterpenes (C₂₀), triterpenes (C₃₀), tetraterpenes (C₄₀), and polyterpenes. These compounds are biologically not only gibberellins, but also involved in synthesis of the primary metabolites as sterols, carotenoids, chlorophyll side chains and also abscisic acid, and producing secondary metabolites including essential oils or defensive compounds [19]. Their roles can include regulating growth through hormones including gibberellins (GA) and abscisic acid (ABA), photosynthesis via chlorophylls or carotenoids and membrane stability because of sterols, all of which are vital to ecological balance.

Besides their functions: Cytokinins are responsible for promoting cell division and moving in a non-polar manner via xylem. Gaseous hormone ethylene regulates fruit ripening and leaf abscission in response to stress. Abscisic Acid, commonly believed to be a stress hormone, helps keep seed dormancy. Brassinosteroids promote cell expansion while supporting vascular

differentiation under stress. Compounds such as salicylic acids and jasmonates confer defenses against herbivores or pathogens. At the end of the day, strigolactones inhibit shoot branching, modulating root architecture, as well as symbiotic relations with mycorrhizal fungi.

Table 1: Steps in Gibberellin Biosynthesis

Steps	Biosynthesis
1. Initiation in Plastids	Precursor: Geranylgeranyl diphosphate (GGDP) Enzymes: ent-Copalyl diphosphate synthase (CPS) → ent-Kaurene synthase (KS) Product: ent-Kaurene
2. Conversion in ER	Enzymes: ent-Kaurene oxidase (KO) → ent-Kaurenoic acid oxidase (KAO) Product: GA ₁₂
3. Modification in Cytosol	Enzymes: GA 20-oxidase → GA 3-oxidase Product: Bioactive GAs such as GA ₁ , GA ₃ , GA ₄
4. Deactivation	Enzyme: GA 2-oxidase converts active GAs into inactive forms by adding hydroxyl groups.

Furthermore—microbial metabolites produced by beneficial microorganisms play vital roles serving ecologically friendly alternatives replacing chemical fertilizers/pesticides thereby contributing positively towards sustainable agriculture initiatives worldwide! Phytohormones function prominently regulating key aspects involving development/reproduction/stress responses orchestrated via directional transport mechanisms occurring throughout various plant tissues ensuring maximum efficacy during critical phases influencing overall life-cycle transitions observed among diverse species present today!

Moreover, beneficial microbes—such as Plant Growth-Promoting Rhizobacteria (PGPR)—and other agents contribute indirectly to plant growth by enhancing development without directly supplying nutrients or hormones; instead focusing on alleviating stresses or suppressing pathogens while improving soil health [20].

Induced Systemic Resistance (ISR) is a plant defense that is initiated by beneficial microorganisms like rhizobacteria and fungi that live in the local vicinity of plant roots. Unlike microorganisms responsible for the eradication of pathogens per se, these microbes help prepare the plant's immune system to mount a quicker and stronger attack. For example, the plant roots can recognize specific molecules emitted by these beneficial microbes, such as *Pseudomonas fluorescens* and species of *Trichoderma*. These molecules, called elicitors, contain lipopolysaccharides, siderophores, and flagellin fragments. Unlike Systemic Acquired Resistance (SAR), where salicylic acid (SA) is needed, activation of signaling pathways involved in ISR specifically relies on jasmonic acid (JA) and ethylene (ET). As a result of this priming, defense-related genes are not fully expressed, and when the plant becomes "primed," it is highly capable

of rapidly responding to pathogen invasion. Systemic signals also propagate from roots through shoots and leaves, leading to spread of resistance, rather than its diffusion localized to roots [21].

Table 2: Indirect Mechanisms of Microbes and Their Benefits to Plants

Microbes	Indirect mechanisms	Plant benefits
<i>Pseudomonas fluorescens</i>	Antibiotic production: PGPR produce antifungal/antibacterial compounds (e.g., phenazines, pyoluteorin). Siderophore production: Chelates iron, making it unavailable to pathogens but accessible to plants. Induced systemic resistance (ISR): Trigger plant defense pathways (via jasmonic acid/ethylene signaling), making plants more resistant to diseases.	Disease suppression in cereals
<i>Bacillus subtilis</i>	Biofilm formation: Protects roots from desiccation and pathogen invasion, ISR	Reduced fungal infect
<i>Azospirillum</i> spp.	Abiotic stress tolerance: PGPR produce ACC deaminase, lowering plant ethylene levels under stress (salinity, drought, flooding). Improved root architecture: By reducing stress hormones, roots grow deeper and wider, enhancing water/nutrient uptake.	Better root growth under drought.
<i>Trichoderma</i> spp.	Mycoparasitism, ISR	Control of soil borne pathogens.

When an invading pathogen or pest arrives, the primed plant demonstrates an enhanced response with accelerated cell wall reinforcement through callose and lignin deposition, production of antimicrobial compounds such as phytoalexins and pathogenesis-related proteins, and activation of a multitude of defense enzymes such as peroxidases and chitinases [22].

CRISPR-Cas9 is transforming the future of sustainable agriculture by enabling precise genetic modification of crops in ways that maximize yields, reduce stress responsiveness, improve nutrition, minimize reliance on chemical treatment and unsustainable practices. In this regard, it is already used to increase yields and sustainability in cereals, legumes, and horticulture crops. CRISPR-Cas9 applies to sustainable agriculture to increase the yields of crops for better crops. Yield enhancement of rice alterations (e.g., GS3/GW2) for crops; yield enhancement of wheat and grain yield; and biofortification of vitamins and minerals-rich crops for nutritional quality checking [23]. For prolonging shelf-life in fruits and vegetables, genetic editing of fruits and vegetables to delay ripening to prevent food loss. Stress resilience for abiotic stress tolerance (crops in an abiotic manner where modified to resist drought, salinity, and heat resistance); biotic resistance of the crop is better protection from better immunity to infection against fungi,

bacteria, and viruses that can cause illness and climate resiliency which is required for crops which can withstand erratic weather variability. Reduced chemical dependency for less use of pesticide treatments and less chemical sprays and fertilizers used to spray. Optimized to improve the uptake efficiency for efficient insecticides and sustainable farming techniques reduce environmental impact for efficient insecticides. Applied to other fields such as animal husbandry application by way of CRISPR in the case of livestock, aquaculture application for fish growth and resistance to disease, and microbial biotechnological engineering for producing the most beneficial microbes in terms of fertility and health of the crops. The challenges and future directions of use are that of non-uniform effectiveness and not because of potential inconsistency, however, the efficacy of microorganism inoculants can differ by environmental conditions. Further research is needed to maximize their application to all soil and climatic conditions [25]. Then the regulatory gateways that are necessary to approve a product are long and convoluted and, therefore, not very attractive for farmers to use. Knowledge gaps for various species of microorganisms and their interactions on soil health and crop product.

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MICROBIAL CONSORTIA IN SUSTAINABLE AGRICULTURE: INTEGRATIVE ROLES IN BIOFERTILIZATION AND BIOPESTICIDE DEVELOPMENT

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Abstract

Sustainable farming techniques play an important role in meeting the food requirements of the world's population while preserving the environment. Microbial consortia, where two or more species are used in combination, have been recognized as effective biological tools for the replacement of chemical fertilizers and pesticides. Studies have confirmed that the use of consortia enhances the growth of plants by an average of 48%, which is significantly higher than the growth observed with the use of single species. The consortia act through various modes, such as the fixation of nitrogen, solubilization of phosphorus, and inhibition of harmful plant pathogens. The consortia also provide support to crops during adverse climatic conditions such as drought and salt stress, although the efficacy of consortia in the field is subject to change due to fluctuations in the environment. The major hurdles in the commercial application of consortia are the compatibility between the microbes used and the strict regulatory requirements. The future lies in the application of emerging technologies such as Artificial Intelligence and genomics.

Keywords: Biofertilizers, Biopesticides, Microbial Consortia, PGPR.

1. Introduction

Sustainable agriculture is increasingly becoming more imperative in addressing global food security and environmental issues with the world's population projected to rise to around 9.6 to 9.7 billion by 2050 (Hettsee *et al.*, 2025). To meet the increasing demand, there is a need to increase food production by around 60%, but there is also a challenge of having limited fertile land coupled with climate change (Khan, 2012). The widespread use of synthetic agrochemicals in agriculture has caused significant environmental degradation, including pollution of groundwater, soil, and atmospheric pollution (Kour *et al.*, 2020). Chemical fertilizers have low nutrient utilization efficiency, with only 30-40% being absorbed by plants, while the rest is lost into the environment, causing eutrophication and greenhouse emissions (Bharti *et al.*, 2025). Synthetic agrochemicals also have components that include heavy metals and radionuclides, which persist in the environment, posing significant risks to human and animal health (Kumar *et al.*, 2022). Moreover, overreliance on synthetic chemicals for controlling pests and diseases has led to increased resistance in these pathogens and pests, making conventional methods less effective over time. Microbes, collectively known as "plant probiotics," play an important role in

maintaining crop productivity by improving crop growth through direct and indirect pathways. The direct pathways include biological nitrogen fixation, solubilization of phosphate, and production of essential growth hormones like auxins and gibberellins, which help in improving nutrient uptake and root growth (Thamizharasan *et al.*, 2024). The indirect pathways include biocontrol of phytopathogens through antibiosis and production of growth hormones like auxins and gibberellins, as well as induction of systemic acquired resistance (SAR) (Tiwari *et al.*, 2025). Certain microbes also produce an enzyme called 1- aminocyclopropane-1-carboxylic acid (ACC) deaminase, which helps in improving drought and salinity stress tolerance in crops by deaminating ACC and reducing ethylene production.

2. Microbial Consortia: Concept and Principles

2.1 Definition and Characteristics of Microbial Consortia

The consortia of microbes have been defined as the populations of two or more species or strains of microbes that live in one environment. The consortia are recognized by their efficiency, robustness, modularity, and reliability in performing complex ecological functions that individual microbes may be incapable of performing. The consortia may be classified into artificial, synthetic, and semi-synthetic consortia. The consortia may be made up of strains that do not normally occur in the wild and may be made up of either natural or genetically engineered microbes. (Tiwari *et al.*, 2025).

2.2 Types of Microbial Interactions

Microbial interactions are generally divided into cooperative (positive) and non-cooperative (negative) types. Mutualism is the most common cooperative interaction between two organisms, where both organisms benefit e.g., heterotrophic bacteria supply vitamins and nutrients to microalgae, whereas the microalgae supply oxygen and organic carbon in return (Sadvakasova *et al.*, 2023). In commensalism, one species benefits, whereas the host is not affected; this is commonly seen in epiphytic microbes (Thamizharasan *et al.*, 2024). Synergism is the interaction between two or more strains, where the effect is greater than the sum of the individual strains; the inoculation of *Bacillus* and *Pseudomonas* strains increases biofilm development and the suppression of pathogens (Tiwari *et al.*, 2025).

3. Microbial Consortia in Biofertilizers

3.1 Overview of Biofertilizers

Biofertilizers are preparations that comprise living or dormant microbial cells that reside in the rhizosphere or plant tissue and promote the availability of nutrients. Biofertilizers are used as an alternative to synthetic fertilizers because they are environmentally friendly and inexpensive. Biofertilizers fix nitrogen and mineral solubilization in the soil. Biofertilizers differ from synthetic fertilizers in that they can improve the structure of the soil and biodiversity. Biofertilizers promote long-term fertility in the soil (Khan, 2022).

3.2 Microorganisms Used in Consortia

Nitrogen Fixing Bacteria Symbiotic N fixers such as *Rhizobium* and *Bradyrhizobium* for legumes, and free-living N fixers such as *Azotobacter* and *Azospirillum* (Sadvakasova *et al.*, 2023). Phosphate Solubilizing Microorganisms (PSM) The most dominant PSM are *Bacillus* and *Pseudomonas* species of bacteria and fungi such as *Aspergillus* and *Penicillium*. The most important Potassium Solubilizing Microorganisms (KSM) are *Acidithiobacillus ferrooxidans*, *Bacillus mucilaginosus*, and *Burkholderia* that secrete potassium from mineral sources (Khan *et al.*, 2022). Plant Growth Promoting Rhizobacteria (PGPR) comprises various species of bacteria such as *Agrobacterium*, *Arthrobacter*, *Enterobacter*, and *Serratia* that facilitate growth through multiple direct and indirect mechanisms

3.3 Mechanisms of Nutrient Mobilization

Nitrogen fixation is process where the nitrogenase enzyme complex of diazotrophs fixes atmospheric nitrogen gas in the form of ammonia, which is used by plants for protein synthesis Fig. 1 (Khan *et al.*, 2022). In Phosphate solubilization microorganisms solubilize phosphate by producing organic acids, which decrease the soil pH, or by producing phosphatases, which degrade organic phosphate (Seenivasagan *et al.*, 2021).Potassium mobilization KSMs dissolve silicate minerals, releasing K⁺ ions in the soil, which is made possible by the production of organic acids and bioactive materials (Kour *et al.*, 2020).PGPRs produce various hormones, such as auxins (IAA) for root development, gibberellins (GA) for stem elongation, and cytokinins for cell division (Sadvakasova *et al.*, 2023).

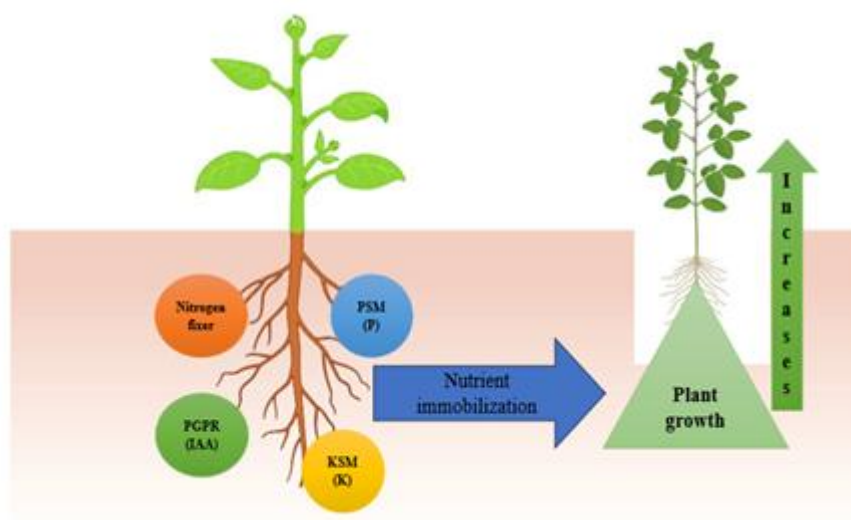


Figure 1: Microbial consortia in rhizosphere and their role in nutrient mobilization

4. Microbial Consortia in Biopesticides

4.1 Biopesticides

Biopesticides are biocontrol agents that are derived from living organisms or natural products and are used for controlling pests and diseases (Kumar *et al.*, 2022). This is an eco-friendly approach that is specific in its actions and helps in reducing the need for chemicals. The

scientific literature indicates that there is an increased trend towards biopesticides due to their applications in sustainable agriculture (Awal *et al.*, 2025).

4.2 Microbial Agents Used in Biopesticide Consortia

Bacillus species are used for the production of antifungal lipopeptides such as iturin. *Pseudomonas* species produce phenazine and HCN to inhibit the growth of the pathogen (Samantaray *et al.*, 2024). *Trichoderma* species show mycoparasitic activity against various fungal pathogens such as *Fusarium* and *Rhizoctonia*. Entomopathogenic fungi such as *B. bassiana* and *Metarhizium* infect the body of the insect. *Streptomyces* species are the most potent producers of antibiotics and lytic enzymes such as chitinases that lyse the cell walls of the pathogen (Seenivasagan *et al.*, 2021).

4.3 Mechanisms of Pest and Disease Suppression

Antibiosis is the mechanism where microbes produce antimicrobial compounds that kill the competing pathogens (Sharma *et al.*, 2025). In competition microbes colonize the ecological niches of the plant, i.e., rhizosphere and phyllosphere, very quickly, and this denies the pathogens space and iron. *Trichoderma* displays parasitic characteristics as it interacts with the host hyphae and uses enzymes to lyse them Fig. 2 (Benchlih *et al.*, 2025). In induced stress response (ISR) microbes induce a state of immunization in the plant, and this allows for a quicker reaction against the pathogens (Dwisandi *et al.*, 2025).

5. Formulation and Development of Microbial Consortia

5.1 Selection of Compatible Microbial Strains

Formation of a consortium involves selecting strains that are both functional and compatible. The compatibility of the strains is verified by a disk assay or a dual culture assay, where it is ensured that there are no inhibitory interactions between strains (Tiwari *et al.*, 2025). Design strategies in this area involve top-down approaches such as functional community definition and bottom-up approaches such as the identification of interactions. Other strategies involve the identification of the "core microbiomes" or the "hub-microbiomes" that are central to plant health and the supplementation of these microbiomes for stability.

5.2. Carrier Materials and Formulation Techniques

The carrier must be able to preserve the viability of the strains over long periods. The most common carriers used in the formulation of the carrier-based approach are charcoal, biochar, peat, and clay (Dwisandi *et al.*, 2025). Water and organic solvents such as glycerol are the most common liquid carriers. The liquid carriers are used in the formulation of liquid-based approaches. The microbes are protected against UV and drying stresses with the application of modern technologies such as microencapsulation in alginate and the application of the biofilm-based approach. The viability of cells at the time of application is a significant technological hurdle (Samantaray *et al.*, 2024). Bacterial species belonging to the spore-formers category, such as *Bacillus* species, are generally favored due to their naturally stable endospores during storage.

For non-spore formers, lactose and trehalose are used as protective agents for cell membranes during the drying process (Tiwari *et al.*, 2025).

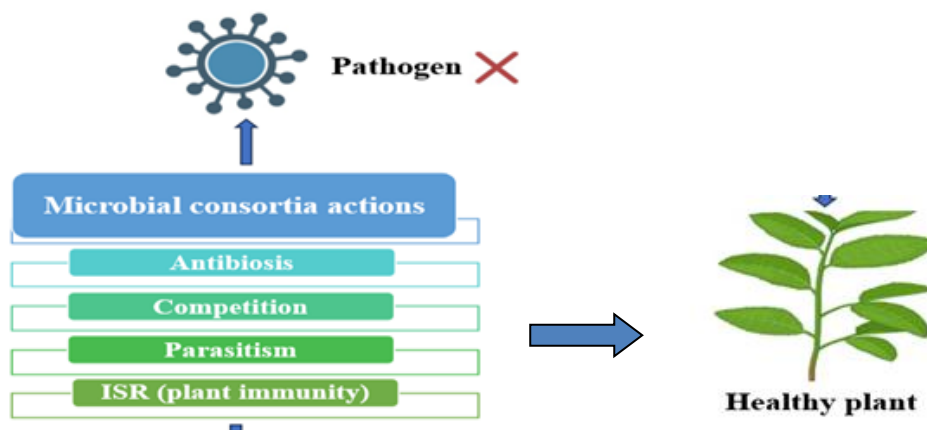


Figure 2: Biocontrol mechanism of microbial consortia against plant pathogens

6. Application Methods in Agriculture

6.1 Seed Treatment

Table 1: Application of microbial consortia in different crops and their benefits

S. No.	Microbial Consortium	Target Crop	Outcomes and Key Benefits	Reference
1.	<i>Bacillus subtilis</i> + <i>Trichoderma harzianum</i>	Potato	Suppressed common scab disease (reduced index by 46.1%) and increased tuber yields by up to 32.2%.	Wang <i>et al.</i> , 2019
2.	<i>Pseudomonas</i> + <i>Microbacterium</i>	Tomato	Provided protection against bacterial canker, reduced lesion size, and significantly promoted root development.	Benchlih <i>et al.</i> , 2025
3.	"Mammoth PTM" (<i>Enterobacter</i> , <i>Citrobacter</i> , <i>Pseudomonas</i> , and <i>Comamonas</i>)	Tomato, Basil, Wheat	Improved phosphate availability and increased plant productivity by up to 91%.	Khan <i>et al.</i> , 2022
4.	<i>Bradyrhizobium japonicum</i> + <i>Rhizobium tropici</i>	Soybean	Achieved significant yield increases of 16.1% in soybean and 19.6% in common beans.	Khan <i>et al.</i> , 2022
5.	<i>Azotobacter</i> , <i>Bacillus</i> , <i>Pseudomonas</i> , and <i>Glomus</i>	Maize	Enhanced vegetative growth (+17%), shoot nitrogen uptake (+34%), phosphorus acquisition (+25%).	Hett <i>et al.</i> , 2023

The process seed treatment involves applying a coating of formulations with beneficial microorganisms on the seeds before planting. This method of application guarantees direct interaction of the inoculant with the developing roots, thus enhancing early colonization and

symbiotic association (Tiwari *et al.*, 2025). Some of the seed treatment techniques include seed dressing, which involves applying a formulation on the seeds, and bio-priming, which involves the use of a combination of seed hydration and inoculation to improve seed germination and soil phosphorus acquisition. Application of beneficial microorganisms such as *Trichoderma-Pseudomonas* consortia on the seeds for inoculation has proved effective in reducing seedling mortality and managing soil-borne diseases in crops such as soybean and maize (Sadvakasova *et al.*, 2023).

6.2 Soil and Foliar Application

Soil application is defined as “the direct application of microbial consortia to the soil in liquid, granular, or carrier-based inoculant formulations” (Sadvakasova *et al.*, 2023). This mode of application can cover vast areas of the rhizosphere with microorganisms, thereby promoting diversity in the soil microbiota. In addition, it can be applied during land preparation or through fertigation for efficient nutrient delivery (Awal *et al.*, 2025). Soil application of biofilm biofertilizers has shown promising results in enhancing nutrient status and grain yields in large-scale rice cultivation, as indicated by field trial results. In addition, carriers such as zeolite or biochar can be used in solid form and mechanically incorporated into the soil for long-term survival of applied strains (Hett *et al.*, 2023). The process of foliar application is the spraying of microbial solutions or their extracts onto the leaves of the plants, where the nutrients and bioactive compounds are absorbed through the stomata or the epidermal cells (Awal *et al.*, 2025). This is considered to be a very efficient process for the immediate uptake of nutrients and the management of foliar pathogens and pests (Thamizharasan *et al.*, 2024).

7. Impact of Microbial Consortia on Crop Productivity

7.1 Effects on Plant Growth and Yield

The use of microbial consortia has been recognized as the key to the intensification of sustainable agriculture, which seeks to create biological equilibrium with minimal use of synthetic chemicals. A global meta-analysis of inoculants showed that the inoculants resulted in a plant growth increase of 48%, a higher increase than the 29% increase that can be achieved by single-species inoculants. A rhizosphere-based inoculant comprising *Bacillus subtilis* and *Trichoderma harzianum* was observed to increase potato yield by 23.0% to 32.2% while controlling common scab diseases (Wang *et al.*, 2019). For Tomato Co-inoculation of Tomato plants with compatible strains of *Pseudomonas* and *Microbacterium* resulted in shoot length increase of up to 90.38% even in the presence of infection (Hett *et al.*, 2023).

7.2 Nutrient Use Efficiency (NUE)

Improving Nutrient Use Efficiency (NUE) is a key approach made possible through the use of microbial consortia to disassociate productivity from costly synthetic fertilizers. Microbial inoculants of alga cyanobacterial or bacterial consortia can make it possible to reduce the use of synthetic nitrogen fertilizers by 40-80 kg/ha without affecting grain yield (15). Tripartite

interactions between AM fungi, rhizobia, and plants revolutionize the conventional models of competition, with consortia increasing the acquisition of P by up to 57% and transfer of nitrogen from legumes to cereals by up to 17%. Advanced consortia can efficiently solubilize iron (Fe), zinc (Zn), and manganese (Mn) in the rhizosphere, thus improving grain quality to combat "hidden hunger" in cereal-based diets (Kour *et al.*, 2020). Biochar in combination with consortia can improve nitrogen use efficiency by 87% in tomato cultivation compared to individual treatments (Wang *et al.*, 2019).

Conclusion

The transition to sustainable agriculture is the key to food security at the global level. Microbial consortia are the key to sustainable agriculture. The transition is from single-function agents to multi-function agents that provide protection to plants, promote plant growth, and rejuvenate the soil. Microbial consortia have been proven to promote plant growth by an average of 48%. The efficacy of microbial consortia in promoting plant growth is much higher when compared to the efficacy of single-strain agents. Microbial consortia have already been proven to promote the growth of important crops such as potato, tomato, and maize (Benchlih *et al.*, 2025). In addition to promoting plant growth, microbial consortia have already been proven to control plant diseases. Microbial consortia are called plant probiotics. Microbial consortia can be used in conjunction with biochar and waste recycling to create a circular economy and minimize the use of chemical fertilizers. However, challenges such as microbe compatibility, environmental factors, and stringent laws hinder their application in the field. More studies are required to ensure their effectiveness in different geographical locations (Hett *et al.*, 2023). It is essential to develop international collaborations to integrate these biological approaches into the food chain in a resilient and sustainable way (Khan *et al.*, 2022).

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BIODEGRADABLE MULCHES AS SUSTAINABLE ALTERNATIVES TO PLASTIC MULCHING IN AGRICULTURE

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Abstract

Biodegradable mulches are being developed as a sustainable option for traditional plastic-based agricultural mulching. Conventional polyethylene-based agricultural mulches increase crop yields by retaining moisture, regulating temperature, and controlling weeds. However, this practice poses significant environmental problems, including white pollution, microplastics, and soil destruction. To overcome these problems, biodegradable mulch films (BDMs) are developed, which decompose in the soil through microbial action, converting into CO₂, H₂O, and biomass. Biodegradable mulch films are manufactured from bio-based polymers, petroleum-based biodegradable plastics, and composite materials such as biochar-based films. The advantages of biodegradable agricultural mulches include a lower carbon footprint, improved soil quality, and elimination of post-harvest removal. However, there are limitations to the use of biodegradable agricultural mulches, including high costs, low mechanical properties, and leaching of additives. Recent advances in agricultural mulches include smart mulches, liquid mulches, and AI-based material development. In conclusion, biodegradable agricultural mulches are a sustainable option for agricultural practice.

Keywords: BDM, Microplastics, White Pollution, Environmental Sustainability.

1. Introduction

Mulching is an accepted agronomic practice that involves maintaining a protective covering on the surface of the soil with the aim of improving soil conservation, water conservation, and crop development. Mulching is defined as “a persistent or transient covering on the surface of the soil. The covering is usually made up of organic or inorganic materials. Over time, mulching has grown from using traditional materials such as paper and glass to using synthetic materials such as plastic. Mulching is recognized today as an essential tool in meeting global food security requirements, especially in regions that have been affected by environmental conditions such as drought, low temperatures, or insufficient sunshine. The mulching method is also essential in controlling soil temperature. The film is known to increase soil surface temperature to optimize seed germination. The method is also effective in controlling weeds. Despite the success story, it has also led to severe environmental degradation known as "white pollution." The mulch film is mainly composed of low-density polyethylene (LDPE), which is highly resistant to degradation. The film is known to remain in the soil for decades and even centuries. The film has led to the

accumulation of 50-260 kg/hm² in the topsoil. In the long term, these residues are broken down into small particles called microplastics and nano plastics. Microplastics and nano plastics are then incorporated into the human food chain and can adsorb other harmful substances such as heavy metals. (Campanale *et al.*, 2024; Dada *et al.*, 2024)

2. Plastic Mulching in Agriculture

Plastic mulching is a fundamental practice of modern intensive farming, as it was initially introduced in the USA in 1948 and then gradually replaced traditional products like paper and glass. In total, around the world, there are approximately 20 million hectares of agricultural land where plastic mulching is applied, and this constitutes a significant part of the "agri-plastics" market. The most prevalent types of plastics used for this purpose are low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE), as they are characterized by high tensile strength, elasticity, durability, and economy. Other types of plastics, which are applied for specific agricultural requirements, are high-density polyethylene (HDPE), polyvinyl chloride (PVC), ethylene-vinyl acetate (EVA), and ethylene-butyl acrylate (EBA). The thickness and colours of these plastics vary, most often being black, transparent, and white, in order to control the microclimate and the radiation of heat from the soil around the crops Fig.1 (Graf *et al.*, 2024; Kasera *et al.*, 2026).

2.1 Agricultural Benefits of Plastic Mulch

The extensive usage of plastic mulch is largely due to its effectiveness in enhancing crop yields and quality. In this case, it is noted that an increase in crop yields can be realized between 25% and 45%, depending on environmental conditions. Some of the main benefits of include Fig.2.

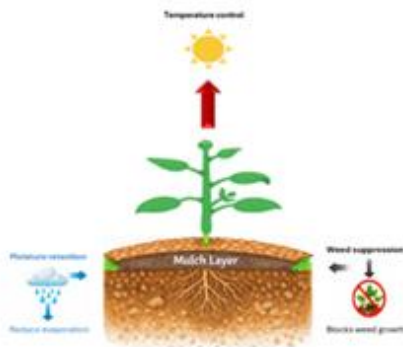


Figure 1: Mulch in Agriculture

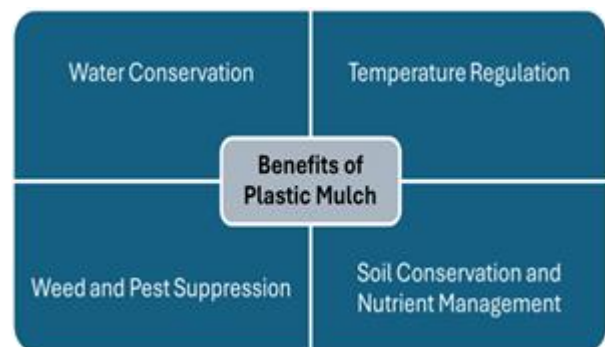


Figure 2: Benefits of Mulch

2.2 Environmental Problems Associated with Plastic Mulching

Though plastic mulching is effective in increasing crop production, the non-biodegradable plastics cause a worldwide environmental disaster called "White Pollution." Persistence and Soil Accumulation here the non-biodegradable plastics are more stable and do not decompose easily. Long periods of plastic mulching led to the accumulation of plastics in the soil, up to 50-260 kg/hm² of remaining plastics in the topsoil. Conventional plastic mulches are the source of non-biodegradable additives, which include phthalate esters (PAEs), bisphenol A (BPA), and ultraviolet stabilizers. Non-biodegradable plastics do not contain these additives chemically; hence, they are released into the soil and act as endocrine disruptors. The collection of used films

is labor-intensive and not always successful, especially because of fragmentation. Plastic mulching can stimulate the decomposition of soil organic carbon and result in a large increase in N₂O emissions, leading to a great climatic impact (Campanale *et al.*, 2024; Habarakada Liyanage *et al.*, 2025; Reay *et al.*, 2025)

3. Biodegradable Mulches

Biodegradable plastic mulches (BDMs) are carefully planned to offer an eco-friendly solution to conventional polyethylene (PE) films. Unlike conventional plastic films, which have to be removed from the soil surface manually after harvesting, BDMs are designed to be incorporated directly into the soil, where natural microorganisms such as bacteria, fungi, and algae are expected to degrade them (Habarakada Liyanage *et al.*, 2025; Shah *et al.*, 2026).

3.1 Types of Biodegradable Mulch Materials

Biodegradable mulches are categorized into three primary classes in Table 1

Table 1: Types of Mulches

Class	Subtypes / Examples	Key Characteristics	Sources
Bio-based Polymers	Starch-based	Widely available; often blended to fix brittleness and low water resistance.	Liyanage <i>et al.</i> , 2025
	Polylactic Acid (PLA)	High strength/rigidity; slow soil degradation due to high glass transition temperature.	Bai <i>et al.</i> , 2026
	Polyhydroxyalkanoates (PHAs)	Microbial fermentation origin; excellent biodegradability; high production costs.	Amusat <i>et al.</i> , 2026
	Natural Fibers	Cellulose/Paper or Coconut coir; sustainable but may degrade too fast in wind/rain.	Li <i>et al.</i> , 2026; Salva <i>et al.</i> , 2025
	Protein-based	Tannery waste or soy; nitrogen-rich; suppresses weeds while enhancing fertility.	Esha <i>et al.</i> , 2025
Petroleum-derived	Polybutylene adipate terephthalate (PBAT)	Flexible and tough; often blended with PLA or starch to balance properties.	Liyanage <i>et al.</i> , 2025
	Polybutylene succinate (PBS)	High thermal resistance and chemical stability (similar to polypropylene).	Campanale <i>et al.</i> , 2024; Dada <i>et al.</i> , 2024
Innovative Composites	Biochar-reinforced	Enhances strength/thermal stability; provides long-term carbon sequestration.	Li <i>et al.</i> , 2025
	Sprayable Liquid Mulches	Biomass/industrial waste; sprayed in-situ to reduce labor and handle difficult terrain.	Kasera <i>et al.</i> , 2026

3.2 Mechanism of Biodegradation in Soil

Biodegradation of BDMs in the soil is an intricate process influenced by the interrelationship between biotic and abiotic factors (Campanale *et al.*, 2024). The biodegradation of BDMs in the soil is generally believed to involve four different stages Fig.3:



Figure 3: Mechanism of degradation

Biodeterioration the initial exposure of the polymer to abiotic factors such as UV rays, heat, and humidity. This makes the formation of a biofilm and the physical disintegration of the biofilm easier (Bai *et al.*, 2025; Coutris *et al.*, 2025). Next step is depolymerization the microorganisms secrete enzymes such as hydrolases that degrade the long chains of the polymer into shorter chains of molecules, which include oligomers, dimers, and monomers. The presence of weaker ester bonds makes them highly susceptible to depolymerization in comparison to the carbon-carbon bonds in other plastic materials (Graf *et al.*, 2024; Habarakada Liyanage *et al.*, 2025). Then assimilation these short chains of molecules are transported into the microbial cell membranes and assimilated into the microbial metabolism (Saleh *et al.*, 2026). Final step, mineralization where the assimilated carbon is converted into oxidized simple molecules such as CO₂, H₂O, and biomass under aerobic conditions or CH₄ (methane) under anaerobic conditions and is released back into the environment (Li *et al.*, 2024).

4. Environmental Benefits and Challenges of Biodegradable Mulches

4.1 Environmental Benefits

Biodegradable plastic mulch films (BDMs) have been recognized as an eco-sustainable solution for agricultural mulching by eliminating the labour-intensive and costly practice of post-harvest film retrieval. The first environmental benefit is that BDMs avoid "white pollution," which is caused by the accumulation of residual fragments in the soil. Such pollution can reach levels of 50–260 kg/hm² in the topsoil. Moreover, life cycle assessments (LCAs) have confirmed that BDMs have a lower carbon footprint and reduced cumulative energy demand than polyethylene (PE) films. A global-scale meta-analysis study confirmed that BDMs could reduce global warming potential (GWP) by 18.27%, whereas conventional plastics have no significant impact. When BDMs are tilled into the soil, they act as organic carbon inputs that could stimulate microbial activity in the soil. Specifically, microbial activity is increased by up to 37.6% in the topsoil layers. This could improve physical properties in the soil (Campanale *et al.*, 2024; Shah *et al.*, 2026).

4.2 Limitations and Challenges

However, the large-scale use of BDMs is mainly restricted by economic factors, as the price of BDMs is generally two to three times higher than that of traditional PE mulch materials. From a

technical point of view, BDMs also have relatively low mechanical strength, elongation capacity, and tearing properties, which could cause tearing and irregular distribution during mechanical application. The most serious functional limitation is the early degradation of BDMs, which degrades too early in the growth season and therefore compromises the effectiveness of weed suppression and moisture conservation. Lastly, the absence of harmonized universal standards and differences in product labelling between 'compostable' and 'soil-biodegradable' products continue to undermine the faith and confidence of growers and further complicate regulatory oversight (Amusat *et al.*, 2026; Sun *et al.*, 2025).

5. Recent Advances and Future Perspectives

Recent technological progress in mulch materials has moved beyond material substitution to the development of state-of-the-art, multifunctional mulch materials. A notable achievement in mulch technology is the development of biochar-reinforced biodegradable mulch films that incorporate biochar as a porous component to improve mechanical, thermal, and water retention properties. Another notable achievement is the introduction of polyglycolic acid (PGA), which offers superior mechanical and degradation properties in contrast to conventional polylactic acid (PLA). Moreover, liquid mulch technology, which employs lignosulfonate and chitosan derived from industrial waste and cow dung waste, is set to revolutionize mulch applications in difficult terrain, thus eliminating capital and labor costs associated with film installation. Advanced computational techniques, such as "CSM-Evo," have enabled the development of the DCTPC_4M_S122H enzyme variant, which has shown potential in the efficient depolymerization of PBAT-based films into high-purity terephthalic acid, which is essential in the recycling process. Furthermore, "smart" mulch films are being developed to deliver sustained release agents of pesticides and fertilizers, which could reduce the dosage of these chemicals by up to 70%. Future research must focus on the need to investigate the cumulative effects of mulch residues on the soil microbial community, nutrient cycling, and carbon sequestration through extensive field-based investigations. This includes the use of techniques such as Laser Direct Infrared (LDIR) and Optical Photothermal Infrared (O-PTIR) spectroscopy in the determination of the micro-bioplastics and their subsequent degradation compounds. Addressing the "pollution swapping" potential of leachable inorganic and organic additives continues to be a significant safety issue for the next generation of biodegradable mulches. To achieve the transition to a sustainable agroecosystem, there will need to be significant economic incentives, such as subsidies and tax credits, as well as the establishment of global standards and certification protocols for soil biodegradable products (Amusat *et al.*, 2026; Mazzon *et al.*, 2026; Sun *et al.*, 2025).

Conclusion

Biodegradable plastic mulching films (BDM) are an emerging technology to address the issue of "White Pollution" in agriculture. These films possess similar properties to conventional plastic

films but have shown 18.27% less Global Warming Potential. Despite these positive attributes, farmers are reluctant to adopt these films due to their higher cost compared to conventional plastic films. In addition, these films are also prone to tearing. In cold climates, such as in Nordic countries, these films may take years to degrade. Recent advances in technology, such as biochar-based films and spray-based liquid films, are improving film durability. These films are also proving to be effective in carbon sequestration in soils. Artificial intelligence and machine learning are also being used to further improve these films. Future research in this area is required to ensure safe degradation in soils. In addition, it is also important to develop international standards, such as EN 17033:2018, to ensure farmers' trust. In conclusion, it is evident that BDM technology can be used to align global food security with environment and soil integrity.

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TEMPORAL TREND OF SUGARCANE AREA IN MAHARASHTRA

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Introduction

Sugarcane (*Saccharum officinarum L.*) is one of the most important commercial crops in India and plays a vital role in the agricultural economy. It provides raw material for the sugar industry and several by-products such as molasses, bagasse, ethanol and press mud. The crop also contributes significantly to employment generation and rural development. Maharashtra is one of the leading sugarcane producing states in India, along with Uttar Pradesh and Karnataka. The state has witnessed a significant increase in the area under sugarcane cultivation during the last three decades. The expansion is largely due to economic incentives, government policies, irrigation development and technological advancements in sugarcane production (Sugar Commissionerate. 2024, ICAR, 2021).

Over the years, the area under sugarcane in Maharashtra has increased from approximately 4–5 lakh hectares in the early 1990s to more than 14 lakh hectares in recent years. This growth reflects the increasing importance of sugarcane as a commercial crop in the state. The expansion has been supported by the development of the sugar industry, particularly the cooperative sugar sector, which plays a crucial role in rural development (Sugar Commissionerate, 2024).

This chapter examines the major factors responsible for the increase in sugarcane cultivation area in Maharashtra during the last thirty years.

Growth of the Sugar Industry

Cooperative Sugar Movement

The cooperative sugar movement has played a key role in the expansion of sugarcane cultivation in Maharashtra. Cooperative sugar factories were established with the objective of empowering farmers and improving rural livelihoods. The cooperative model ensures that farmers are not only suppliers of sugarcane but also stakeholders in the sugar factories. This system provides several benefits such as:

- Assured procurement of sugarcane
- Access to agricultural inputs
- Technical guidance
- Profit sharing among members

Expansion of Sugar Mills

The expansion of sugar mills has been a major factor contributing to the growth of sugarcane cultivation in Maharashtra. Over the past few decades, the number of sugar factories in the state has increased significantly due to strong cooperative movements, private investments and supportive government policies. Maharashtra currently has more than 200 sugar factories, including both cooperative and private sector mills. These factories are widely distributed across major sugarcane-growing districts such as Kolhapur, Sangli, Satara, Pune, Solapur and Ahilyanagar. The establishment of new mills and the modernization of existing ones have strengthened the sugar industry and increased the processing capacity of the state.

The cooperative sugar movement has played a particularly important role in the development of the sugar sector in Maharashtra. Many sugar factories were established under the cooperative model, where farmers themselves are shareholders of the mills. This structure has helped create a strong linkage between farmers and sugar factories, ensuring a stable market for sugarcane. Institutions such as the Vasantdada Sugar Institute have also supported the development of the sugar industry by providing technical guidance, research support and training to sugar factories and farmers. The expansion of crushing capacity has created a continuous and assured demand for sugarcane, which has encouraged farmers to increase the area under sugarcane cultivation. Sugar mills require a regular supply of cane to operate efficiently during the crushing season, and therefore they actively promote sugarcane development programmes in their command areas. Many factories provide farmers with improved seed material, technical guidance and support for irrigation and mechanization. As a result, the expansion of sugar mills has not only increased sugar production but has also strengthened the rural economy by generating employment and improving income opportunities for sugarcane farmers.

Economic Profitability of Sugarcane

Higher Returns Compared to Other Crops

Sugarcane provides higher economic returns compared to many other crops such as jowar, bajra, maize and pulses (FAO, 2022). The crop offers relatively stable income because it has a long growing period and a well-established marketing system.

Farmers prefer sugarcane cultivation because:

- It ensures stable income
- There is guaranteed procurement by sugar mills
- Payment is regulated by government policies

Fair and Remunerative Price (FRP)

The Government of India announces a minimum price for sugarcane known as the Fair and Remunerative Price (FRP). This price ensures that farmers receive a minimum return for their produce (Government of India, 2023). The implementation of FRP has significantly increased farmer confidence in sugarcane cultivation. As the FRP has increased over the years, farmers have been encouraged to allocate larger areas to sugarcane cultivation.

Development of Irrigation Infrastructure

Major Irrigation Projects

The expansion of irrigation infrastructure has played a major role in the growth of sugarcane cultivation in Maharashtra. Large irrigation projects such as the Koyna Dam and Ujani Dam have provided reliable water supply to agricultural regions. These irrigation systems support sugarcane cultivation in western Maharashtra, where canal irrigation is widely practiced.

Micro-Irrigation Technologies

Micro-irrigation technologies have become an important component of modern sugarcane cultivation, particularly in water-scarce regions of Maharashtra. In sugarcane traditional irrigation methods such as flood or furrow irrigation often led to significant water losses through evaporation, runoff and deep percolation. The adoption of micro-irrigation systems, especially drip irrigation, has helped improve water use efficiency and optimize irrigation management in sugarcane fields. These systems deliver water in small and controlled quantities directly to the root zone of the crop, ensuring that plants receive the required moisture with minimal wastage.

Among micro-irrigation methods, the Drip Irrigation system is widely used in sugarcane cultivation. In this system, water is supplied through a network of pipes, laterals and emitters placed along the crop rows. The emitters release water slowly and uniformly near the plant roots, maintaining optimum soil moisture conditions. This method can reduce irrigation water use by 30–50 percent compared with conventional irrigation practices. In addition to saving water, drip irrigation also helps improve nutrient use efficiency when combined with fertigation, where fertilizers are applied through the irrigation system. This ensures better nutrient availability to plants, leading to improved cane growth, higher yields and better sugar recovery.

The adoption of drip irrigation in sugarcane has been actively promoted through various government initiatives. The Maharashtra Government provide financial assistance to encourage farmers to install micro-irrigation systems. These subsidy programmes significantly reduce the cost of installation, making the technology accessible to small and medium farmers. As a result, micro-irrigation technologies are playing a key role in improving water productivity, enhancing crop yields and supporting sustainable sugarcane production in Maharashtra.

Technological Advancements in Sugarcane Production

Improved Sugarcane Varieties

Technological advancements in sugarcane production have played a significant role in improving crop productivity, sugar recovery and overall profitability of sugarcane farming. Among these advancements, the development of improved sugarcane varieties has been one of the most important achievements of agricultural research. New varieties are developed through systematic breeding programmes that aim to increase cane yield, enhance sugar content and improve resistance to diseases and pests. These improved varieties help farmers obtain higher production from the same area of land, thereby increasing the efficiency of sugarcane cultivation. The Vasantdada Sugar Institute conduct extensive research on sugarcane breeding and varietal

development. Through hybridization and selection programmes, scientists have developed varieties that possess desirable traits such as high yield potential, better ratooning ability, tolerance to drought and salinity and improved sugar recovery. The introduction of such varieties has helped stabilize sugarcane production even under varying climatic and soil conditions.

Improved sugarcane varieties also offer resistance or tolerance to major diseases and pests that commonly affect the crop. Varieties with resistance to diseases such as Red Rot, Smut and pests like Sugarcane Top Borer have helped reduce crop losses and minimize the need for chemical plant protection measures. As a result, farmers can maintain healthier crops with lower production risks. The availability of region-specific improved varieties has also encouraged farmers to expand sugarcane cultivation, leading to increased productivity and greater stability in sugar production. These technological developments continue to strengthen the sugarcane sector and support sustainable agricultural growth.

Improved Agronomic Practices

Improved agronomic practices have significantly contributed to enhancing sugarcane productivity and sustainability in major sugarcane-growing area of Maharashtra. Modern cultivation techniques focus on efficient use of resources such as water, nutrients and space while maintaining soil health. These practices help achieve higher yields, better cane quality and reduced production costs. The Vasantdada Sugar Institute have played an important role in developing and promoting improved agronomic technologies for sugarcane cultivation.

One of the important practices is wider row spacing, which allows better sunlight penetration, improved air circulation and easier intercultural operations. Wider spacing also facilitates mechanization and drip irrigation installation. Trash mulching, which involves spreading sugarcane dry leaves on the soil surface, helps conserve soil moisture, suppress weed growth and improve soil organic matter. Another important technique is fertigation, where fertilizers are applied through drip irrigation systems. This method ensures precise and efficient nutrient application directly to the root zone, reduces fertilizer losses and improves nutrient use efficiency. Adoption of drip irrigation combined with fertigation has resulted in higher yields and better water-use efficiency, particularly in states like Maharashtra.

Farmers are also increasingly adopting intercropping systems in sugarcane, especially during the early growth stages when there is sufficient space between rows. Crops such as pulses, vegetables and oilseeds can be grown as intercrops, providing additional income and improving land-use efficiency. Intercropping also helps in better weed management and enhances soil fertility, particularly when leguminous crops are used. These improved agronomic practices not only increase productivity but also contribute to sustainable sugarcane cultivation and better economic returns for farmers.

Mechanization

Mechanization has played an important role in improving the efficiency and expansion of sugarcane cultivation in Maharashtra. Traditionally, sugarcane farming relied heavily on manual

labour for operations such as planting, intercultivation, earthing-up and harvesting. However, increasing labour scarcity and rising labour costs have encouraged farmers to adopt mechanized practices. The use of farm machinery has helped reduce drudgery, improve operational efficiency and ensure timely field operations, which ultimately enhances sugarcane productivity.

Several types of machines are now being used in sugarcane cultivation. Mechanical sugarcane planters are used for uniform planting of cane setts, which helps maintain proper spacing and reduces seed and labour requirements. Tractor-operated cultivators and intercultivation implements are widely used for weed control, soil loosening and earthing-up operations. In recent years, the adoption of the Sugarcane Harvester has increased significantly. These harvesters can cut, strip and load sugarcane quickly, reducing dependence on manual labour and enabling faster harvesting during the crushing season.

Mechanization also supports large-scale sugarcane cultivation and improves farm management. Timely planting, precise fertilizer placement, efficient weed management and rapid harvesting help improve yield and reduce crop losses. In addition, mechanization reduces production costs in the long run and helps farmers cope with labour shortages during peak agricultural operations. With increasing support from sugar factories, government subsidy programmes and custom hiring centers, mechanization is expected to play an even greater role in the sustainable growth and modernization of the sugarcane industry.

Ethanol Blending Programme

The Government of India has implemented the Ethanol Blending Programme, which aims to mix ethanol with petrol to reduce dependence on fossil fuels. Ethanol is produced mainly from sugarcane molasses and juice. The promotion of ethanol production has increased the demand for sugarcane. Sugar mills have invested in distillery units to produce ethanol, which has provided additional revenue sources. As a result, farmers have been encouraged to increase sugarcane cultivation to meet the growing demand from ethanol industries (International Sugar Organization. 2023).

Maharashtra is one of the leading ethanol-producing states in India due to its large sugarcane cultivation area and well-developed sugar industry. Ethanol in the state is mainly produced from sugarcane-based raw materials such as molasses, B-heavy molasses, and sugarcane juice through distilleries attached to sugar mills. With the rapid expansion of distillery infrastructure, Maharashtra has achieved an installed ethanol production capacity of **around 350–400 crore litres per year**, making it the largest contributor to ethanol production in the country.

The growth of ethanol capacity in Maharashtra has been strongly supported by the Ethanol Blending Programme, implemented by the Government of India. Under this programme, ethanol is blended with petrol to reduce dependence on imported fossil fuels and promote renewable energy sources. To meet the increasing demand for ethanol, many sugar mills in the state have invested in distillery units and expanded their production capacity with financial support and policy incentives provided by the government.

The expansion of ethanol production has significantly benefited the sugar sector and sugarcane farmers in Maharashtra. Diversion of surplus sugar and molasses toward ethanol production has improved the financial stability of sugar mills and created an additional revenue stream. As a result, farmers are encouraged to increase sugarcane cultivation, and the improved cash flow in mills has helped ensure more timely payments to farmers, thereby strengthening the overall sugarcane-based rural economy.

Sugarcane and its by-products such as molasses, bagasse and press mud are used to produce several value-added industrial products and bio-chemicals. These products increase the economic value of the sugar industry and contribute to the growth of sugarcane cultivation, especially in Maharashtra. Some of the important products derived from sugarcane waste and by-products are described below.

Green Hydrogen

Sugar industry residues such as molasses, bagasse and distillery effluents can also be utilized in emerging bioenergy technologies to support the production of Green Hydrogen. Hydrogen produced using renewable energy or biomass-based processes is considered a clean fuel because it does not emit carbon dioxide during use. Research is being conducted to integrate sugar factories with bio-refinery concepts where sugarcane biomass can contribute to hydrogen production and other renewable energy systems.

Xylitol

Xylitol is a natural low-calorie sweetener produced from xylose obtained from plant biomass such as bagasse and agricultural residues. It is widely used in chewing gum, confectionery products and pharmaceutical formulations. Xylitol is also beneficial for dental health because it helps prevent tooth decay and bacterial growth in the mouth.

Sugarcane Wax

Sugarcane Wax is extracted from press mud, which is a by-product generated during sugar processing. Sugarcane wax is used in the production of polishes, cosmetics, carbon paper, pharmaceuticals and food coatings. Although produced in relatively small quantities, it has high commercial value.

Acetic Acid

Acetic Acid can be produced through fermentation processes using sugarcane molasses or ethanol as a raw material. Acetic acid is widely used in the manufacture of vinegar, chemicals, plastics, textiles and food preservatives. Molasses-based fermentation industries play an important role in producing this chemical.

Market Demand and Industrial Development

Increasing Sugar Consumption

The demand for sugar in India has been increasing due to population growth and changes in consumption patterns. Sugar is widely used in food processing industries, confectionery, and beverage manufacturing.

This growing demand has encouraged sugar mills to increase production, thereby increasing the demand for sugarcane.

Development of Allied Industries

The sugar industry supports several allied industries, including:

- Distilleries
- Cogeneration power plants
- Paper and board manufacturing

These industries utilize by-products such as molasses and bagasse, making the sugar industry more profitable and sustainable.

Government Policies and Institutional Support

Government policies have played a crucial role in promoting sugarcane cultivation in Maharashtra. Key policies include:

- Fair and Remunerative Price (FRP) for sugarcane
- Subsidies for drip irrigation
- Financial assistance for sugar mills
- Incentives for ethanol production

These policies have reduced financial risks for farmers and strengthened the sugar industry

Rural Employment and Socioeconomic Impact

Sugarcane cultivation generates large employment opportunities in rural areas. Activities such as planting, irrigation, harvesting and transportation require significant labour. The sugar industry also provides employment in sugar factories, transport sectors, and allied industries. As a result, the expansion of sugarcane cultivation has contributed to rural development and poverty reduction.

Agro-Climatic Suitability of Maharashtra

Maharashtra has favorable agro-climatic conditions for sugarcane cultivation. The crop thrives in regions with:

- Tropical climate
- Adequate sunshine
- Long growing season

Western Maharashtra districts such as Solapur, Pune, and Kolhapur are particularly suitable for sugarcane cultivation due to their soil and climate conditions.

Challenges and Sustainability Issues

Although the expansion of sugarcane cultivation has brought economic benefits, it also poses certain challenges.

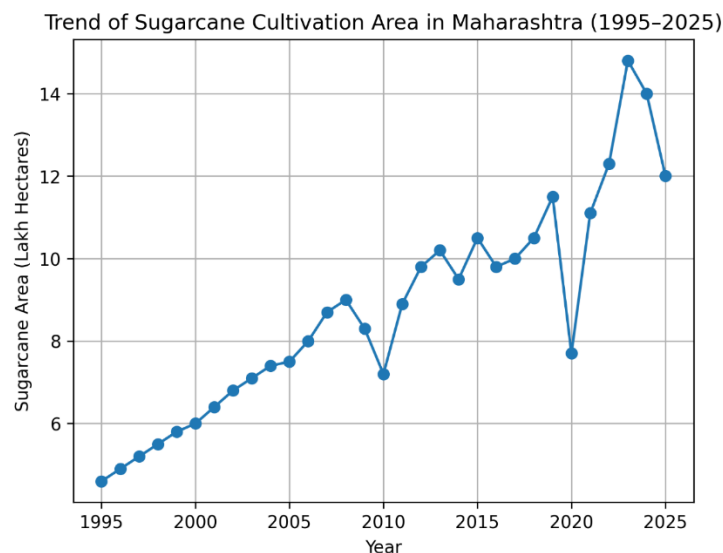
- **Water Consumption:** Sugarcane is a water-intensive crop, and excessive cultivation can put pressure on water resources.

- **Crop Diversification:** Large-scale sugarcane cultivation may reduce crop diversity in agricultural systems.
- **Climate Variability:** Droughts and irregular rainfall patterns can significantly affect sugarcane production.

Therefore, sustainable practices such as drip irrigation and improved crop management are necessary.

Conclusion

The increase in sugarcane cultivation area in Maharashtra during the last thirty years is the result of multiple interacting factors. The growth of the sugar industry, government support policies, irrigation development, technological advancements, and increasing demand for sugar and ethanol have all contributed to the expansion. While the growth of sugarcane cultivation has improved rural incomes and strengthened the agricultural economy, it is important to ensure sustainable resource management, particularly with regard to water use. Future agricultural policies should focus on improving water efficiency, promoting sustainable farming practices, and ensuring balanced crop diversification.



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