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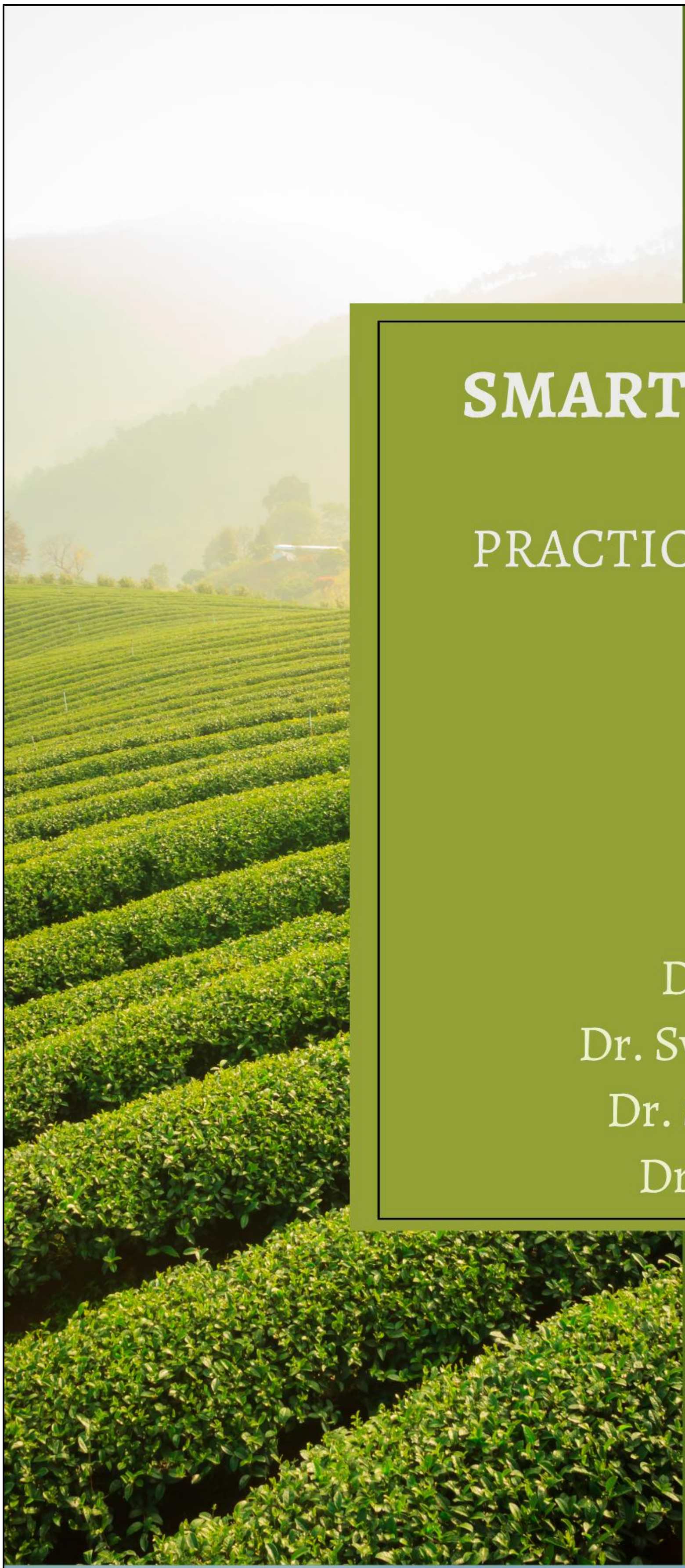

SMART AGRICULTURE
POLICY,
PRACTICE & TECHNOLOGY
VOLUME I

Editors:
Dr. Samir Show
Dr. Swatilekha Mohanta
Dr. Sagar Vhanalakar
Dr. Abhiram Dash

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Editors

Dr. Samir Show

Department of Economics,

Kumarganj College under the

University of Gour Banga, West Bengal

Dr. (Mrs.) Swatilekha Mohanta

Department of Nematology,

College of Agriculture,

OUAT, Chiplima, Odisha

Dr. Sagar Vhanalakar

Department of Zoology,

Karmaveer Hire College, Gargoti,

Kolhapur, Maharashtra

Dr. Abhiram Dash

Department of Agricultural Statistics,

College of Agriculture, OUAT,

Bhubaneswar, Odisha

Bhumi Publishing

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PREFACE

Agriculture has always been the backbone of human civilization, sustaining economies, livelihoods, and food security across the globe. In the twenty-first century, however, agriculture faces unprecedented challenges arising from climate change, declining natural resources, population growth, biodiversity loss, and increasing demands for sustainable food production. These challenges necessitate innovative approaches that integrate scientific advancement with practical farming systems. In this context, smart agriculture has emerged as a transformative paradigm that combines policy support, modern technologies, and sustainable agricultural practices to improve productivity, efficiency, and resilience.

The book *Smart Agriculture: Policy, Practice and Technology* aim to provide a comprehensive understanding of the rapidly evolving landscape of modern agriculture. It explores the integration of digital technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), remote sensing, drones, precision farming, blockchain technology, robotics, and big data analytics in agricultural systems. At the same time, the book emphasizes the importance of farmer-centric policies, climate-resilient practices, resource conservation, and sustainable rural development.

This volume brings together contributions from researchers, academicians, scientists, policymakers, extension workers, and industry experts who have shared their valuable insights and experiences in the field of smart agriculture. The chapters included in this book highlight both theoretical foundations and practical applications, offering readers a multidisciplinary perspective on contemporary agricultural innovations and challenges.

The editors sincerely hope that this book will serve as a valuable resource for students, researchers, teachers, policymakers, agricultural professionals, and progressive farmers. It is intended not only to enrich academic knowledge but also to inspire practical solutions for sustainable agricultural development and food security.

We express our heartfelt gratitude to all contributors, reviewers, and well-wishers whose support and cooperation made this publication possible. We also thank the publishers for their dedication and efforts in bringing this work to fruition.

- Editors

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IMPACT OF BIOCHAR INTEGRATION ON SOIL HEALTH AND YIELD OPTIMIZATION

Megha Vishwakarma
Shri Vaishnav Institute of Agriculture,
Shri Vaishanv Vidyapeeth Vishwavidyalaya, Indore (M.P.), India
Corresponding author E-mail: meghavishwakarma007@gmail.com

Abstract

Global agriculture faces the critical challenge of maintaining soil fertility while reducing the environmental impact of synthetic fertilizers. Biochar, a carbon-rich material produced through the pyrolysis of organic biomass, has emerged as a multifunctional solution for sustainable soil management. This chapter reviews the role of biochar as a potent soil amendment and nutrient reservoir, specifically focusing on its impact on Soybean (*Glycine max L.*) productivity.

The review highlights that pyrolysis temperature serves as the primary determinant of biochar's efficacy, influencing its surface area, pH, and Cation Exchange Capacity (CEC). Mechanistically, biochar improves soil health by reducing nitrogen leaching by up to 94%, enhancing phosphorus availability, and providing a porous habitat for beneficial soil microbes and nitrogen-fixing bacteria. Synthesis of various studies reveals that biochar application-particularly when integrated with inorganic fertilizers-can increase soybean yields by over 96% and significantly boost root nodulation. The chapter concludes that biochar is an essential tool for 'Integrated Nutrient Management', offering a synergistic pathway to enhance crop yields, sequester carbon, and ensure long-term food security.

Keywords: Biochar, Pyrolysis, Soil Fertility, Soybean Yield, Nutrient Retention, Sustainable Agriculture.

1. Introduction

In the contemporary era of sustainable agriculture, the quest for soil amendments that can simultaneously enhance crop productivity and mitigate environmental degradation has led to the resurgence of Biochar. Biochar is defined as a carbon-dense, porous material produced through the thermochemical decomposition of organic biomass in an oxygen-limited environment, a process formally known as pyrolysis (Lehmann and Joseph, 2009). While historically utilized in ancient soil management practices, such as the *Terra Preta* soils of the Amazon, modern scientific inquiry has repositioned biochar as a strategic 'nutrient carrier' and 'soil conditioner'.

The global agricultural sector faces a dual crisis: the diminishing efficiency of synthetic fertilizers and the escalating rate of soil carbon loss. Intensive chemical fertilization often leads to nutrient leaching, where essential elements like Nitrogen and Phosphorus are washed away into groundwater, causing both economic loss for farmers and ecological damage (e.g., eutrophication). Biochar addresses these challenges through its unique physical and chemical architecture. Unlike raw organic matter or lignin, biochar possesses a much higher proportion of aromatic carbon and condensed aromatic structures, which grant it exceptional stability against microbial decay (Schmidt and Noack, 2000).

The fundamental value of biochar as a fertilizer source is rooted in its structural complexity. Depending on the production parameters, biochar can exhibit various carbon forms, including amorphous carbon at lower temperatures and turbostratic or graphite-like carbon at higher temperatures (Nguyen *et al.,* 2010). These structures are characterized by: High Specific Surface Area (SSA): Providing extensive sites for nutrient adsorption. Porosity: A network of micro- and macropores that serve as reservoirs for water and habitats for beneficial soil biota. Cation Exchange Capacity (CEC): The presence of oxygenated functional groups (e.g., carboxyl and hydroxyl groups) that allow biochar to bind and slowly release essential plant nutrients.

Among various crops, legumes like Soybean stand to benefit significantly from biochar amendments. Soybean productivity is heavily dependent on soil aeration, water retention, and the health of nitrogen-fixing bacteria (Rhizobia). This review aims to assess the physicochemical characteristics of biochar formed under varying conditions and evaluate its efficacy as a sustainable fertilizer source, specifically focusing on its impact on the growth attributes and yield of Soybean.

2. Biochar Production Science and the Influence of Pyrolysis Temperature

The conversion of raw biomass into high-quality biochar is a complex thermochemical transformation. The efficacy of the resulting char as a soil amendment is primarily dictated by the pyrolysis parameters, specifically the peak temperature, heating rate, and residence time. Understanding these dynamics is essential for producing ‘designer biochars’ tailored for specific agricultural needs.

2.1 The Three Stages of Thermal Decomposition

The transformation of biomass into biochar generally proceeds through three distinct thermal stages (Lee *et al.,* 2017):

i. **Pre-pyrolysis (Ambient to 200°C):** This initial phase is characterized by the evaporation of internal moisture and the release of light volatile compounds. During this stage, the breakage of weak chemical bonds begins, leading to the formation of hydroperoxide and carbonyl (–CO) groups (Cárdenas-Aguiar *et al.,* 2017).

ii. **Main Pyrolysis (200°C to 500°C):** This is the most critical phase for biochar formation. It involves the rapid devolatilization and decomposition of hemicellulose and cellulose (Ding *et al.,* 2014). This stage is responsible for the development of the basic pore structure.

iii. **Formation of Carbonaceous Products (>500°C):** At temperatures exceeding 500°C, the degradation of lignin- the most thermally stable component of biomass occurs. This leads to the formation of a condensed, aromatic carbon matrix, which provides the biochar with its long-term stability in soil environments.

2.2 Temperature as a Master Controller of Biochar Properties

Pyrolysis temperature is strongly correlated with the structural and physicochemical evolution of biochar (Asadullah *et al.,* 2007). The following parameters are directly influenced by the thermal intensity:

A. Specific Surface Area (SSA) and Porosity

Increasing the pyrolysis temperature leads to a significant increase in the surface area and pore volume. This occurs because, at higher temperatures, ‘pore-blocking’ substances (tars and volatiles) are thermally cracked or driven off, making the internal micropores accessible (Rafiq *et al.,* 2016). While biochar produced at low temperatures (<500°C) often have surface areas as low as 5-10 m^2/g high temperature biochar can reach values exceeding 400 m^2/g, drastically improving their capacity to host soil microbes and retain water.

B. pH and Alkalinity (The Liming Effect)

There is a positive correlation between temperature and biochar pH (Yuan *et al.,* 2011). As temperature increases: Alkali Salts: Inorganic carbonates and alkali salts (K, Ca, Mg) separate from the organic matrix and concentrate in the ash. Functional group loss: acidic functional groups (like –COOH) disappear, while basic groups emerge. The resulting biochar typically exhibits a pH range of 6.5 to 10.8, making high temperature biochar excellent ‘liming agents’ for neutralizing acidic soils, which is particularly beneficial for soybean cultivation.

C. Carbon and Ash Content

As the temperature rises, the carbon content becomes more concentrated due to a higher degree of polymerization and carbonization (Domingues *et al.,* 2017). Simultaneously, the ash content increases (by 5.7% to 18.7% or more) as organic matter is lost while inorganic minerals remain (Cao and Harris, 2010). This ash acts as a direct, albeit slow-release, source of minerals like Potassium (K), Calcium (Ca), and Magnesium (Mg).

D. Volatile Matter (VM) and Stability

High-temperature pyrolysis results in a lower content of volatile matter. Low VM is generally preferred for soil application because high concentrations of certain volatiles (like phenols) found in low-temperature chars can sometimes inhibit root growth. However, the volatiles in low-temp biochar can also provide ‘labile carbon’ that stimulates initial microbial activity.

3. Impact of Biochar on Soil Chemical Properties

The incorporation of biochar into the soil matrix induces profound changes in the chemical environment, acting as a buffer and a nutrient reservoir. Unlike traditional fertilizers that provide a quick pulse of nutrients, biochar modifies the soil's fundamental ability to retain and exchange ions.

3.1 Cation Exchange Capacity (CEC) and Nutrient Retention

The **Cation Exchange Capacity (CEC)** is perhaps the most significant chemical property of biochar in the context of plant nutrition. CEC is the ability of the soil/biochar to hold onto positively charged ions (cations) like Ammonium, Potassium, Calcium, and Magnesium.

- **Surface Charge:** Biochar surfaces are dominated by oxygen-containing functional groups such as carboxylate and phenolate groups (Mia *et al.,* 2017). These negatively charged sites 'grab' nutrients from the soil solution, preventing them from being washed away by rain or irrigation.
- **Temperature Trade-off:** Biochars produced at lower temperatures (300-450ºC) often possess a higher density of these functional groups and thus a higher initial CEC compared to high-temperature biochars, where these groups are lost through deoxygenation (Mukherjee *et al.,* 2011).

3.2 Nitrogen Dynamics and Leaching Reduction

Nitrogen is the most limiting nutrient for crop growth, and its loss through leaching is a major environmental concern. Biochar plays a dual role in Nitrogen management:

- **Adsorption:** Biochar can physically and chemically adsorb Ammonium and Nitrate. Singh *et al.* (2010) demonstrated that the addition of poultry manure biochar reduced the leaching of NH_4 by 87% in Alfisols and 94% in Vertisols.
- **Fixation and Bioavailability:** In soybean cultivation, biochar enhances the nitrogen-fixing capacity by improving the soil environment for *Rhizobium* bacteria. Studies have shown that biochar combined with nitrogen fertilizers increases total nitrogen uptake and soil nitrogen retention (Bindu *et al.,* 2016).

3.3 Phosphorus and Potassium Availability

Biochar significantly alters the availability of Phosphorus and Potassium, often acting as a direct source through its ash content.

- **Phosphorus (P):** In acidic soils, P is often 'fixed' by Iron and Aluminum oxides, making it unavailable to plants. Biochar increases soil pH, which 'unlocks' this fixed P. Kuppusamy *et al.* (2011) recorded a staggering 199.2% increase in available P over the control with acacia wood biochar application. Abdulrahman *et al.* (2016) also noted that combining biochar with phosphate-solubilizing bacteria increased available P from 28 mg/kg to 96 mg/kg.
- **Potassium (K):** Biochar is naturally rich in K. Kraska *et al.* (2016) reported that available soil K content increased from 132 mg/kg to 235 mg/kg after biochar incorporation, with the effect lasting for up to 36 months.

3.4 Soil pH and Electrical Conductivity (EC)

- **Alkalization:** Biochar generally has an alkaline pH. Application to acidic soils reduces exchangeable acidity and increases the base saturation. Gautam *et al.* (2017) observed that 5 t/ha of biochar raised the pH of degraded soil from 4.79 to 5.23.
- **Electrical Conductivity (EC):** EC is an indicator of the concentration of soluble salts (nutrients) in the soil. Several researchers, including Nigussie *et al.* (2012) and Conz *et al.* (2017), have reported progressive increases in soil EC following biochar application, which suggests a higher concentration of available nutrient ions in the soil solution.

3.5 Soil Organic Carbon (SOC) and Stability

Biochar is primarily composed of stable carbon. Sara *et al.* (2018) found that applying biochar at 80 t/ha increased soil organic carbon from 0.71% to 0.99%. Unlike compost or manure, which decompose within a few years, biochar carbon remains in the soil for centuries, providing a long-term structural framework for chemical activity.

3.6 Biochar as a Microbial Refugia

The most prominent physical feature of biochar is its highly porous architecture. These pores, ranging from macropores (derived from the plant's vascular bundles) to micropores, serve a dual purpose in soil biology (Compant *et al.,* 2010):

- **Protection from Predators:** The internal pore spaces are large enough to house beneficial bacteria and fungi (such as *Mycorrhizae* and *Actinomycetes*) but small enough to exclude larger predators like protozoa and nematodes.
- **Moisture and Nutrient Hubs:** Pores retain water and dissolved organic carbon, providing a consistent supply of moisture and food for microbial colonies, even during dry periods.
- **Fungal Symbiosis:** Biochar has been shown to particularly favor Arbuscular Mycorrhizal Fungi (AMF), which extend their hyphae into the biochar pores, enhancing the plant's ability to absorb Phosphorus and water (Thies and Rillig, 2009).

3.7. Soil Enzymatic Activity

Enzymes are the primary drivers of nutrient cycling in the soil. Biochar application has been consistently linked to an increase in soil enzymatic activity, which serves as a key indicator of high soil quality (Ouyang *et al.,* 2014).

- **Urease Activity:** Urease is the enzyme responsible for breaking down urea into ammonia and carbon dioxide. Mierzwa-Hersztek *et al.* (2016) reported a 44.0% increase in urease activity following biochar amendment. This is crucial when biochar is used in combination with nitrogenous fertilizers, as it ensures the efficient conversion of urea into plant-available nitrogen.

- **Dehydrogenase Activity:** This enzyme is an indicator of the overall oxidative activity of soil microbes. Research has shown that biochar can increase dehydrogenase levels by approximately **19.0%** (Mierzwa-Hersztek *et al.,* 2016), signaling a more active and healthy microbial community.
- **Phosphatase Activity:** By stimulating microbes that produce phosphatase, biochar helps in the mineralization of organic phosphorus, further contributing to the 'fertilizer effect'.

4.8 Influence on Soil Fauna

The impact of biochar extends to larger soil organisms, such as earthworms, which are essential for soil aeration and organic matter decomposition:

- **Population Dynamics:** While some studies initially reported negative effects on earthworms due to sudden pH changes (Haefele *et al.,* 2011), long-term observations suggest that earthworm activity eventually stabilizes or improves as the soil structure matures.
- **Mitigation Strategies:** Li *et al.* (2011) recommended the wet application of biochar. Applying biochar in a moist state prevents the desiccation (drying out) of earthworm skin and helps them acclimate to the new soil environment more effectively.

4.9 Synergistic Biological Improvements

Biochar doesn't just add microbes; it changes the 'neighborhood' to make it more hospitable. By reducing soil acidity and increasing the content of organic carbon and nitrogen, biochar creates a 'bottom-up' effect where the improved chemical state fuels a biological boom (Mierzwa-Hersztek *et al.,* 2016). This biological activity, in turn, helps in the further breakdown of minerals, creating a self-sustaining cycle of fertility.

5. Impact on Crop Growth and Yield Attributes

The efficacy of biochar as a sustainable fertilizer source is best validated through its impact on diverse cropping systems. Research conducted globally across different soil types and climatic conditions consistently indicates that biochar acts as a powerful bio-stimulant. This section details the specific research findings categorized by crop types and application strategies.

Legumes are particularly responsive to biochar because their productivity is intrinsically linked to the health of nitrogen-fixing bacteria (*Rhizobia*). Liu *et al.* (2022) conducted an extensive pot experiment using dryland purple soil. Their findings revealed that biochar applications ranging from 35 to 50 t ha^{-1} increased soybean grain yield by 96.7%. Most notably, they recorded a staggering increase in seed dry weight, demonstrating biochar's ability to maximize reproductive output in moisture-stressed soils. Paul *et al.* (2023) focused on the morphological development in sandy clay loam soils. They observed that 40 t ha^{-1} of biochar led to a 117.2% increase in shoot weight and a 114.5% increase in root weight. This suggests that biochar facilitates a more robust root architecture, enabling plants to access nutrients from deeper soil layers. Wu *et al.* (2022)

investigated the biological synergy on *Hapli-Udic Cambisol* soil. They discovered that a high rate of 48 t ha^{-1} increased the number of root nodules by 2.88 times and dry nodule weight by 2.78 times compared to the control. This proves that biochar provides an ideal alkaline environment and porous habitat for nitrogen-fixing symbiosis.

Budania *et al.* (2014) observed in a controlled pot experiment that applying PGPR-blended biochar along with Phosphorus increased chickpea grain yield from 28.10 g to 108.99 g per pot. This massive jump highlights biochar's role as an effective carrier for plant growth-promoting rhizobacteria (PGPR). Carnaje and Malaluan (2015) studied mung beans in acidic soil environments. They reported a 27% increase in plant height and a 10.2% increase in the number of pods per plant. This indicates that biochar successfully neutralized soil acidity, which is usually a major constraint for mung bean growth.

Cereals are heavy feeders of Nitrogen and Phosphorus. The following studies demonstrate how biochar improves the Nutrient Use Efficiency (NUE) of these crops. Uzoma *et al.* (2011) examined maize in sandy soils, finding that biochar at 15 and 20 t ha^{-1} increased grain yield by 150% and 98%, respectively. This dramatic improvement is attributed to biochar's ability to hold moisture in otherwise porous sandy soils. Zhang *et al.* (2012) further confirmed that combining biochar 40 t ha^{-1} with nitrogen fertilizer increased maize yield by 12.1%. This synergy prevents the volatile loss of nitrogen, keeping it available for the plant during the critical grain-filling stage. Zaitun *et al.* (2011) integrated 10 t ha^{-1} of biochar with NPK in rice fields, resulting in a yield increase from 4.32 to 6.79 t ha^{-1}. They also noted a significant increase in plant height (up to 78.23 cm), suggesting improved vegetative vigor. Hasan *et al.* (2024) recently conducted a study on wheat in silty loam soil. By using a "quarter-combination" (mixing poultry manure biochar, rice husk biochar, and vermicompost), they achieved a grain yield of 4.11 t ha^{-1}, compared to only 2.29 t ha^{-1} in the control group. This highlights the effectiveness of using biochar in multi-component organic blends.

5.1 Synergistic Effects of Combined Fertilizer Applications

A major theme in recent literature is that biochar performs best when used as a part of an Integrated Nutrient Management (INM) system. Dawar *et al.* (2022) proved that the combination of VC + BC + NPK was the most effective treatment for maize, increasing biological yield by 43.12% and grain yield by 39.59%. Bio-fertilizer Inoculation: Arabi *et al.* (2018) found that soybean yield reached its maximum (3440 kg ha^{-1}) when 8 t ha^{-1} of biochar was used in tandem with bio-fertilizers. This combination resulted in a 51% yield increase compared to the control, proving that biochar supports the survival of inoculated microbes. Hussain *et al.* (2017) noted that 25 t ha^{-1} of biochar combined with farm yard manure (FYM) increased mung bean biological yield by over 1000 kg ha^{-1} compared to traditional practices.

5.2 Residual and Long-Term Field Observations

One of the unique advantages of biochar is its longevity. Unlike chemical fertilizers, its benefits persist over multiple seasons. Aarif *et al.* (2021) studied a wheat-maize-wheat system and concluded that 10 t ha^{-1} of biochar consistently improved soil carbon and health over several years. Katterer *et al.* (2019) applied a high dose of 50 t ha^{-1} and observed a yield increase of 1.17 t ha^{-1} for maize and 0.43 t ha^{-1} for soybean, confirming that biochar provides a stable foundation for long-term food security.

5.3 Economic and Environmental Synergy

Beyond the farm gate, biochar offers a unique 'win-win' scenario. It provides a circular economy solution for managing agricultural wastes (like rice husks, corn stover, and poultry litter) while simultaneously sequestering carbon in a stable form for centuries. This makes biochar a dual-purpose tool for enhancing food security and mitigating climate change.

Challenges and Future Directions

Despite the overwhelming technical benefits, several challenges remain for the widespread adoption of biochar-based fertilization:

- **Standardization:** Biochar quality varies significantly based on feedstock and pyrolysis temperature. Future research must focus on 'Designer Biochars' tailored to specific soil types and regional crop requirements.
- **Application Technology:** Developing mechanized methods for large-scale, dust-free biochar application (such as wet-application or pelletization with chemical fertilizers) is essential.
- **Long-term Field Studies:** While short-term results are promising, more decadal studies are needed to understand the residual effects of biochar on soil health over multiple crop rotations.

Conclusion

In conclusion, biochar stands as a transformative technology in the pursuit of sustainable intensification. When used in synergy with Recommended Doses of Fertilizer (RDF) and bio-inoculants, it provides a robust framework for increasing Soybean productivity while safeguarding the ecological integrity of the soil. As global agriculture moves toward a "green" transition, biochar will undoubtedly play a pivotal role in the future of resilient and productive farming systems.

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DISEASES OF SWEET POTATO (*IPOMOEA BATATAS* L.) AND THEIR MANAGEMENT

Vijay Kumar*[1] and Ashok Chhetri[2]
[1]Department of Plant Pathology, Multi Technology Testing Centre & Vocational Training Centre, Lembucherra, Tripura, Central Agricultural University, Imphal, India
[2]Department of Horticulture-Fruit Science, Multi Technology Testing Centre & Vocational Training Centre, Lembucherra, Tripura, Central Agricultural University, Imphal, India
*Corresponding author E-mail: vnarwal777@yahoo.com

1. Introduction

Sweet potato (*Ipomoea batatas* L.) is a globally important root crop cultivated in tropical and subtropical regions. Sweet potato is a dicotyledonous root crop of the family Convolvulaceae, valued for its enlarged storage roots rich in edible reserves, often surpassing those of Irish potato (*Solanum tuberosum*). The crop exhibits considerable morphological diversity, with stem and leaf coloration ranging from green to purple due to anthocyanin accumulation, and leaf shapes varying from entire to deeply lobed. Storage roots differ in shape (round to elongated or irregular) and in skin and flesh colour, which may range from white to orange or purple depending on genotype and environmental conditions (Woolfe, 1992; Laurie and Niederwieser, 2004). Although its exact origin remains unclear, sweet potato is believed to have originated in the lowland regions of Central or South America, particularly between the Yucatan Peninsula and the Orinoco basin, with cultivation dating back to around 3000 B.C. and subsequent global dissemination by early explorers (Zhang *et al.,* 2004; Clark *et al.,* 2013).

Sweet potato is the only economically important member of Convolvulaceae and is a major global food crop, particularly significant in sub-Saharan Africa where it contributes to food security due to its adaptability, short growth cycle, and suitability for low-input systems. It is predominantly grown by smallholder farmers for subsistence and income generation (Ewell and Mutuura, 1994). Agronomically, the crop is easy to propagate, requires minimal inputs, and produces high yields, making it suitable for resource-limited regions. In addition to its role as a staple food, sweet potato has industrial applications in ethanol production, starch extraction, and natural dye synthesis. Nutritionally, its storage roots contain high carbohydrate content, primarily digestible starch, while orange- and purple-fleshed varieties are rich in beta-carotene and antioxidants, respectively (Shin *et al.,* 2005). Its productivity is constrained by numerous fungal, bacterial, viral pathogens, and physiological disorders, which affect yield, storage quality, and planting material health (Ogero *et al.,* 2019).

2. Fungal Diseases of Sweet Potato

Major fungal diseases of sweet potato include black rot (*Ceratocystis fimbriata*), Fusarium wilt or stem rot (*Fusarium oxysporum*), foot rot (*Plenodomus destruens*), Java black rot (*Lasiodiplodia theobromae*), Rhizopus soft rot (*Rhizopus stolonifer*), surface rot (*Fusarium solani*), and scurf (*Monilochaetes infuscans*), all of which significantly reduce yield and storage quality.

Other important fungal diseases comprise Alternaria leaf spot and blight (*Alternaria bataticola*, *A. tenuissima*, *A. alternata*), Cercospora and Pseudocercospora leaf spots (*Passalora bataticola*, *Pseudocercospora timorensis*), leaf and stem scab (*Sphaceloma batatas*), Phomopsis leaf spot (*Phomopsis ipomoea-batatas*), charcoal rot (*Macrophomina phaseolina*), circular spot and sclerotial blight (*Sclerotium rolfsii*), violet root rot (*Helicobasidium mompa*), Geotrichum sour rot (*Geotrichum candidum*), and dry rot (*Diaporthe phaseolorum*). Minor diseases include punky rot (*Trichoderma koningii*), blue mold rot (*Penicillium* spp.), gray mold (*Botrytis cinerea*), Sclerotinia rot (*Sclerotinia sclerotiorum*), Phymatotrichum root rot (*Phymatotrichopsis omnivora*), Fusarium root rots (*Fusarium solani*, *F. javanicum*), Septoria leaf spot (*Septoria bataticola*), white rust (*Albugo ipomoeae-panduratae*), Rhizoctonia stem canker (*Rhizoctonia solani*), and slime molds (*Fuligo*, *Physarum*, *Stemonitis* spp.).

2.1 Black Rot

2.1.1 Etiology

Black rot is caused by *Ceratocystis fimbriata*, a soil- and seed-borne fungus that infects roots, stems, and storage tissues. The pathogen produces perithecia and spreads via infected planting material and contaminated soil (Ogero *et al.,* 2019).

2.1.2 Symptoms

Symptoms appear as small, circular, dark brown to black lesions on storage roots. These lesions enlarge, becoming sunken and firm, often with a characteristic bitter taste. Internally, the tissue turns black due to fungal colonization. On vines, lesions may appear at nodes and cause wilting.

2.1.3 Epidemiology

The pathogen survives in soil and infected crop residues. Infection occurs through wounds during harvesting or handling. Warm and humid conditions favour disease development, especially during storage. Spread occurs through infected vines and contaminated tools.

2.1.4 Disease Management

The disease management relies on disease-free planting material, crop rotation, and sanitation. Curing roots before storage reduces infection. Fungicidal dips and proper storage conditions (low humidity and temperature) are effective. Resistant varieties should be promoted.

2.2 Fusarium Wilt (Stem Rot)

2.2.1 Etiology

The disease is caused by *Fusarium oxysporum*, a soil-borne, filamentous fungus belonging to the phylum Ascomycota. It is a facultative parasite that invades plants primarily through the root system, entering via wounds or natural openings. Once inside, the pathogen colonizes the xylem vessels, producing mycelia and spores that obstruct water transport. Additionally, it secretes toxins and enzymes that degrade host tissues, leading to systemic infection. The pathogen is highly persistent in soil due to the formation of chlamydospores, which can survive for many years in the absence of a host.

2.2.2 Symptoms

Initial symptoms typically include slight chlorosis (yellowing) of lower leaves, followed by progressive wilting, especially during the hottest part of the day. As the disease advances, leaves may curl, dry, and eventually abscise. A characteristic feature is vascular discoloration, visible as brown streaks in the stem when cut longitudinally. Stem bases may exhibit rotting, weaken the plant structure and cause lodging or complete collapse. Infected roots often show internal browning and decay, with reduced feeder root development. In severe cases, the entire plant may die prematurely.

2.2.3 Epidemiology

Fusarium oxysporum survives in soil and plant debris as chlamydospores, enabling long-term persistence even under unfavorable conditions. The pathogen spreads through contaminated soil, irrigation water, farm tools, and especially infected planting materials such as vines or cuttings. Disease development is favored by warm temperatures (typically 25–30°C), high soil moisture, and poorly drained or compacted soils. Continuous monocropping increases inoculum buildup, thereby enhancing disease incidence. The pathogen may also exhibit host-specific forms (formae speciales), which determine its host range and virulence.

2.2.4 Disease Management

An integrated disease management approach is essential for effective control. The use of certified disease-free planting material prevents initial infection, while crop rotation with non-host crops helps reduce soil inoculum. Proper soil drainage and avoidance of waterlogging minimize favorable conditions for the pathogen. Soil solarization can further lower pathogen populations, and biological control agents such as *Trichoderma* spp. and *Pseudomonas fluorescens* suppress disease development. The use of resistant varieties, along with strict sanitation practices, also plays a key role in limiting disease spread.

2.3 Java Black Rot

2.3.1 Etiology

The disease is caused by *Lasiodiplodia theobromae*, a wound-invading, opportunistic fungal pathogen that primarily infects storage roots through mechanical injuries. It produces enzymes that degrade host tissues, leading to rapid deterioration.

2.3.2 Symptoms

Infected roots develop dark brown to black, firm rot that usually begins at wound sites. As the disease progresses, tissues become dry, shriveled, and mummified, with distinct internal discoloration extending into the flesh.

2.3.3 Epidemiology

The pathogen is commonly present in soil and plant debris and infects roots mainly during harvesting, handling, and storage. Warm temperatures and high humidity conditions significantly enhance disease development and spread.

2.3.4 Disease Management

Minimizing mechanical injury during harvesting and handling is crucial. Proper curing of roots before storage helps heal wounds and reduce infection. Maintaining optimal storage conditions-low humidity, adequate ventilation, and moderate temperatures along with sanitation practices, effectively limits disease incidence.

2.4 Rhizopus Soft Rot

2.4.1 Etiology

The disease is caused by *Rhizopus stolonifer*, a fast-growing, saprophytic fungus commonly associated with post-harvest decay. It primarily infects storage roots through wounds and rapidly colonizes tissues under favourable conditions.

2.4.2 Symptoms

Affected roots become soft, watery, and leaky due to rapid tissue breakdown. A characteristic foul odor develops as decay progresses. In advanced stages, abundant white, cottony fungal growth appears on the surface, often accompanied by black sporangia.

2.4.3 Epidemiology

The pathogen is widely present in the environment and infects roots mainly during storage, particularly when they are bruised or damaged. High temperature and humidity, along with poor ventilation, strongly favor disease development and spread.

2.4.4 Disease Management

Careful handling to prevent mechanical injury is essential. Proper ventilation and maintaining cool, dry storage conditions help inhibit fungal growth. Sanitation and removal of infected roots are also important to reduce disease spread.

2.5 Alternaria Leaf Spot/ Leaf Petiole/ Stem Blight

2.5.1 Etiology

The disease is caused by multiple species of *Alternaria*, primarily *A. bataticola*, *A. tenuissima*, and *A. alternata*. These fungi are opportunistic pathogens with a broad host range and are capable of surviving on infected sweet potato plants, crop debris, alternative hosts, and in the soil. They produce abundant conidia that serve as the primary inoculum source.

2.5.2 Symptoms

The disease is characterized by the appearance of brown lesions on older leaves, typically showing concentric rings that give a target-like appearance with well-defined margins. In some cases, lesions are surrounded by wide yellow halos. On stems and petioles, small gray to black oval lesions develops, often with lighter centres that may appear bleached under dry conditions. Under humid conditions, lesions enlarge, turn dark, and coalesce, eventually girdling and killing affected stems and petioles. Severe infections may lead to defoliation, particularly of older leaves.

2.5.3 Epidemiology

The pathogens survive between cropping seasons in plant debris, soil, and alternative hosts. Conidia are disseminated primarily by wind and splashing rainwater. Disease development is favoured by high humidity, rainfall, and prolonged leaf wetness, including conditions of moderate to heavy dew. Symptom expression typically occurs within 3–6 days after infection under favourable environmental conditions.

2.5.4 Management

Effective management includes the use of disease-free planting material and resistant varieties where available. Cultural practices such as field sanitation through removal and destruction of infected plant debris, along with crop rotation, help reduce inoculum levels. Maintaining proper field hygiene and minimizing conditions favorable for pathogen spread are essential for disease control.

2.6 Chlorotic Leaf Distortion (*Fusarium denticulatum*)

2.6.1 Etiology

Chlorotic leaf distortion is caused by *Fusarium denticulatum* (formerly *Fusarium lateritium*). The fungus colonizes the external surfaces of shoot tips, meristems, and young developing leaves without penetrating internal plant tissues. It grows on exuded substances present on young tissues and produces mycelia and conidia that appear as white deposits.

2.6.2 Symptoms

The disease primarily affects young leaves at vine terminals, which develop chlorosis and may turn bright yellow or bleached. In purple-leaved cultivars, infected tissues may show a pinkish discoloration. As leaves mature, they often regain their normal color. In some cases, leaf distortion and plant stunting occur. A characteristic feature is the presence of white, salt-like deposits on partially expanded leaves, which consist of fungal mycelia and conidia.

2.6.3 Epidemiology

The pathogen survives on infected planting material and spreads through vegetative propagation. Conidia are disseminated by wind, splashing rainwater, and contaminated true seed. Infection occurs on young, developing tissues, while older leaves remain unaffected. Disease development is favored by warm, sunny, and humid conditions, and symptoms typically appear 3–6 weeks after infection. As leaves expand and expose fungal structures, fungal growth ceases, allowing partial recovery.

2.6.4 Management

Management primarily involves the use of disease-free planting material and avoiding the use of botanical seeds from infected plants. Since the disease generally causes minimal economic damage, chemical control measures are not recommended. Good nursery and field sanitation practices help limit its spread.

2.7 Cercospora and Pseudocercospora Leaf Spots

2.7.1 Etiology

Cercospora leaf spot is caused by *Passalora bataticola* (syn. *Cercospora bataticola*, *Phaeoisariopsis bataticola*), while Pseudocercospora leaf spot is caused by *Pseudocercospora timorensis* (syn. *Cercospora timorensis*, *C. batatas*). Although initially considered a single disease, they are now recognized as two closely related but distinct fungal pathogens.

2.7.2 Symptoms

Both diseases produce similar leaf lesions, though Cercospora lesions are generally smaller. The spots vary in color from dark brown to black or pale gray, often with light centers and darker margins. Lesions may be circular or irregular in shape, especially when limited by leaf veins, giving a somewhat angular appearance.

2.7.3 Epidemiology

The pathogens survive on infected plant debris and alternative weed hosts. They produce conidia on long conidiophores emerging through stomata, primarily on the lower leaf surface. These spores are dispersed by wind and splashing rainwater. Disease development is favored by warm, humid, and wet conditions. Although widely distributed across Africa, Asia, Australia, and parts of the Americas, significant yield losses are relatively uncommon and occur only under conducive environmental conditions.

2.7.4 Management

Specific control measures are rarely required due to the generally low economic impact of these diseases. However, cultural practices such as crop rotation, removal and destruction of infected plant debris, and maintaining field sanitation can help reduce inoculum levels and limit disease incidence.

2.8 Phomopsis Leaf Spot (Phyllosticta Leaf Blight) (*Phomopsis ipomoea-batatas*)

2.8.1 Etiology

The disease is caused by *Phomopsis ipomoea-batatas*, a fungal pathogen that produces hyphae and unicellular conidia within pycnidia. The pycnidia are small, dark fruiting bodies that serve as diagnostic structures and are formed within infected leaf tissues.

2.8.2 Symptoms

Infected leaves develop irregularly shaped lesions that are whitish, tan, or light brown, often surrounded by dark brown to purple margins. Lesions occur on both leaf surfaces but are more prominent on the upper side and typically measure 5–10 mm in diameter. A distinguishing feature is the presence of black pycnidia at the center of lesions, which appear as small dots and aid in disease identification. The disease mainly affects older leaves, especially toward the end of the growing season.

2.8.3 Epidemiology

The pathogen survives in decaying plant debris, particularly fallen leaves, and is not known to have significant alternative hosts. It spreads primarily through splashing rainwater, though wind and infected planting material may also contribute to dissemination. Disease development is favored by humid and wet environmental conditions, which enhance spore production and infection.

2.8.4 Management

Since the disease has minimal economic impact and rarely affects yield, specific control measures are generally not required. However, good field sanitation practices, including removal and destruction of infected plant debris, can help reduce inoculum levels and limit disease occurrence.

2.9 Foot Rot (Die-off)

2.9.1 Etiology

Foot rot is caused by *Plenodomus destruens*, a fungal pathogen closely related to *Phomopsis phaseoli*. The pathogen produces pycnidia on infected tissues and survives mainly on plant debris, although it does not persist long in soil. In Brazil, the disease has also been reported to be associated with *Diaporthe kongii* (Almeida *et al.,* 2020).

2.9.2 Symptoms

Severely infected plants show yellowing of lower leaves followed by wilting and eventual death. In mild cases, brown to black necrotic lesions develop at or just below the soil surface, often originating from infected seed roots and extending up the stem. The basal stem rots, leading to disintegration of the root system. Black pycnidia are commonly observed on infected tissues. Storage roots exhibit decay starting at the proximal end, resulting in firm, dry, dark brown necrosis that may cover a large portion of the root. Peeling the periderm reveals embedded pycnidia (Lopes and Silva, 1993).

2.9.3 Epidemiology

The pathogen survives on infected plant debris and spreads primarily through infected but symptomless planting material. Conidia can persist on infected roots and sprouts and infect healthy roots, especially through wounds during storage. Disease development coincides with the vegetative growth stage of the crop. The fungus is not highly persistent in soil but can be transmitted through contaminated planting materials and storage contact (Lopes and Silva, 1993; Almeida *et al.,* 2020).

2.9.4 Management

Effective management involves the use of disease-free planting material and implementation of clean seed programs, which have significantly reduced disease incidence in regions such as the USA. Field sanitation, including removal of infected debris, and careful handling to avoid wounds during harvesting and storage are essential practices. Avoiding the use of infected vines or roots for propagation is critical to limiting disease spread (Lopes and Silva, 1993).

3. Bacterial Diseases of Sweet Potato

The major bacterial diseases of sweet potato include bacterial wilt caused by *Ralstonia solanacearum* and bacterial soft rot caused by *Erwinia chrysanthemi* (now reclassified as *Dickeya* spp.). These pathogens are significant contributors to yield and post-harvest losses, with bacterial wilt primarily affecting the vascular system in the field, while soft rot commonly causes decay of storage roots under warm and humid conditions.

3.1 Bacterial Wilt

3.1.1 Etiology

Caused by *Ralstonia solanacearum*, a soil-borne bacterium that infects the vascular system.

3.1.2 Symptoms

Plants exhibit sudden wilting, often without yellowing. Cutting stems reveals milky bacterial ooze. Roots may show vascular discoloration.

3.1.3 Epidemiology

The pathogen survives in soil, water, and alternate hosts. It spreads through irrigation water and infected planting materials. Warm and moist conditions favor disease development.

3.1.4 Disease Management

Use resistant varieties, crop rotation with non-hosts, and clean planting materials. Avoid waterlogging and sanitize tools.

3.2 Bacterial Soft Rot

3.2.1 Etiology

Caused by *Erwinia chrysanthemi* (syn. *Dickeya spp.*), a wound-infecting bacterium.

3.2.2 Symptoms

Roots become soft, watery, and foul-smelling, rapidly decomposing into a mushy mass.

3.2.3 Epidemiology

The bacteria enter through wounds and spread under high humidity and temperature.

3.2.4 Disease Management

Avoid injuries, maintain hygiene during harvesting and storage, and ensure proper ventilation.

3.3 Sweet potato Little Leaf (Witches'-broom)

3.3.1 Etiology

Sweetpotato little leaf disease is caused by the phytoplasma *"Candidatus Phytoplasma aurantifolia"*, belonging to the peanut witches'-broom group. The pathogen infects phloem tissues and has a wide host range, including several *Ipomoea* species.

3.3.2 Symptoms

Initial symptoms include vein clearing, followed by the development of small, chlorotic leaves. A characteristic feature is the proliferation of axillary shoots, giving plants a bushy or witches'-broom appearance. Leaves may exhibit upward curling at the margins. Infected plants show stunted growth, and roots and stems often lack latex. The root system may also become highly branched and reduced in size, contributing to significant yield losses.

3.3.3 Epidemiology

The disease is transmitted by leafhopper vectors, particularly *Orosius lotophagorum* and *Nesophrosyne ryukyuensis*. Its spread is closely associated with vector population dynamics, with higher incidence in dry regions that favor leafhopper multiplication. The phytoplasma is also disseminated through infected planting material. A long incubation period (50–186 days) facilitates unnoticed spread through vegetative propagation.

3.3.4 Management

Management strategies include the use of disease-free planting material selected from healthy plants and strict field sanitation. Infected plants should be promptly uprooted and destroyed to prevent further spread. Removal of alternate hosts, especially wild morning glory species, and control of insect vectors are also important in reducing disease incidence.

3.4 Streptomyces Soil Rot

3.4.1 Etiology

Streptomyces soil rot is caused by *Streptomyces ipomoeae*, a soil-borne actinomycete capable of surviving in soil for many years as resistant spores, even in the absence of a host. It can also infect other members of the Convolvulaceae (morning glory) family.

3.4.2 Symptoms

The disease is characterized by the development of shallow, necrotic lesions on storage roots, which may be circular or irregular, typically less than 5 mm deep and up to 3 cm in diameter. In some cases, constrictions form at infection sites, resulting in a characteristic dumbbell-shaped root. Adventitious roots may exhibit black necrotic decay, and severe infection can lead to vine stunting, chlorosis, bronzing of foliage, wilting, and premature flowering, ultimately reducing yield and quality.

3.4.3 Epidemiology

The pathogen persists in soil as spores and spreads through movement of contaminated soil, infected planting material, and even through livestock that consume infected roots. Infection occurs through direct penetration of fibrous roots. Disease development is favored by dry, alkaline soils (pH above 5.2). The pathogen can overwinter as spiral chains of spores, ensuring long-term survival in the field.

3.4.4 Management

Effective management includes the use of resistant varieties, which have been successfully developed in some regions. Cultural practices such as maintaining slightly acidic soil conditions (e.g., through sulfur application), crop rotation, and ensuring adequate soil moisture through timely irrigation help reduce disease severity. Soil fumigation and the use of disease-free planting material from non-infested areas are also recommended strategies.

3.5 Bacterial Stem and Root Rot

3.5.1 Etiology

Bacterial stem and root rot is caused by *Dickeya dadantii* (formerly *Pectobacterium chrysanthemi* and *Erwinia chrysanthemi*), a soft rot–causing bacterium that infects plant tissues primarily through wounds. The pathogen survives in infected plant debris and alternative hosts but does not persist freely in soil for long periods.

3.5.2 Symptoms

Infected plants initially show yellowing of leaves, followed by the development of black, water-soaked rot at the base of stems, which progressively extends upward. Severe infections result in complete plant collapse and death. Storage roots develop a characteristic internal soft rot, leading to rapid tissue breakdown without significant external discoloration. The rot is often more pronounced inside the root, making early detection difficult. The disease may also affect roots used for vine production, reducing planting material quality.

3.5.3 Epidemiology

The pathogen is prevalent in warm, humid environments and spreads mainly through infected planting material. It can also be transmitted via contaminated irrigation water, tools, and harvesting equipment. Infection occurs through wounds, and disease development is favored by high temperatures (above 30°C) and low oxygen conditions. The bacterium remains relatively inactive in well-aerated soils or at temperatures below 27°C.

3.5.4 Management

Management involves the use of less susceptible varieties and disease-free planting material. Care should be taken to minimize wounding during all stages of cultivation, harvesting, and storage. Vine cuttings should be taken from healthy plants and cut above the soil surface to reduce contamination risk. Proper sanitation and handling practices are essential to limit disease spread.

4. Viral Diseases of Sweet Potato

The major viral diseases of sweet potato include Sweet Potato Virus Disease (SPVD), which is caused by the synergistic interaction of Sweet Potato Feathery Mottle Virus (SPFMV) and Sweet Potato Chlorotic Stunt Virus (SPCSV). Other important viral diseases include sweet potato feathery mottle caused by SPFMV, and sweet potato chlorotic stunt caused by SPCSV. These viruses may occur independently but often lead to more severe symptoms when present together. Additional viral diseases include sweet potato leaf curl caused by begomoviruses and sweet potato mild mottle caused by Sweet Potato Mild Mottle Virus (SPMMV), belonging to the sweepovirus group. Collectively, these viral pathogens significantly affect plant growth, yield, and quality, particularly due to their accumulation through vegetative propagation and transmission by insect vectors.

4.1 Sweet Potato Virus Disease (SPVD)

4.1.1 Etiology

SPVD is caused by a synergistic interaction between Sweet Potato Feathery Mottle Virus (SPFMV) and Sweet Potato Chlorotic Stunt Virus (SPCSV) (Ogero & van der Vlugt, 2018).

4.1.2 Symptoms

Severe symptoms include stunting, leaf distortion, chlorosis, vein clearing, and drastic yield reduction. Leaves may become narrow and malformed.

4.1.3 Epidemiology

Spread by insect vectors such as aphids and whiteflies. Vegetative propagation accelerates disease accumulation.

4.1.4 Disease Management

Use virus-free planting material, control vectors, and rogue infected plants. Tissue culture-based clean seed systems are highly effective.

4.2 Sweet Potato Feathery Mottle Virus (SPFMV)

4.2.1 Etiology

Caused by SPFMV, transmitted by aphids.

4.2.2 Symptoms

Mild symptoms include feathery mottling, chlorotic spots, and vein clearing.

4.2.3 Epidemiology

Widely distributed and often latent unless combined with SPCSV.

4.2.4 Disease Management

Use clean planting material and vector control strategies.

4.3 Sweepoviruses

4.3.1 Etiology

Sweepoviruses are sweet potato–infecting viruses belonging to the genus *Begomovirus* in the family *Geminiviridae*. They are phylogenetically distinct from both Old World and New World begomoviruses and are collectively referred to as sweepoviruses.

4.3.2 Symptoms

Infected plants typically show upward curling of young leaves, vein swelling, and vein chlorosis. Depending on the genotype, plants may exhibit either leaf curl or yellow vein symptoms, but rarely both simultaneously. Symptoms are more evident in young plants, while mature plants often show mild or no visible symptoms despite infection.

4.3.3 Epidemiology

Sweepoviruses are transmitted from plant to plant by whiteflies, particularly *Bemisia tabaci*, in a semi-persistent manner. Disease spread is influenced by vector population density and duration of feeding. The viruses are also perpetuated through vegetative propagation, as infected planting material is reused across seasons. Yield losses can range from 10% to 80% depending on cultivar susceptibility (Kim *et al.,* 2015; Wanjala *et al.,* 2020).

4.3.4 Management

Management of sweepoviruses relies on integrated approaches similar to other viral diseases of sweet potato, including the use of virus-free planting material, control of whitefly vectors, and removal of infected plants. Avoiding the recycling of infected vines and maintaining field sanitation are essential to reduce disease spread.

4.4 Sweet Potato Mild Mottle Virus (SPMMV)

4.4.1 Etiology

Sweet potato mild mottle virus (SPMMV) belongs to the genus *Ipomovirus* and is a viral pathogen infecting sweet potato. It is primarily transmitted by the whitefly *Bemisia tabaci* in a non-persistent manner.

4.4.2 Symptoms

Infected plants exhibit mild to moderate symptoms including leaf mottling, distortion, and systemic vein chlorosis. Stunting may also occur in some cases. However, symptoms are often subtle and difficult to detect under field conditions, which can lead to unnoticed spread of the virus.

4.4.3 Epidemiology

The virus is transmitted by whiteflies (*Bemisia tabaci*) and spreads rapidly in areas with high vector populations. It is also perpetuated through vegetative propagation, as infected planting materials are reused across cropping cycles. The disease is widely distributed across Africa, Asia, and parts of Oceania and South America, although its exact impact on yield is not well established.

4.4.4 Management

Management strategies are similar to those used for other sweet potato viruses, including the use of virus-free planting material, control of whitefly vectors, and removal of infected plants. Avoiding the reuse of infected vines and maintaining field sanitation are critical to limiting disease spread.

5. Physiological Disorders of Sweet Potato

Common physiological disorders of sweet potato include internal cork, hollow heart, cracking, and chilling injury, each associated with specific environmental or nutritional factors. Internal cork is primarily caused by nutrient imbalance, particularly boron deficiency, leading to the formation of corky tissues within storage roots. Hollow heart results from irregular growth conditions, causing the development of internal cavities. Cracking of storage roots is associated with fluctuations in soil moisture, especially following periods of drought and sudden rainfall or irrigation. Chilling injury occurs when roots are exposed to low temperatures, resulting in physiological damage that affects storage quality and shelf life.

5.1 Internal Cork

5.1.1 Etiology

Internal cork is primarily associated with boron deficiency, a critical micronutrient required for cell wall formation and normal root development. Deficiency disrupts physiological processes such as carbohydrate translocation and tissue differentiation, leading to abnormal development of storage roots. The disorder is often exacerbated by environmental stresses such as drought, which limit nutrient uptake and mobility within the plant.

5.1.2 Symptoms

The disorder is characterized by the formation of brown, corky, and dry patches within the internal tissues of storage roots. These affected areas are typically irregular in shape and may not be visible externally, making detection difficult until roots are cut open. In severe cases, the corky tissue expands, leading to poor texture, reduced palatability, and significant decline in market quality. Although the external appearance of roots may remain unaffected, internal damage renders them unsuitable for consumption and processing.

5.1.3 Epidemiology

Internal cork commonly occurs in soils deficient in boron, particularly sandy or highly leached soils where micronutrient availability is low. Conditions such as prolonged drought further reduce boron uptake by roots, intensifying the disorder. Fluctuations in soil moisture and poor soil fertility management contribute to increased incidence. The disorder is more prevalent in regions with inconsistent rainfall and in fields lacking balanced fertilization practices.

5.1.4 Management

Effective management involves the application of balanced fertilization with adequate boron supplementation, either through soil application or foliar sprays. Maintaining uniform soil moisture through proper irrigation practices is essential to ensure consistent nutrient uptake. Regular soil testing and correction of micronutrient deficiencies, along with good agronomic practices, help prevent the occurrence of internal cork.

5.2 Cracking of Roots

5.2.1 Etiology

Cracking of roots is a physiological disorder caused by irregular water availability and rapid root expansion. When plants experience drought stress followed by sudden water availability, rapid uptake of water leads to internal pressure within storage roots, resulting in splitting of tissues.

5.2.2 Symptoms

Affected roots develop deep longitudinal or transverse cracks on the surface, which may extend into the internal tissues. These cracks reduce the visual appeal and marketability of the roots and may also predispose them to secondary infections by pathogens. Severely cracked roots may become deformed and unsuitable for storage or consumption.

5.2.3 Epidemiology

The disorder is most common under conditions of prolonged dry periods followed by heavy rainfall or irrigation. Rapid changes in soil moisture levels create uneven growth rates in root tissues, leading to mechanical rupture. Soils with poor water-holding capacity and inconsistent irrigation practices further increase susceptibility.

5.2.4 Management

Management focuses on maintaining consistent soil moisture levels through regular and controlled irrigation. Avoiding sudden fluctuations in water supply is critical to prevent rapid tissue expansion. Good field management practices, including proper drainage and soil conditioning, help regulate moisture availability and reduce the incidence of root cracking.

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ARTIFICIAL INTELLIGENCE IN AGRICULTURAL EXTENSION: TYPES, ADVANTAGES, DISADVANTAGES AND HOW IT WORKS FOR BENEFIT OF FARMERS

Payal Choudhary[1], Laksheeta Chauhan[1] and Sunil Kumar Sharma[2]
[1]Department of Extension Education, Rajasthan College of Agriculture, MPUAT, Udaipur
[2]SMS, Krishi Vigyan Kendra, Pokaran

Abstract

Artificial Intelligence (AI) is emerging as a powerful and transformative tool in modern agriculture. With the global population increasing rapidly, ensuring food and nutritional security has become a major challenge. Traditional agricultural extension systems, which guide and support farmers, are under pressure, especially in developing countries where small and marginal farmers dominate. These systems often face limitations such as a shortage of extension workers and difficulty in reaching remote areas. AI provides an effective solution by offering data-driven and real-time support to farmers. It enables precision agriculture through advanced technologies like drones, satellite imaging, and smart sensors, helping in efficient use of water, fertilizers, and pesticides while increasing productivity. AI-based crop monitoring systems can identify diseases, pest attacks, and nutrient deficiencies at an early stage and provide timely recommendations. In addition, chatbots and virtual assistants help farmers access important agricultural information instantly, breaking geographical and communication barriers. AI also plays a key role in data analysis, weather prediction, and market intelligence, helping farmers make informed decisions and adapt to changing climatic conditions. It supports farmer training and continuous learning through digital platforms. However, challenges such as high costs, lack of awareness, technical issues, and dependence on human interaction still exist. Initiatives like M-Velanmai in India and apps such as Plantix demonstrate the practical benefits of AI in agriculture. Furthermore, integration with blockchain, remote sensing, and big data analytics will strengthen transparency, traceability, and sustainability, ensuring long-term agricultural development and global food security.

Keywords: Artificial Intelligence, Data, Information, Extension, Farmers, Agriculture, Digital.

Introduction

Artificial Intelligence (AI) represents a rapidly emerging and dynamic technological advancement within the agricultural sector, with a strong vision of evolving into a major industry in the near future. AI encompasses the development of intelligent machines and software systems based on the principle that machines can simulate and replicate human intelligence, enabling them to efficiently perform tasks ranging from simple routine activities to highly complex decision-making processes (Adilakshmi *et al.,* 2021). The growing importance of AI-driven technologies in agriculture is closely linked to the continuous and rapid increase in the global population. According to the World Population Data Sheet (2022), the global population is projected to rise from 8 billion in mid-November 2022 to 8.5 billion by 2030, and further to approximately 9.7 billion by 2050, possibly reaching 10.4 billion thereafter. This exponential growth will inevitably exert immense pressure on agricultural systems worldwide.

As a result, there is an urgent need to increase global agricultural production by approximately 60–70 percent to meet the rising food demand by 2050, as highlighted by Silva (2018). Achieving this target requires the adoption of more intelligent, efficient, and technology-driven farming approaches. In this context, digital agricultural transformation becomes essential, and within it, agricultural extension systems play a pivotal role. In developing and emerging countries, traditional extension systems serve as a key source of knowledge dissemination and farmer support. However, their reach remains limited when compared to the vast population of smallholder farmers. Globally, about 570 million small and family farms exist (Lowder *et al.,* 2016), supporting over 1 billion people engaged in agriculture and accounting for more than 28 percent of the global workforce (Cassidy and Snyder, 2019).

Crop productivity is significantly affected by pests, diseases, and nutrient deficiencies, often resulting in losses of up to 30 percent. This highlights the urgent need for effective dissemination of agricultural technologies and timely advisory services (Kumar *et al.,* 2020). Additionally, farmers require continuous access to accurate and updated information on improved farming practices, efficient input use, and sustainable crop management strategies. However, during peak cropping seasons, extension systems face tremendous pressure in reaching farmers, especially in remote and rural areas. For instance, in certain regions of India, the extension worker-to-farmer ratio is as high as 1:2000, making it extremely difficult to deliver timely and personalized services (Rupavatharam *et al.,* 2017). Furthermore, only about 6.8 percent of farmers in India have access to extension services, with women farmers being even more marginalized (GFRAS, 2012).

Although various Information and Communication Technology (ICT)-based tools have been introduced to support farmers, many of them fail to provide real-time, location-specific, and problem-oriented solutions during critical crop growth stages. Therefore, despite continuous advancements in agricultural research and innovation, their benefits remain limited if they do not effectively reach farmers at the grassroots level. In this regard, AI emerges as a powerful catalyst in strengthening agricultural extension systems. By integrating AI technologies such as machine learning, remote sensing, predictive analytics, and natural language processing, extension services can become more efficient, responsive, and inclusive.

AI can enable real-time crop monitoring, early detection of pests and diseases, weather forecasting, and personalized advisory services tailored to specific farm conditions. It also facilitates two-way communication between farmers and experts through digital platforms, mobile applications, and AI-powered chatbots, thereby overcoming geographical and infrastructural barriers. Moreover, AI enhances decision-making by analyzing large datasets related to soil health, climate variability, and market trends, ultimately improving farm productivity and profitability.

In addition, AI can play a significant role in capacity building by providing digital training modules, multilingual support, and adaptive learning systems for farmers. It can also improve transparency and efficiency in supply chains through integration with emerging technologies like big data and blockchain. Thus, the integration of AI into agricultural extension systems not only ensures the timely delivery of relevant information but also empowers farmers to make independent, informed decisions. Ultimately, this aligns with the core objective of agricultural extension—enhancing the socio-economic status of rural communities and enabling sustainable agricultural development.

What is Artificial Intelligence (AI)?

Artificial Intelligence (AI) is a rapidly advancing field of technology that refers to the ability of machines to perform tasks that normally require human intelligence. These tasks include thinking, learning, reasoning, problem-solving, and decision-making. In simple terms, AI enables machines to simulate human cognitive functions and respond to different situations in a way that resembles human behavior. It is a branch of computer science that focuses on designing and developing systems capable of working independently, learning from data, and improving their performance over time without direct human intervention.

In modern applications, AI systems are designed to perceive their environment, process information, and take appropriate actions based on that information. They can analyze large volumes of data much faster and more accurately than humans, making them highly valuable in solving complex problems. AI-powered software can assist in predicting future outcomes, identifying patterns, and providing solutions in real-time. For example, these systems can support decision-making in fields such as agriculture, healthcare, finance, and education by offering insights that would otherwise require extensive human expertise.

Artificial Intelligence is inherently a multidisciplinary field, integrating knowledge and techniques from various domains. It combines computer science with data analysis and statistics to process and interpret information efficiently. It also involves hardware and software engineering for developing intelligent systems, while disciplines like linguistics contribute to natural language processing, enabling machines to understand and communicate in human languages. Additionally, insights from neuroscience help in modeling how the human brain functions, while psychology and philosophy contribute to understanding human behavior, reasoning, and ethics.

Furthermore, AI includes subfields such as machine learning, deep learning, robotics, and expert systems, each contributing to its overall capabilities. As AI continues to evolve, it is becoming an essential tool for innovation and development across industries. Its ability to enhance efficiency, reduce human effort, and provide intelligent solutions makes it a key driver of future technological progress.

How AI works in general?

In essence, Artificial Intelligence (AI) systems function by processing large volumes of structured and labeled data, which serve as training inputs for learning. These systems analyze the data to identify patterns, relationships, and trends, and then use this learned information to make predictions or decisions about new, unseen situations. This process is commonly known as machine learning, where algorithms improve their performance over time as they are exposed to more data.

For example, a chatbot that is trained on vast collections of text data can learn the structure, tone, and context of human language, enabling it to generate responses that closely resemble natural human conversation. Similarly, image recognition systems are trained using millions of images, allowing them to accurately detect, classify, and describe objects, faces, or patterns within new images. These capabilities are widely used in applications such as medical diagnosis, security systems, and agricultural monitoring. In addition to these advancements, generative AI has emerged as a powerful branch of artificial intelligence. It enables machines to create entirely new content, such as realistic text, high-quality images, music, and even videos. Tools based on generative AI can produce human-like writing, design visuals, compose music, and assist in creative tasks. This rapid progress is transforming industries by enhancing productivity, creativity, and efficiency. As a result, AI is not only capable of analyzing and interpreting data but also of generating innovative outputs, making it a highly impactful technology in today's digital era.

AI programming centers around cognitive abilities that encompass the following:

1. **Learning:** This aspect of Artificial Intelligence focuses on acquiring data and converting it into useful and actionable information. AI systems learn from large datasets through methods such as machine learning, where algorithms are trained to recognize patterns and relationships within the data. These algorithms act as step-by-step instructions that guide machines in performing specific tasks efficiently. Over time, as more data is processed, the system improves its accuracy and performance without needing explicit reprogramming.

2. **Reasoning:** Reasoning in AI involves the ability of a system to make logical decisions by selecting the most suitable algorithm or approach to achieve a desired outcome. It enables machines to analyze different possibilities, evaluate conditions, and arrive at the best possible solution. This capability is particularly important in problem-solving situations where multiple variables and uncertainties are involved.
3. **Self-correction:** This facet of AI ensures continuous improvement in system performance. AI models are designed to identify errors in their outputs and adjust their algorithms accordingly. Through techniques such as feedback loops and iterative learning, systems refine their predictions and decisions over time, leading to higher accuracy and reliability in results.
4. **Creativity:** Creativity in AI refers to its ability to generate new and original content. By using advanced techniques such as neural networks, rule-based systems, and statistical models, AI can produce realistic text, images, music, and innovative ideas. This capability is particularly evident in generative AI, which is transforming creative industries by enabling machines to mimic human creativity and produce novel outputs.

Types of Artificial Intelligence

Artificial Intelligence (AI) can be classified in different ways based on its capabilities and stages of development. One widely accepted classification divides AI into four major types, reflecting its level of advancement and functional ability:

1. Reactive Machines:

Reactive machines represent the most basic form of AI systems. These systems operate solely on present data and respond to specific inputs with predefined outputs. They do not store memories or learn from past experiences, which limits their ability to improve over time. Their functioning is entirely rule-based and task-specific. A classic example is IBM Deep Blue, the chess-playing computer that defeated world champion Garry Kasparov in 1997. Despite its success, it could not learn or adapt beyond its programmed capabilities.

2. Limited Memory:

Limited memory AI is more advanced and forms the basis of most modern AI applications. These systems can store and use past data for a short period to improve decision-making. They learn from historical data and continuously update their performance through training. Technologies such as machine learning and deep learning fall under this category, where artificial neural networks are used to recognize patterns and make predictions. Examples include self-driving cars, recommendation systems, and many agricultural AI tools.

3. Theory of Mind:

Theory of mind AI is still in the research and development stage. This type of AI aims to understand human emotions, beliefs, intentions, and social interactions. It would be capable of interacting with humans in a more natural and emotionally intelligent way, similar to human communication. Such systems would be able to interpret feelings and adjust their responses accordingly, making them highly useful in areas like healthcare, education, and customer service. However, this level of AI has not yet been fully achieved.

4. Self-Aware AI:

Self-aware AI represents the most advanced and hypothetical stage of artificial intelligence. These systems would possess self-consciousness, awareness of their own existence, and the ability to understand their internal states, similar to humans. They would have independent thinking, emotions, and decision-making abilities. However, self-aware AI remains purely theoretical and does not exist with current technological capabilities.

Agricultural Extension

Agricultural extension plays a vital role in the development and modernization of the agricultural sector. It involves the effective dissemination of knowledge, provision of resources, and guidance to farmers for adopting improved agricultural practices. Extension training programs are essential in shaping farmers' attitudes, enhancing their skills, and encouraging the adoption of innovative technologies, ultimately contributing to rural development and improved livelihoods (Kassem *et al.,* 2021). Agricultural extension services include a wide range of institutions and activities that support farmers and other stakeholders in agriculture. These services aim to help individuals overcome challenges, gain access to new knowledge, and adopt modern techniques to increase productivity and income. According to Davis, Babu, and Ragasa (2020), agricultural extension not only focuses on technology transfer but also emphasizes capacity building, problem-solving, and empowerment of farming communities to achieve sustainable development.

Extension services are delivered through three major sectors, each playing a distinct but complementary role:

1. Public Sector:

This sector includes government organizations such as ministries and departments of agriculture, agricultural universities, and research institutions. These bodies are primarily responsible for policy formulation, research, and large-scale dissemination of agricultural technologies. They often provide free or subsidized advisory services, training programs, and demonstrations to farmers, ensuring wider outreach, especially in rural areas.

2. Private Non-Profit Sector:

This sector consists of non-governmental organizations (NGOs), foundations, community-based organizations, and international development agencies. These organizations focus on community development, capacity building, and inclusive growth. They often work closely with marginalized groups, including smallholder and women farmers, providing tailored extension services, training, and support through participatory approaches.

3. Private For-Profit Sector:

The private sector includes agribusiness companies, input suppliers (such as seed, fertilizer, and pesticide companies), agro-processing firms, and consultancy services. These entities provide extension services as part of their business operations, often offering technical advice, product information, and market linkages. In some cases, progressive farmers and farmer-led organizations also act as knowledge providers, creating a farmer-to-farmer extension system.

Artificial Intelligence in Agricultural Extension

Artificial Intelligence (AI) is rapidly transforming the field of agricultural extension by improving the way information is delivered, decisions are made, and modern farming practices are adopted. It enhances the efficiency, accuracy, and reach of extension services, making them more responsive to farmers' needs. The key roles of AI in agricultural extension are as follows:

1. Precision Farming:

AI-driven technologies such as drones, satellite imagery, and smart sensors enable real-time data collection on soil health, weather conditions, crop growth, and field variability. This data is analyzed to provide precise recommendations on planting time, irrigation scheduling, fertilizer application, and pest management. As a result, farmers can optimize resource use, reduce input costs, and increase crop productivity.

2. Crop Surveillance:

AI-based image recognition and computer vision systems allow continuous monitoring of crops. These systems can detect early signs of diseases, pest infestations, and nutrient deficiencies by analyzing images. Timely alerts and corrective recommendations help farmers take preventive measures, thereby minimizing crop losses and improving yield quality.

3. Chatbots and Virtual Assistants:

AI-powered chatbots and virtual assistants provide instant and accessible advisory services to farmers. Through mobile applications or voice-based systems, farmers can receive guidance on crop management, weather updates, pest control, and market prices, even in remote areas with limited access to extension personnel.

4. Data Analytics:

AI processes large volumes of agricultural data from multiple sources such as weather stations, soil databases, and satellite systems. This enables accurate forecasting of pest outbreaks, prediction of yield, optimization of sowing time, and selection of suitable crop varieties, leading to informed and data-driven decision-making.

5. Language Processing:

Natural Language Processing (NLP) enables AI systems to translate agricultural information into local languages. This improves accessibility and ensures that farmers from diverse linguistic backgrounds can understand and benefit from extension services effectively.

6. Market Analysis:

AI tools analyze market trends, price fluctuations, and demand patterns. This helps farmers make better decisions regarding crop selection, harvesting time, and selling strategies, ultimately maximizing their profits and reducing market risks.

7. Climate Adaptation:

AI models assist farmers in adapting to climate variability by analyzing long-term weather patterns and providing recommendations on climate-resilient crops, water management practices, and risk mitigation strategies. This enhances the resilience of farming systems.

8. Farm Management Systems:

AI-based farm management platforms integrate data from various sources such as IoT devices, weather data, and historical records. These systems help farmers monitor farm activities, track resource usage, and plan operations efficiently, improving overall farm management.

9. Training and Education:

AI-powered e-learning platforms provide customized training modules, videos, and advisory content tailored to farmers' needs. This helps in continuous learning, skill development, and adoption of advanced agricultural technologies.

10. Support for Extension Workers:

AI tools assist extension personnel by providing real-time information, recommending best practices, and prioritizing farmer interactions based on urgency and need. This improves the effectiveness and outreach of extension services.

In conclusion, Artificial Intelligence (AI) is significantly transforming agricultural extension by providing timely, accurate, and data-driven insights to both farmers and extension personnel. It enhances the efficiency and reaches of advisory services, enabling better decision-making and faster problem-solving at the field level. By integrating advanced technologies such as data analytics, machine learning, and real-time monitoring, AI supports the adoption of improved farming practices and optimal resource management. Moreover, AI contributes to increasing agricultural productivity while promoting sustainability and environmental conservation. It helps farmers adapt to changing climatic conditions, minimize risks, and improve overall farm resilience. As global challenges like climate change, population growth, and food insecurity continue to intensify, AI-driven extension systems offer a promising solution. Thus, the integration of AI into agricultural extension is not only strengthening existing systems but also paving the way for a more efficient, resilient, and sustainable future in agriculture.

Advantages of Artificial Intelligence

Target Audience:

Artificial Intelligence (AI) significantly strengthens agricultural extension systems by enabling them to reach a larger number of farmers in a shorter time span. Unlike traditional methods, which are often limited by manpower and geographical barriers, AI-powered platforms ensure wider coverage and inclusivity. This is particularly beneficial for smallholder and marginal farmers who are often left out of conventional extension services. With the growing acceptance of digital technologies and improved infrastructure, farmers are becoming more familiar with mobile applications, digital platforms, and online advisory systems. This not only helps them access information easily but also empowers them to voice their opinions, share feedback, and actively participate in decision-making processes, thereby contributing to their overall socio-economic development.

Seamless Connectivity:

AI enables continuous and flexible communication between farmers and extension agents without the need for physical presence in the field. Through tools such as mobile apps, chatbots, and virtual advisory systems, both stakeholders can interact at their convenience. This ensures uninterrupted flow of information and strengthens communication channels, especially in remote and rural areas where physical access is often limited. As a result, farmers can receive guidance anytime, reducing dependency on scheduled visits by extension workers.

Real Time:

Agriculture is highly dependent on dynamic and uncertain factors such as weather conditions, pest outbreaks, disease incidence, input availability, and market fluctuations. AI systems provide real-time information and timely alerts based on current data and predictive analytics. This enables farmers to take immediate and appropriate actions, reducing risks and improving productivity. Timely dissemination of information ensures that farmers can respond effectively to emerging challenges during critical stages of crop growth.

Efficiency:

AI enhances the overall efficiency of agricultural extension systems by reducing the time, labor, and cost involved in traditional service delivery. Automated data collection, processing, and advisory generation minimize human effort and increase accuracy. This leads to better resource utilization and reduces wastage in implementation. Extension workers can also focus on more complex tasks, as routine advisory services are handled by AI systems.

Records:

AI facilitates digital record-keeping through cloud-based storage systems, eliminating the need for manual documentation. All data related to farm activities, advisory services, and outcomes can be stored, accessed, and analyzed easily. This improves transparency and accountability in extension services. It also allows monitoring of progress over time, helping policymakers and extension agents evaluate the effectiveness of interventions and make necessary improvements.

Data Updating:

One of the key strengths of AI systems is their ability to continuously update and refine data. Information is regularly enhanced through inputs from research institutions, extension agencies, and feedback from farmers. This dynamic updating ensures that the system remains relevant to changing agricultural conditions, emerging challenges, and farmers' needs. AI, with its ability to mimic certain aspects of human cognition, acts as an additional support system for extension workers by providing timely insights and recommendations. This ultimately strengthens the overall extension framework and contributes to sustainable agricultural development.

Disadvantages of Artificial Intelligence in Agricultural Extension:

Costly Installation:

One of the major limitations of Artificial Intelligence (AI) in agricultural extension is the high initial cost of installation. Although AI systems may become cost-effective in the long run, their setup requires significant investment in infrastructure such as high-speed internet connectivity, data servers, cloud storage systems, advanced computing devices, and communication networks like fiber optics or wireless towers. Establishing such infrastructure in rural and remote areas is challenging and expensive, especially in developing countries. This financial burden can limit large-scale adoption and slow down the implementation of AI-based extension services.

Low Acceptance and Adaptability:

A large proportion of farmers belong to economically weaker sections and may have limited educational backgrounds. Additionally, strong adherence to traditional farming practices and cultural beliefs can create resistance to adopting new technologies. This lack of acceptance makes it difficult for extension agencies to effectively introduce AI-based solutions. Building trust and encouraging behavioral change among farmers becomes a slow and complex process, which may hinder the success of such interventions.

Digital Education Gap:

The effective use of AI technologies requires a certain level of digital literacy, which is often lacking among both farmers and extension workers. Many stakeholders are not adequately trained to operate smartphones, applications, or advanced digital tools. This creates a knowledge gap that must be addressed through extensive training programs, awareness campaigns, and capacity-building initiatives. Such efforts require additional time, resources, and financial investment.

Technical Failures and Risks:

AI systems, like all technological tools, are not free from failures. Issues such as system crashes, server downtime, software bugs, or hardware malfunctions can disrupt services. In a technology-dependent extension system, even a temporary failure can delay the delivery of critical information, especially during important crop stages. Additionally, risks such as cyberattacks, malware infections, data breaches, and reduced system performance after updates can further complicate operations. In extreme cases, system failures may require complete reinstallation, causing interruptions and losses.

Dependence on Infrastructure:

AI-based systems rely heavily on stable electricity supply and internet connectivity. In many rural areas, frequent power cuts and poor network coverage can limit the effectiveness of these technologies. Without reliable infrastructure, farmers may not be able to access timely information, reducing the overall efficiency of AI-driven extension services.

Loss of Human Element:

Traditional agricultural extension systems are built on personal interaction, trust, and field-level understanding. Extension workers often provide emotional support, practical insights, and context-specific solutions based on direct observation. AI, despite its advanced capabilities, lacks human emotions, empathy, and experiential understanding. It cannot fully replace the human touch that is essential in addressing complex, location-specific, and socially sensitive issues faced by farmers.

Data Privacy and Reliability Concerns:

AI systems depend heavily on data collection and analysis. Concerns related to data privacy, misuse of information, and reliability of data sources can affect farmer trust. Incorrect or biased data may lead to inappropriate recommendations, which can negatively impact farm outcomes.

Real-Life Examples of Artificial Intelligence in Agricultural Extension

Artificial Intelligence (AI) has moved beyond theoretical applications and is now actively transforming agricultural extension systems through practical, field-level innovations. Several successful initiatives demonstrate how AI can improve information delivery, enhance decision-making, and empower farmers. Some of the most notable real-life examples are discussed below:

i) M-Velanmai

M-Velanmai is an innovative mobile-based agricultural advisory service developed through a public-private partnership led by Tamil Nadu Agricultural University (TNAU). The primary objective of this initiative is to provide timely, need-based, and location-specific agricultural information directly to farmers through mobile technology. It represents a major step toward digitizing agricultural extension services and ensuring last-mile connectivity. The system operates by collecting real-time data from farms using advanced technologies such as sensor networks and Automatic Weather Stations (AWS). These tools capture important parameters like soil conditions, temperature, humidity, rainfall, and other environmental factors. In addition, farmers can upload images of crops, pest infestations, and disease symptoms using their mobile phones. These images are analyzed by experts, who then provide customized recommendations for crop management, pest control, and nutrient application.

One of the key strengths of M-Velanmai is its ability to deliver advisory services in local languages and dialects, making it highly accessible to farmers. The system is integrated with the TNAU Agritech Portal, which includes features such as dynamic market information, weather forecasts, and agri-clinic services. It also helps in creating a comprehensive digital database of farmers, including details about soil type, water quality, pH levels, cropping patterns, and farm history.

The project is implemented through a cluster-based approach. Each cluster consists of around 20 farmers, and multiple clusters are formed around Automatic Weather Stations. In the pilot phase, the initiative covered 28 districts of Tamil Nadu, involving approximately 2,800 farmers across 140 clusters. Each cluster is supported by a trained local facilitator, often a progressive farmer or agri-clinic operator, who acts as a link between farmers and experts. Additionally, project associates are responsible for content development, farmer training, and technical support. The collaboration involves organizations such as the Electronics Corporation of Tamil Nadu (ELCOT), the Government of Tamil Nadu, TNAU, and Tata Consultancy Services. Based on its success, the program has the potential to be scaled up to cover all villages, thereby creating a robust and comprehensive farmer advisory system.

ii) Plantix App

The Plantix app is a globally recognized AI-based agricultural application developed by a German startup. It is specifically designed for Android smartphones and provides real-time, personalized advisory services to farmers. The app uses advanced technologies such as artificial intelligence, machine learning, and deep neural networks to diagnose crop problems accurately. The core feature of Plantix is its ability to identify plant diseases, pest attacks, and nutrient deficiencies through image recognition. Farmers simply need to capture and upload a photograph of the affected plant. The app processes the image using AI algorithms and provides a diagnosis within seconds. It also offers detailed information about the symptoms, causes, and suitable control measures, including both biological and chemical options.

In addition to disease diagnosis, Plantix offers several advanced features:

- **Digital Repository:** The app contains a vast database of over 700 types of plant damage, categorized by crop and growth stage. This helps farmers understand various issues and their solutions in detail.
- **Interactive Community:** Plantix provides a platform where farmers, experts, and stakeholders can interact, share knowledge, and seek advice. Thousands of posts are created and answered daily, promoting collaborative learning.

- **Crop Advisory:** The app provides step-by-step guidance throughout the crop cycle, including land preparation, sowing, irrigation, fertilization, and pest management.
- **Fertilizer Calculator:** Farmers can calculate the required quantity and timing of fertilizer application based on crop type and field size.
- **Disease Alerts:** By using geolocation data, the app sends real-time alerts about disease outbreaks within a specific radius, helping farmers take preventive measures.
- **Weather Forecasting:** It offers localized weather-based recommendations for farm operations such as spraying, irrigation, and harvesting.
- **Retailer Connectivity:** The app connects farmers with nearby input suppliers, ensuring access to appropriate and quality products.

The success of Plantix in countries like India has been supported by improved internet connectivity and reduced data costs since 2015. Organizations like the International Crops Research Institute for the Semi-Arid Tropics have collaborated to expand its reach among smallholder farmers. Overall, Plantix empowers farmers with instant, science-based solutions, significantly improving crop productivity.

iii) Early Warning System for Pest Management

Another significant application of AI in agricultural extension is the development of early warning systems for pest management. In India, the government is promoting Integrated Pest Management (IPM), which is a scientific and environmentally sustainable approach to controlling pests. AI plays a crucial role in strengthening this system. Traditionally, extension workers collect data on pest infestations from selected sample farms and upload it into a centralized database. This data is analyzed to generate general recommendations for farmers in a particular region. However, AI has significantly enhanced this process by making it faster, more accurate, and more localized. A notable example is the AI-based pest detection model developed by Wadhwani AI. This system uses images captured by farmers or extension workers to identify and count pests present in traps. The model works through a smartphone application and has the advantage of functioning even in offline mode, making it highly suitable for rural and remote areas with limited connectivity.

The system analyzes pest density and compares it with the Economic Threshold Level (ETL), which is the level at which pest populations begin to cause economic damage. If the pest population exceeds this threshold, the system generates real-time alerts and provides immediate recommendations for control measures. This allows farmers to take timely action and prevent significant crop losses. Such early warning systems improve the precision and effectiveness of pest management strategies. They reduce unnecessary pesticide use, lower production costs, and promote environmentally sustainable practices. Moreover, they enhance the efficiency of extension services by enabling targeted and timely interventions.

Conclusion

Artificial Intelligence (AI) is rapidly emerging as a transformative force in agricultural extension, redefining the way knowledge, information, and advisory services are delivered to farmers. Traditionally, agricultural extension relied heavily on face-to-face interactions, field visits, and manual dissemination of information. While effective, these approaches often faced limitations in terms of reach, timeliness, and resource availability. AI-driven technologies are now overcoming these barriers by enabling faster, more precise, and scalable solutions tailored to the diverse needs of farming communities. One of the most significant contributions of AI in agricultural extension is its ability to provide real-time, location-specific, and personalized recommendations. By integrating data from multiple sources such as weather stations, soil sensors, satellite imagery, and farmer inputs, AI systems can generate accurate advisories related to crop management, pest control, irrigation, and nutrient application. This not only enhances productivity but also helps farmers make informed decisions, reducing risks associated with climate variability and pest outbreaks. Moreover, AI-powered tools such as mobile applications, chatbots, and image recognition systems have improved accessibility to agricultural knowledge. Farmers, even in remote areas, can now receive expert guidance through smartphones in their local languages. This democratization of information has significantly strengthened the last-mile delivery of extension services. In addition, features like early warning systems, disease detection, and market intelligence are empowering farmers to respond proactively to challenges and opportunities. However, despite its immense potential, the adoption of AI in agricultural extension is not without challenges. High initial investment costs, lack of digital literacy among farmers and extension workers, infrastructural constraints, and resistance to technological change remain significant barriers. Furthermore, the absence of the “human touch” in AI-driven systems may limit their effectiveness in addressing socio-cultural and context-specific issues that require personal understanding and trust-building. To fully harness the benefits of AI, it is essential to adopt a balanced and inclusive approach. Capacity building through training and digital education must be prioritized to enhance the technological competence of both farmers and extension personnel. Investments in rural digital infrastructure, such as internet connectivity and affordable smart devices, are equally crucial. Additionally, AI should be integrated with traditional extension systems rather than replacing them, ensuring that technology complements human expertise.

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MODERN AGRICULTURAL PRACTICES USING DRONE TECHNOLOGY: A COMPREHENSIVE REVIEW

Sanghomitra Sarma*, Babita Tamuli,
Chayanika Thakuriya, Sarmistha Borgohain and Shantanu Paul
Krishi Vigyan Kendra, Dibrugarh, AAU, Jorhat
*Corresponding author E-mail: sanghomitrasharmaaau@gmail.com

Introduction

Agriculture sector is the most promising sector, dealing with the lot of problems now a day's one of the innumerable problems is labour unavailability for farming. 815 million people suffer from food insecurity worldwide each year. Farming communities need to adjust to new technologies in order to produce more food grains and boost productivity. One of the most recent examples of modern technology is the usage of drones, or small unmanned aerial vehicles (UAVs). These days, drones are employed in a vast array of non-military applications, such as firefighting, search and rescue, surveillance, traffic monitoring, weather monitoring, personal drone use, business drone photography, videography, agricultural, and even delivery services. The aircraft can be operated remotely or it can receive and land on its own using software-controlled flight plans in fixed systems that communicate with GPS and onboard sensors.

Classification of Drones

1. Based on Form, Feature and Functions

- Possess two identical wing designs to an aero plane.
- Function at a maximum speed of 50 km/h.
- Maps of large fields.
- They are unable to take off vertically. they cannot transport heavy loads over long distances fixed wing drone

a. Single Rotor Drone

- Only possess one rotor.
- Capable of vertical takeoff and landing.
- More effective than drones with several rotors.
- Approved for agrochemical spraying.

b. Multi Rotor Drone

- Utilize four out of every eight rotors.
- Only a 10–20-minute lifespan.
- Launch and descend vertically.
- Take photos and move small amounts of cargo.

- Mostly utilized for pesticide spraying.

c. Hybrid Drone

- Equipped with both wings and rotors.
- Can take off and land vertically.
- Cover far longer distances.
- Carry heavier cargo than multi-rotor drones.

d. Ducted Fan Drone

- can take off and land vertically
- Used for crop monitoring.

2. Based on Maximum Takeoff Weight (Including Payload)

The classification of civil remotely piloted aircraft is based on their maximum takeoff weight.

- Nano: weighing less than 250 grams
- Micro: more than 250 grams and up to or including 2 kg.
- Small: more than 2 kg and up to or including 25 kg.
- Medium: weighing more than 25 kg but not more than 150 kg.
- Large: weighing more than 150 kg.

Sensors Used in Agricultural Drones

1. Visual Sensor

- Aerial mapping
- Imaging
- Plant counting
- Surveying

2. Thermal Sensor

- Heat signature detection
- Livestock detection
- Surveillance
- Water source detection
- Emergency response

3. Multispectral Sensor

- Measurements of plant health
- evaluation of water quality
- Vegetation index
- Plant counting

4. Hyper Spectral Sensor

- Full spectral sensing
- Spectral research and development

- Vegetation index calculation
- Water quality assessment

Application of Drones in Agriculture

- **Soil and Field Analysis**: Agricultural drones can be used to mount sensors to evaluate moisture content in the soil, soil erosion, nutrients content, and fertility of the soi
- **Crop Monitoring:** This includes providing fertilizers at the right time, checking for pest attack, and monitoring the effect of weather conditions. Drones can inspect the field with infrared cameras and based on their real-time information, farmers can take active measures to improve the condition of plants.
- **Plantation:** Drones can help in planting trees and crops. This will not only save labor but also help in saving fuels.
- **Livestock Management:** Drones can be used to monitor and manage huge livestock as their sensors have high-resolution infrared cameras.
- **Crop Spraying:** Agri-drones can be used to spray chemicals to crops in very little time.
- **Check Crop Health:** Drones with infrared mapping can monitor the health of soil and crop in a matter of hours.
- **Avoid Overuse of Chemicals:** Drones are effective in reducing the overuse of pesticides, insecticides, and other chemicals. Drones can detect minute signs of pest attacks, and provide accurate data regarding the degree and range of the attack.
- **Prepare for Weather Glitches:** Drones can detect upcoming weather conditions. Advance notice of storms or lack of rain can be used to plan the crop.
- **Monitor Growth:** Drones can provide accurate data about every stage of crop growth, and report any variations before they become a crisis. For example, stressed crops will reflect less near-infrared light as compared to healthy crops.
- **Geofencing:** The thermal cameras installed over drones can easily detect animals or human beings

Benefits of Using Drones

1. **Fast data acquisition for accurate farm analysis**: Drone photometry can create highly accurate maps and 3D models. With drone mapping software such as Pix4DFields, images captured can be used to get a topographical map of the farmland. This will help farmers make necessary adjustments for a healthy and productive land.
2. **Time & cost saving**: Drones are more time efficient than manned aircraft for mapping, surveillance, and crop spraying. Operations in drones are carried out through intelligent flight modes, they are semiautomated hence time efficient thus less time is spent on the field which saves farmers money on labour equipment.

3. **Improved crop yields**: Using remote sensing technology, farmers can easily identify areas of the field that are not producing healthy crops, and adopt required management practices. This will improve the overall quality of the crops, improve yield and save money in the long term.
4. **Safer way to spray crops**: Spraying chemicals manually pose health hazards. Using drones to treat infected plants is much safer and more efficient than manual labour and using land-based machinery.
5. **Helping Fight Climate Change**: Reduce the use of chemicals through data-driven targeted treatment and the need for fossil fuels as drones are powered by intelligent batteries. Drones can help reduce pollution, help the environment and help in the fight against climate change

Disadvantages

1. **Costly:** A drone costs anywhere between ₹10 lakh and ₹12 lakh. An ordinary farmer will not be able to afford it.
2. **Contamination:** Aerial spraying may contaminate water bodies and affect small water streams. Animals can also become victims.
3. **Unsuitability to all crops:** Drones cannot be used for all crops e.g. they cannot be used for spraying on grapes whose leaves form a canopy making spraying difficult.
4. **Vulnerable:** Agriculture drones are more vulnerable to adverse weather conditions**.**
5. **Federal laws:** The use of agricultural drones is considered commercial. This means the farmer needs to undergo Federal Aviation Administration (FAA)

Conclusion:

Drones are helpful for farming management in terms of observing, measuring, and taking action based on real-time crop and livestock data. It erases the need for guesswork in modern farming and instead gives farmers the ability to maximize their yields and run more efficient organizations, all while enhancing crop production.

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EFFECT OF DIFFERENT PACKAGING MATERIALS OF DRY CHILLI FOR BETTER STORAGE

D. Geetha Priyanka*, Lakshmi Madhavi Surisetty and Gudapati Vamsi Prasad
P.G. Department of Horticulture,
School of Agricultural Sciences, Malla Reddy University, Hyderabad, Telangana, India
*Corresponding author E-mail: geethapriyanka2003@gmail.com

Abstract

Dry chilli (*Capsicum annuum* L.) is an important spice crop valued for its colour, pungency and flavour. Improper storage and unsuitable packaging materials lead to moisture absorption, colour loss, fungal infestation and aflatoxin contamination, resulting in heavy post-harvest losses. Packaging plays a major role in maintaining the quality and shelf life of dry chillies during storage and transportation. Explains the importance of different packaging materials used for dry chilli storage, including gunny bags, LDPE, HDPE, polypropylene, aluminium laminated films and vacuum packaging. The effect of packaging materials on moisture content, colour retention, capsaicin, oleoresin and microbial infestation has also been discussed. Packaging properties such as moisture barrier, oxygen barrier and light protection are important in preserving chilli quality.

Studies showed that aluminium laminated films and vacuum packaging are more effective in maintaining colour, pungency and storage stability compared with traditional packaging materials. Proper packaging along with suitable storage conditions helps in reducing post-harvest losses and improving the shelf life and market quality of dry chillies.

Keywords: Dry Chilli, Moisture Barrier, Aluminium Laminate, Vacuum Packaging, LDPE, HDPE, Polypropylene, Capsaicin, Oleoresin, Aflatoxin, Shelf Life, Quality Retention, Post Harvest Management.

Introduction

Dry chilli (*Capsicum annuum* L.) is one of the most important spice crops cultivated throughout the world because of its colour, pungency, flavour and medicinal value. India is one of the leading producers and exporters of dry chilli. The quality of dry chilli mainly depends upon its bright red colour, low moisture content, pungency and freedom from microbial contamination. During storage, dry chillies are highly prone to moisture absorption, colour fading, fungal infestation and quality deterioration. Improper storage conditions and unsuitable packaging materials lead to heavy post-harvest losses and reduced market value.

Packaging plays a major role in preserving the quality and extending the shelf life of dry chillies. Proper packaging materials protect the produce from moisture, oxygen, light, insects and microorganisms. Modern packaging systems help in retaining important quality parameters such as capsaicin, oleoresin, capsanthin and ascorbic acid during storage. Research studies reported that aluminium laminated films and vacuum packaging are more effective in maintaining storage quality compared with traditional gunny bags and ordinary plastic materials.

Dry chillies are hygroscopic in nature and absorb moisture rapidly from the surrounding atmosphere, especially under high relative humidity conditions. Increased moisture content encourages fungal growth and development of harmful mycotoxins such as aflatoxins, which reduce product safety and export acceptability. Exposure to oxygen and light during storage also causes oxidation of pigments and flavour compounds, resulting in loss of colour, pungency and nutritional quality. Therefore, selecting suitable packaging material is essential for maintaining the commercial and nutritional value of dry chillies during long-term storage.

Different packaging materials vary in their barrier properties against moisture, oxygen and light. Traditional packaging materials such as gunny bags and jute bags are economical and easily available, but they provide limited protection against environmental conditions. In contrast, modern packaging materials including low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), metallized polyester films, aluminium laminated pouches and vacuum packaging systems provide better storage stability and quality retention. These materials help in reducing moisture absorption, minimizing microbial infestation and preserving colour and pungency for longer periods.

Importance of Packaging in Dry Chilli Storage

Packaging is an essential post-harvest practice that protects dry chillies from environmental factors during storage and transportation. Dry chillies are hygroscopic in nature and absorb moisture rapidly from the atmosphere. Increased moisture content results in fungal growth, insect infestation and aflatoxin contamination. Packaging materials act as protective barriers and help in maintaining safe moisture levels inside the package.

Proper packaging also helps in reducing physical damage during handling and transport. During long storage periods, exposure to oxygen and sunlight causes oxidation of pigments and deterioration in flavour. Suitable packaging materials help in maintaining the original quality characteristics of dry chillies for longer periods.

Importance of Packaging	Functions of Packaging
• Maintains product quality • Prevents moisture absorption • Reduces fungal contamination • Preserves colour and pungency • Extends shelf life • Improves export quality • Reduces post-harvest losses	• Protects against humidity • Prevents oxygen entry • Reduces light exposure • Avoids mechanical damage • Prevents microbial contamination • Maintains nutritional quality • Enhances consumer appeal

Packaging Material Properties Affecting Storage

The efficiency of packaging materials depends upon their physical and chemical properties. Packaging materials used for dry chilli storage should possess good moisture barrier, oxygen barrier and mechanical strength to preserve quality during storage. Good packaging materials help in maintaining low moisture content and reduce the risk of fungal growth and toxin development. Barrier properties are particularly important because dry chillies are highly sensitive to environmental changes.

1. Moisture Barrier Property

Moisture barrier property is one of the most important characteristics required in chilli packaging materials. Dry chillies absorb moisture easily from the atmosphere, especially under humid conditions. Moisture absorption increases the water activity inside the package, creating favourable conditions for microbial growth and aflatoxin development.

Packaging materials with low water vapour transmission rate help in maintaining product dryness and extending shelf life. Aluminium laminated pouches and metallized films are highly effective moisture barriers compared with gunny bags and paper bags.

- Maintains low moisture content
- Prevents fungal growth
- Reduces aflatoxin contamination
- Maintains crispness
- Extends shelf life

Best moisture barrier materials

- Aluminium laminate
- Metallized polyester
- Polypropylene
- Vacuum pouches

2. Oxygen Barrier Property

Oxygen present inside the package causes oxidation of pigments, vitamins and flavour compounds present in dry chillies. Oxidation leads to fading of red colour and reduction in pungency during storage. Packaging materials with good oxygen barrier properties help in preserving colour and flavour quality. Vacuum packaging is highly effective because it removes oxygen from the package and minimizes oxidative deterioration. Aluminium foil laminate also provides excellent oxygen barrier protection.

Benefits of oxygen barrier

- Retains bright red colour
- Preserves capsaicin
- Maintains flavour and aroma

- Reduces oxidation
- Prevents nutrient loss

Packaging materials with good oxygen barrier

- Aluminium foil laminate
- Vacuum packaging
- Metallized films

3. Light Barrier Property

Exposure to light accelerates degradation of carotenoid pigments and vitamins present in dry chillies. Continuous exposure to sunlight causes bleaching and discoloration of the product. Packaging materials that block light help in maintaining colour stability during storage. Opaque and metallic packaging materials provide better light protection compared with transparent plastic materials.

Advantages of light barrier

- Prevents colour fading
- Maintains pigment stability
- Protects vitamins
- Improves shelf life

Light-resistant packaging materials

- Aluminium laminated films
- Metallized polyester
- Opaque pouches

Mechanical Strength

Packaging materials should possess sufficient strength to withstand handling, stacking and transportation. Weak packaging materials may tear or rupture during storage and transport, leading to product losses. Strong packaging materials help in preventing pod breakage and powder formation during movement and storage.

Importance of Mechanical Strength

- Prevents tearing and rupture during storage and transportation.
- Reduces physical damage and breakage of dry chillies.
- Improves safety during handling, stacking and transport.
- Minimizes quantitative losses during marketing and storage.

Strong Packaging Materials

- HDPE bags provide high durability and strength for bulk storage.
- Polypropylene woven sacks withstand rough handling and transportation.
- Laminated pouches offer good protection against mechanical damage.

Traditional Packaging Materials

Traditional packaging materials are still widely used in many rural areas because of their low cost and local availability. However, these materials provide limited protection against moisture and microbial contamination. The most common traditional packaging material used for dry chillies is the gunny bag made from jute fibres. These bags provide ventilation but

Gunny Bags

Gunny bags are porous bags made from jute fibres and are commonly used for bulk storage and transportation of dry chillies. They are inexpensive and biodegradable but provide very little protection against moisture and microbial contamination. Research studies observed higher moisture content and microbial infestation in chillies stored in gunny bags compared with aluminium packaging. Due to their porous nature, these bags allow easy movement of air and moisture into the package, leading to quality deterioration during storage. However, they are still commonly used because they are economical, reusable and easily available for bulk handling of dry chillies.

Advantages of gunny bags

- Low-cost packaging materials widely used for bulk storage of dry chillies.
- Easily available and commonly used in rural markets.
- Eco-friendly and biodegradable as they are made from jute fibres.
- Provide good ventilation and air circulation during storage.

Disadvantages of gunny bags

- Absorbs atmospheric moisture easily during storage.
- Provides poor protection against oxygen entry.
- Highly susceptible to fungal infestation and microbial contamination.
- Provides shorter storage life compared with modern packaging materials.

Figure 1: Packaging of dry chilli in gunny bags

Jute Bags with Polyethylene Lining

Jute bags lined with polyethylene sheets provide better protection than ordinary gunny bags. The polyethylene lining reduces moisture entry into the package and improves storage stability. These bags are commonly used for medium-term storage where economical packaging is required. The outer jute material provides strength and durability during handling and transportation, while the inner polyethylene layer acts as a protective barrier against humidity and dust. These bags help in maintaining better quality of dry chillies by reducing moisture absorption and minimizing fungal infestation during storage. They are widely preferred by farmers and traders because they are comparatively low in cost and suitable for storing bulk quantities of dry chillies.

Advantages

- Provides better resistance against moisture absorption during storage.
- Reduces fungal growth and microbial contamination.
- Economical and suitable for bulk storage purposes.
- Improves shelf life and storage stability of dry chillies.

Disadvantages

- Provides limited protection against oxygen entry.
- Less effective compared with aluminium laminated packaging.
- Polyethylene lining may tear during rough handling and transport**.**

Low Density Polyethylene (LDPE)

LDPE is one of the most commonly used plastic packaging materials for spices and dry chillies. It is flexible, lightweight and heat sealable. LDPE packaging provides moderate protection against moisture absorption and helps in maintaining product quality during storage. Studies reported that LDPE packaging performed better than gunny bags in preserving chilli quality.

Advantages of LDPE

- Low cost packaging material suitable for commercial use.
- Provides good resistance against moisture absorption.
- Easy to handle, seal and transport during storage.
- Suitable for retail packaging of dry chillies and chilli powder.

Disadvantages of LDPE

- Provides poor protection against oxygen entry.
- Offers limited resistance against light exposure.
- Less suitable for long-term storage compared with advanced packaging materials**.**

High Density Polyethylene (HDPE)

HDPE is stronger and more durable than LDPE because of its higher density. It provides better moisture resistance and mechanical strength. HDPE bags are commonly used for bulk packaging and transportation of dry chillies. These bags can withstand rough handling and stacking during storage and transport without tearing easily. HDPE packaging also helps in reducing moisture absorption and maintaining the quality of dry chillies for a longer period. Because of their durability and reusability, HDPE bags are widely preferred in commercial storage and marketing of spices.

Advantages of HDPE

- Provides high strength and resistance to tearing during storage.
- More durable and reusable compared with ordinary plastic materials.
- Offers improved protection against moisture absorption.
- Suitable for bulk storage and transportation of dry chillies.

Disadvantages of HDPE

- Provides only moderate protection against oxygen entry.
- Less flexible compared with LDPE packaging materials.
- Offers limited protection against light exposure during storage.

Polypropylene (PP)

Polypropylene is another widely used packaging material for dry chilli storage. It provides better strength and moisture resistance compared with LDPE. Polypropylene woven sacks are commonly used in commercial chilli storage. Research findings indicated better retention of pungency and colour in polypropylene packaging compared with ordinary plastic materials. These bags are durable and suitable for bulk handling during transportation and storage. Polypropylene packaging also offers better resistance to tearing and mechanical damage under commercial storage conditions.

Advantages of Polypropylene

- Provides high tensile strength and resistance to mechanical damage.
- Offers good protection against moisture absorption during storage.
- More durable and suitable for repeated handling and transport.
- Suitable for long-term storage of dry chillies and spice products.

Disadvantages of Polypropylene

- Costlier than LDPE packaging materials.
- Provides only moderate protection against oxygen permeability.

Aluminium Laminated Packaging

Aluminium laminated packaging materials are considered the best packaging systems for dry chilli storage because of their excellent barrier properties. These materials prevent entry of moisture, oxygen and light into the package. Studies reported that aluminium films retained maximum ascorbic acid, oleoresin and colour values during storage. They also help in reducing microbial growth and minimizing aflatoxin contamination during long-term storage. Aluminium laminated pouches maintain the natural aroma, pungency and overall quality of dry chillies more effectively than traditional packaging materials. Because of their superior protective properties, these packaging materials are widely preferred for export-quality chilli storage and high-value spice products.

Advantages of aluminium laminate

- Provides excellent protection against moisture absorption.
- Offers superior barrier against oxygen entry during storage.
- Gives complete protection from light exposure and colour fading.
- Reduces fungal growth and microbial contamination effectively.
- Extends shelf life and maintains quality of dry chillies for longer periods.

Disadvantages

- Higher cost compared with conventional packaging materials.
- Difficult to recycle because of multilayer laminated structure.

Metallized Polyester Polyethylene (MPP)

Metallized polyester films are prepared by coating thin metallic layers on polyester materials. These packaging materials provide excellent barrier properties and attractive appearance. MPP packaging is widely used in export-oriented spice industries because it maintains product quality for longer periods. These films effectively reduce moisture and oxygen transmission, thereby preserving colour and pungency during storage. Their glossy appearance and good sealing properties also improve consumer appeal and market value of packaged dry chillies.

Advantages

- Good barrier properties
- Attractive appearance
- Better shelf life
- Suitable for export packaging

Disadvantages

- Expensive
- Less biodegradable

Vacuum Packaging

Vacuum packaging involves removal of air from the package before sealing. Removal of oxygen slows down oxidation and microbial growth during storage. Vacuum packaging is highly effective in maintaining colour, pungency and flavour of dry chillies. Research findings showed that vacuum-packed chilli powder retained higher capsanthin and capsaicin content during storage.

Advantages of vacuum packaging

- Reduces oxygen content
- Preserves colour
- Maintains pungency

- Extends shelf life
- Reduces microbial growth

Disadvantages

- Expensive equipment required
- Higher packaging cost

Figure 2: Vacuum package

Effect of Packaging Materials on Quality Parameters

Packaging materials greatly influence the quality characteristics of dry chillies during storage. Better packaging materials maintain moisture, colour, pungency and microbial safety more effectively. Improper packaging results in rapid deterioration and reduced market value. Suitable packaging helps in preserving important quality compounds such as capsaicin, oleoresin and capsanthin for longer periods. Good packaging materials also reduce post-harvest losses and improve the shelf life and consumer acceptability of dry chillies.

Quality parameters affected

- Moisture content
- Colour value
- Capsaicin content
- Oleoresin content
- Ascorbic acid
- Microbial infestation

1. Effect on Moisture Content

Moisture increase during storage is one of the major causes of spoilage in dry chillies. Packaging materials with poor barrier properties absorb moisture from the atmosphere and increase water activity inside the package. Aluminium laminated films and vacuum packaging showed minimum moisture increase during storage compared with gunny bags.

Effects of high moisture

- Fungal growth

- Aflatoxin contamination
- Insect infestation
- Colour deterioration

2. Effect on Colour Retention

Bright red colour is one of the most important quality characteristics of dry chillies. Exposure to oxygen, light and moisture causes degradation of capsanthin pigments. Packaging materials with better oxygen and light barrier properties maintain colour stability for longer periods. Aluminium laminated films and vacuum packaging are highly effective in preserving the natural red colour during storage. Improper packaging results in fading, dull appearance and reduction in market value of the produce. Maintaining colour quality is especially important in export markets where bright red chillies receive higher consumer preference and better prices.

Best materials for colour retention

- Aluminium laminate
- Vacuum pouches
- Metallized films

Poor materials for colour retention

- Gunny bags
- Paper bags

3. Effect on Capsaicin and Oleoresin

Capsaicin is responsible for pungency while oleoresin contributes to flavour and industrial value. Improper storage conditions reduce capsaicin and oleoresin content during storage. Vacuum packaging and aluminium laminate retained higher capsaicin and oleoresin levels compared with conventional packaging.

Importance of capsaicin and oleoresin

- Determines pungency
- Increases market value
- Important for spice industries
- Used in oleoresin extraction

4. Effect on Microbial Infestation

Improper packaging increases the risk of fungal and bacterial contamination during storage. High moisture conditions favour fungal growth and toxin production. Aluminium laminated packaging and vacuum packaging effectively minimized microbial infestation during storage.

Common storage fungi

- *Aspergillus flavus*
- *Aspergillus parasiticus*
- *Penicillium* species

Effects of microbial growth

- Spoilage
- Toxin production
- Reduced export quality

Aflatoxin Management through Packaging

Aflatoxins are toxic compounds produced by fungi under high humidity conditions. Aflatoxin contamination is one of the major problems in dry chilli export trade. Packaging materials with high moisture barrier properties reduce fungal activity and help in minimizing aflatoxin development. Studies reported that aluminium packaging effectively reduced aflatoxin contamination during storage.

Factors promoting aflatoxin formation

- High humidity
- Poor drying
- Damaged pods
- Improper packaging

Methods to reduce aflatoxin

- Proper drying
- Moisture-proof packaging
- Cool storage
- Hygienic handling

Conclusion

Packaging plays a vital role in preserving the quality and extending the shelf life of dry chillies. Traditional packaging materials such as gunny bags are economical but provide limited protection against moisture and microbial contamination. Modern packaging systems including LDPE, HDPE, polypropylene, aluminium laminate and vacuum packaging provide better barrier protection and maintain important quality parameters such as colour, pungency and oleoresin.

Among all packaging materials, aluminium laminated films and vacuum packaging were found most effective in maintaining storage stability and minimizing fungal contamination and aflatoxin development. Proper packaging combined with suitable drying and storage conditions significantly reduces post-harvest losses and improves market quality of dry chillies.

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THE EXTENSION SERVICES IN ADVANCING ORGANIC FARMING: A GLOBAL PERSPECTIVE

Payal Choudhary[1], Laksheeta Chauhan[1] and Sunil Kumar Sharma[2]
[1]Department of Extension Education, Rajasthan College of Agriculture, MPUAT, Udaipur
[2]SMS, Krishi Vigyan Kendra, Pokaran

Abstract

Agricultural extension plays a pivotal role in facilitating the adoption of sustainable organic farming practices by bridging the knowledge gap between research institutions and farmers. Organic farming has emerged as a viable alternative to conventional agriculture, promoting soil health, biodiversity conservation, and reduced dependency on synthetic inputs while ensuring long-term productivity and environmental sustainability. This review highlights the critical role of agricultural extension in strengthening organic farming through participatory learning approaches, digital interventions, market-oriented strategies, and policy support mechanisms. Key extension strategies include farmer field schools, demonstration plots, ICT-based advisory services, and the development of efficient organic value chains. These approaches enhance farmers' knowledge, skills, and decision-making abilities, thereby improving the adoption of sustainable agricultural practices. However, several challenges hinder the widespread implementation of organic farming, including limited awareness, complex certification procedures, inadequate market access, weak institutional support, and insufficient technical expertise among extension personnel. Addressing these constraints requires a multi-stakeholder approach that integrates research institutions, government agencies, private sector actors, and farmer-led organizations. Strengthening the linkage between research, extension, and farmers is essential to ensure the effective transfer of innovations and best practices. Simplification of certification systems, particularly through Participatory Guarantee Systems (PGS), along with improved market infrastructure, can further enhance farmers' participation in organic farming. Future efforts should focus on digital extension tools, climate-smart organic practices, participatory research approaches, and institutional reforms. Strengthening agricultural extension systems will accelerate the transition toward a resilient, sustainable, and economically viable organic farming ecosystem.

Keywords: Agricultural Extension, Organic Farming, Sustainable Agriculture, Knowledge Transfer, Certification Process.

1. Introduction

Agricultural extension plays a fundamental role in transforming traditional farming systems into sustainable, resource-efficient, and climate-resilient agricultural practices. In recent decades, increasing concerns over environmental degradation, soil fertility decline, and the adverse effects of chemical-intensive agriculture have accelerated the global shift toward sustainable farming systems. Among these, organic farming has gained considerable attention as a holistic approach that integrates ecological balance, biodiversity conservation, and reduced reliance on synthetic inputs (Lorenz & Lal, 2022).

The successful transition to organic agriculture requires a strong foundation of scientific knowledge, technological innovations, and institutional support. Agricultural extension systems serve as a critical interface between research institutions and farming communities, ensuring that advancements in organic farming are effectively disseminated and adopted at the grassroots level (Arowosegbe *et al.,* 2024). Through advisory services, training programs, and field demonstrations, extension agencies facilitate the adoption of improved farming practices, enhance farmers' technical skills, and provide access to market information and certification procedures. Organic farming is grounded in ecological principles such as maintaining soil fertility through organic inputs, promoting biological pest control, and minimizing environmental pollution (Kumari *et al.,* 2023). Despite its numerous benefits, the adoption of organic farming remains limited, particularly among smallholder farmers, due to several challenges. These include lack of awareness, inadequate technical knowledge, market uncertainties, and the complexity of certification processes. Agricultural extension plays a crucial role in addressing these challenges by providing targeted interventions that support farmers throughout the transition process.

Extension services employ diverse approaches such as farmer field schools, participatory rural appraisal, on-farm demonstrations, and digital advisory platforms to enhance farmers' knowledge and skills (Osumba *et al.,* 2021). These approaches not only improve technical competence but also foster confidence among farmers to adopt innovative practices. One of the major constraints in organic farming adoption is the lack of technical expertise in areas such as soil fertility management, composting, crop diversification, and integrated pest management. Extension programs address this gap through capacity-building initiatives, including training workshops, field demonstrations, and collaborative research activities (Chowdhury *et al.,* 2014).

Additionally, extension services assist farmers in navigating organic certification systems by providing guidance on compliance requirements and promoting accessible certification mechanisms such as Participatory Guarantee Systems (PGS) (Kaufmann *et al.,* 2023). Market access is another critical factor influencing the adoption of organic farming. Without proper market linkages, farmers may not receive premium prices for their produce. Extension services play a vital role in developing organic value chains, facilitating direct farmer-consumer linkages, and promoting cooperatives and producer organizations to enhance market access (Bisht *et al.,* 2021). Furthermore, extension professionals contribute to policy advocacy by highlighting the needs of farmers and supporting the formulation of favorable policies, subsidies, and financial incentives (Moojen *et al.,* 2024). The concept of extension originates from the Latin words *'ex'* (out) and *'tensio'* (to stretch), meaning the dissemination of knowledge beyond institutional boundaries. Extension education is a continuous learning process that empowers farmers to make informed decisions based on their local conditions. It plays a vital role in promoting sustainable agriculture by integrating traditional knowledge with modern scientific innovations (Sithole *et al.,* 2024).

In the modern era, the integration of Information and Communication Technologies (ICTs), including mobile applications, remote sensing, and digital advisory systems, has significantly enhanced the effectiveness of extension services (Sindhu & Sindhu, 2017). Additionally, the incorporation of climate-smart practices such as agroforestry, crop rotation, and vermicomposting further strengthens the resilience of organic farming systems. A comprehensive and farmer-centric extension approach is therefore essential to ensure the successful adoption and sustainability of organic agriculture (Chiwaridzo *et al.,* 2024).

2. Concept of Sustainable Agriculture

Sustainable agriculture has emerged as a holistic approach to addressing the growing challenges of food security, environmental degradation, and climate change. With the increasing global population, the demand for food, fiber, and energy continues to rise, placing immense pressure on natural resources. Sustainable agriculture seeks to balance productivity with environmental conservation and social well-being (Hossain *et al.,* 2020). The concept gained global recognition following the Brundtland Report (1987), which defined sustainable development as meeting present needs without compromising the ability of future generations to meet their own needs. In the agricultural context, sustainable agriculture refers to an integrated system of plant and animal production practices that maintain soil health, conserve water resources, reduce environmental pollution, and ensure long-term economic viability.

Key principles of sustainable agriculture include efficient use of natural resources, conservation of biodiversity, reduction in chemical inputs, and promotion of ecological balance. Practices such as conservation tillage, crop rotation, agroforestry, organic farming, and integrated pest management are widely adopted to achieve sustainability goals.

3. Significance of Sustainable Agriculture

Sustainable agriculture plays a critical role in ensuring food security while preserving environmental integrity and improving farmers' livelihoods. It aims to produce sufficient quantities of food, feed, fiber, and energy to meet the needs of a growing population without degrading natural resources.

One of the primary objectives of sustainable agriculture is environmental conservation. By reducing chemical inputs and promoting natural resource management, it helps maintain soil fertility, improve water quality, and protect biodiversity. Sustainable practices also contribute to mitigating climate change by reducing greenhouse gas emissions and enhancing carbon sequestration. Economically, sustainable agriculture ensures the long-term viability of farming systems by optimizing resource use and reducing input costs. It enhances farmers' resilience to market fluctuations and climatic uncertainties. Socially, it improves the quality of life for farmers and rural communities by promoting equitable resource distribution, employment opportunities, and food safety.

4. The role of Extension Services in Sustainable Agriculture Development

Extension education plays a fundamental role in promoting sustainable agriculture by fostering knowledge dissemination, capacity building, and technology adoption. Its significance can be highlighted in the following areas:

4.1 Dissemination of Knowledge

Agricultural extension services serve as a crucial conduit for the effective dissemination of knowledge related to sustainable agricultural practices. They facilitate the transfer of scientifically validated information from research institutions to farmers, thereby enabling the adoption of innovative, resource-efficient, and environmentally sound farming techniques. This includes comprehensive guidance on soil health management through practices such as integrated nutrient management, use of organic amendments, and soil testing. Additionally, extension systems promote crop diversification strategies that enhance farm resilience and reduce dependency on monocropping systems. Farmers are also educated on efficient water management practices, including micro-irrigation, rainwater harvesting, and moisture conservation techniques. Furthermore, extension personnel play a vital role in popularizing organic farming approaches that minimize chemical inputs and promote ecological balance.

4.2 Capacity Building and Skill Development

Capacity building is a fundamental pillar of agricultural extension, focusing on enhancing the technical competencies and practical skills of farmers. Through structured training programs, field demonstrations, farmer field schools, and exposure visits, extension services equip farmers with hands-on experience in sustainable agricultural practices. These include organic pest management using biological control agents, preparation and application of compost and vermicompost, and adoption of conservation agriculture principles such as minimum tillage and residue retention. Such skill development initiatives not only improve farm productivity but also strengthen farmers' adaptive capacity in the face of climate variability and environmental stress. By fostering experiential learning, extension services empower farmers to make informed decisions and adopt location-specific best practices.

4.3 Promoting Adoption of Organic Farming

Organic farming represents a cornerstone of sustainable agriculture, emphasizing the maintenance of ecological equilibrium, enhancement of biodiversity, and reduction in the use of synthetic agrochemicals. Agricultural extension services play a pivotal role in facilitating the transition from conventional to organic farming systems. They provide technical guidance on the preparation and use of organic inputs such as biofertilizers, biopesticides, and botanical extracts. Extension agents also assist farmers in understanding crop rotations, intercropping systems, and integrated nutrient management practices that are essential for sustaining soil fertility. In addition, awareness campaigns and demonstration plots are organized to showcase the long-term economic and environmental benefits of organic agriculture. By addressing farmers' concerns and reducing uncertainties, extension services significantly accelerate the adoption of organic farming practices.

4.4 Conservation of the Environment

Environmental conservation is intrinsically linked to sustainable agricultural development, and extension education plays a vital role in fostering ecological awareness among farmers. By promoting practices that reduce soil erosion, prevent land degradation, and minimize pollution, extension services contribute to the preservation of natural resources. Farmers are encouraged to adopt integrated pest management (IPM) strategies that reduce reliance on chemical pesticides, thereby protecting beneficial organisms and maintaining ecological balance. Additionally, the judicious use of fertilizers and water resources is emphasized to prevent contamination of soil and water bodies. Through these efforts, extension services support the development of environmentally sustainable farming systems that ensure long-term productivity and ecosystem health.

4.5 Adaptation to Climate Change

Climate change poses significant challenges to agricultural sustainability, including increased frequency of droughts, floods, and temperature extremes. Agricultural extension services play a critical role in enhancing farmers' adaptive capacity by providing timely information and practical solutions to mitigate climate-related risks. These include the promotion of climate-resilient crop varieties, improved irrigation techniques such as drip and sprinkler systems, and diversification of farming systems through agroforestry and mixed cropping. Extension systems also disseminate weather-based advisories and early warning systems that enable farmers to make proactive decisions. By integrating climate-smart agricultural practices, extension services help farmers maintain productivity while reducing vulnerability to climate change.

5. The Role of Agricultural Extension in Organic Farming

Agricultural extension plays a transformative role in advancing organic farming by bridging the gap between scientific research and on-field application. In the context of increasing environmental concerns, declining soil fertility, and rising health awareness, organic farming has emerged as a sustainable alternative that ensures ecological integrity, biodiversity conservation, and reduced dependence on synthetic inputs (Gamage *et al.,* 2023). However, the widespread adoption of organic farming is contingent upon the effectiveness of extension services in educating, motivating, and supporting farmers throughout the transition process.

Extension services function as dynamic knowledge systems that provide farmers with access to relevant information, technical expertise, and institutional support necessary for the successful implementation of organic farming practices. They employ participatory approaches, including farmer field schools, demonstration trials, and community-based learning, to enhance understanding and build confidence among farmers. Moreover, extension agents act as facilitators who connect farmers with research institutions, input suppliers, certification agencies, and markets, thereby creating an enabling ecosystem for organic agriculture. Despite their critical role, extension services face several challenges, including limited resources, inadequate training of personnel, and lack of region-specific technologies. Addressing these constraints requires strengthening institutional frameworks, integrating digital tools such as mobile-based advisory services, and promoting public-private partnerships. Opportunities also exist in leveraging indigenous knowledge systems and integrating them with modern scientific approaches to enhance the effectiveness of organic farming practices.

5.1 Farmer Awareness and Training

Extension services organize awareness campaigns and training programs to educate farmers about organic inputs, soil fertility management, and eco-friendly pest control methods. These initiatives emphasize the long-term benefits of organic agriculture, including improved soil health, reduced input costs, and enhanced market value of produce.

5.2 Technology Transfer and Adoption

Extension agencies facilitate the transfer of validated organic farming technologies, such as vermicomposting, crop rotation, use of biofertilizers, and green manuring. They also promote integrated organic farming systems that optimize resource utilization and enhance farm sustainability.

5.3 Organic Certification and Compliance Support

Obtaining organic certification is often a complex and resource-intensive process. Extension services assist farmers in understanding certification requirements, documentation procedures, and compliance standards. They also promote Participatory Guarantee Systems (PGS) as an accessible and cost-effective certification mechanism for smallholder farmers.

5.4 Market Linkages and Value Addition

Extension services play a vital role in connecting farmers with organic markets, retail outlets, and export channels. They encourage value addition through processing, branding, and labeling of organic products, thereby enhancing farmers' income and market competitiveness.

5.5 Policy Advocacy and Institutional Support

Extension organizations engage with policymakers to advocate for supportive policies that promote organic agriculture. They also facilitate access to government schemes, subsidies, and institutional support systems, ensuring that farmers receive the necessary resources to sustain organic farming practices.

6. Extension Strategies for Organic Farming Promotion

For the large-scale adoption of organic farming, agricultural extension systems must adopt innovative, inclusive, and farmer-centric strategies. Traditional top-down approaches are no longer sufficient to address the diverse needs of farmers in the context of sustainability and climate change. Instead, extension services must integrate participatory methods, digital tools, and market-oriented interventions to effectively promote organic agriculture. These strategies aim not only to enhance awareness but also to ensure long-term adoption, economic viability, and ecological sustainability of organic farming systems.

6.1 Participatory Extension Approaches

Participatory extension approaches emphasize the active involvement of farmers in the learning and decision-making process. This farmer-led model recognizes farmers as co-creators of knowledge rather than mere recipients of information. Extension agents collaborate closely with organic farmers, farmer producer organizations (FPOs), cooperatives, and local communities to promote context-specific solutions. One of the most effective tools under this approach is the Farmer Field School (FFS), which provides experiential learning opportunities where farmers gain practical knowledge by engaging directly in field-based activities. Through regular sessions, farmers observe crop growth, pest dynamics, and soil health, enabling them to make informed management decisions. Demonstration plots further strengthen this approach by showcasing successful organic farming practices under real field conditions, thereby increasing farmers' confidence in adopting such practices.

Additionally, knowledge-sharing networks and farmer groups play a vital role in facilitating peer-to-peer learning. Farmers exchange experiences, innovations, and indigenous knowledge, which enhances the collective capacity of the community. This participatory framework not only improves adoption rates but also fosters a sense of ownership and empowerment among farmers.

6.2 Digital and ICT-Based Extension

The integration of Information and Communication Technologies (ICTs) into extension services has revolutionized the dissemination of agricultural information. Digital tools enable extension systems to reach a wider audience efficiently and provide real-time, location-specific advisories to farmers practicing organic agriculture. Mobile applications and SMS-based services are increasingly being used to deliver timely information on organic farming practices, pest and disease management, weather forecasts, and market prices. These platforms ensure that farmers receive critical information even in remote areas with limited access to conventional extension services.

Furthermore, online training modules, e-learning platforms, and webinars have emerged as effective tools for capacity building. Farmers can access expert knowledge, training videos, and best practice guidelines at their convenience, thereby overcoming geographical and logistical barriers. Advanced technologies such as Artificial Intelligence (AI), remote sensing, and Geographic Information Systems (GIS) are also being integrated into organic farming. These technologies support precision agriculture by enabling soil health monitoring, crop growth assessment, and early detection of pest infestations. As a result, farmers can make data-driven decisions that enhance productivity while maintaining organic standards.

6.3 Market-led Extension Approaches

Market-oriented extension strategies are essential for ensuring the economic sustainability of organic farming. Without assured markets and fair pricing, farmers may hesitate to transition from conventional to organic systems. Extension services, therefore, play a crucial role in developing and strengthening organic value chains. This involves linking farmers with domestic and international organic markets, retail outlets, and export agencies. By facilitating direct market access, extension systems help farmers secure better prices for their produce. The promotion of contract farming arrangements and organic cooperatives further enables farmers to engage in bulk marketing, reduce transaction costs, and improve bargaining power.

Moreover, extension services encourage the establishment of direct farm-to-market linkages, such as farmers' markets, community-supported agriculture (CSA), and online marketing platforms. These initiatives minimize the role of intermediaries, ensuring that a larger share of profits reaches the farmers. Value addition through processing, branding, and packaging of organic products is also promoted to enhance market competitiveness and consumer appeal.

6.4 Capacity Building for Extension Personnel

The effectiveness of extension strategies largely depends on the competence and preparedness of extension personnel. Therefore, continuous capacity building of extension workers is essential to equip them with the necessary knowledge and skills in organic farming. Regular training programs should be organized to familiarize extension agents with organic farming principles, certification standards, and emerging technologies. This includes training on soil fertility management, organic pest control, biodiversity conservation, and climate-resilient practices. Cross-learning initiatives, such as exposure visits and collaborative programs with organic farming experts, research institutions, and progressive farmers, further enhance the practical understanding of extension personnel. Such interactions enable extension agents to stay updated with the latest advancements and innovative practices in organic agriculture.

In addition, strengthening institutional support and encouraging interdisciplinary collaboration can significantly improve the efficiency of extension services. Well-trained and motivated extension personnel act as catalysts in promoting organic farming, ensuring effective knowledge transfer, and building trust among farming communities.

7. Role of Agricultural Extension in Promoting Organic Farming for Sustainable Agriculture

Organic farming has emerged as a vital component of sustainable agriculture, providing an eco-friendly and resource-conserving alternative to conventional farming systems. In the face of increasing environmental degradation, soil fertility decline, and health concerns associated with excessive agrochemical use, organic farming offers a pathway toward long-term agricultural sustainability. Agricultural extension plays a pivotal role in accelerating the adoption of organic farming by equipping farmers with the necessary knowledge, technical skills, and institutional support required for this transition (Arowosegbe *et al.,* 2024).

Extension services act as a dynamic interface between research institutions and farming communities, ensuring that scientific advancements are translated into practical applications. Through continuous guidance, training, and advisory support, extension systems enable farmers to adopt organic practices effectively while maintaining productivity and profitability. Furthermore, extension services facilitate access to markets, certification systems, and government schemes, thereby creating a supportive ecosystem for organic agriculture. The integration of extension mechanisms into organic farming not only enhances farm-level sustainability but also contributes to broader environmental conservation and rural development goals.

7.1 Enhancing Soil Fertility and Nutrient Management through Extension Services

Maintaining soil fertility without the use of synthetic fertilizers remains one of the major challenges in organic farming. Agricultural extension services play a crucial role in addressing this issue by promoting natural and sustainable nutrient management practices. Farmers are educated on the use of organic inputs such as farmyard manure (FYM), vermicompost, green manure, crop residues, and biofertilizers (Khan & Kwot, 2024). These organic amendments improve soil structure, enhance water-holding capacity, and stimulate microbial activity, which collectively contribute to improved nutrient availability and long-term soil health. Extension personnel organize field demonstrations, training sessions, and workshops to illustrate the preparation and application of these inputs. By providing hands-on experience, farmers gain confidence in replacing chemical fertilizers with organic alternatives.

Additionally, extension services promote integrated nutrient management approaches that combine organic sources with locally available resources, ensuring cost-effectiveness and sustainability. Soil testing and site-specific nutrient management are also encouraged to optimize input use and maintain soil productivity over time.

7.2 Sustainable Crop Management Strategies through Extension Education

Efficient crop management is essential for achieving stable yields in organic farming systems. Agricultural extension services provide farmers with scientifically validated knowledge on sustainable crop management practices such as crop rotation, intercropping, mixed cropping, and cover cropping (Chouhan *et al.,* 2023). Crop rotation, for instance, helps break pest and disease cycles, improves soil fertility, and reduces nutrient depletion. Intercropping and mixed cropping enhance biodiversity within the farming system, leading to better resource utilization and natural pest suppression. Extension agents work closely with farmers to design cropping systems tailored to local agro-climatic conditions, soil types, and market demands.

Moreover, extension services emphasize the importance of biological pest management techniques, including the use of natural predators, botanical pesticides, and biocontrol agents. Farmers are trained to monitor pest populations and adopt preventive measures rather than relying on chemical interventions. This holistic approach ensures sustainable crop production while preserving ecological balance.

7.3 Integrating Animal Husbandry into Organic Farming Systems

The integration of animal husbandry with crop production is a fundamental principle of organic farming, contributing significantly to nutrient recycling and farm sustainability. Livestock serve as a valuable source of organic manure, which enhances soil fertility and supports crop growth. Additionally, animal-based products such as milk, meat, eggs, and wool provide supplementary income to farmers, thereby improving their livelihoods (Nardone *et al.,* 2004). Agricultural extension services play a key role in promoting integrated farming systems by training farmers in sustainable livestock management practices. This includes guidance on organic feed production, proper housing, animal health care, and disease prevention using non-chemical methods. Extension agents also educate farmers on maintaining animal welfare standards, which is a critical aspect of organic certification. By encouraging the integration of crops and livestock, extension services help create closed-loop farming systems where farm resources are efficiently utilized, and external inputs are minimized. This not only enhances farm productivity but also ensures environmental sustainability and economic resilience for farming communities.

7.4 Market Linkages and Certification Support through Agricultural Extension

One of the major constraints in the adoption of organic farming is the limited access to reliable markets and the complexity of certification procedures. Agricultural extension services play a crucial role in overcoming these barriers by facilitating market linkages and guiding farmers through certification systems. Extension programs assist farmers in understanding the requirements of organic certification, including documentation, inspection, and compliance with established standards. Particularly, extension agencies promote the Participatory Guarantee System (PGS), which serves as a cost-effective and farmer-friendly certification mechanism for smallholders. Through PGS and organic labeling, farmers can differentiate their produce in the market and obtain premium prices (Niederle *et al.,* 2020).

Moreover, extension personnel act as intermediaries who connect farmers with various market channels, including local organic markets, retail outlets, bulk purchasers, and export agencies. By establishing direct linkages between producers and consumers, extension services help reduce the role of intermediaries and ensure better price realization. This market-oriented extension approach significantly enhances the economic viability and long-term sustainability of organic farming systems.

7.5 Training, Capacity Building, and Policy Support

The success and sustainability of organic farming largely depend on continuous learning and skill enhancement. Agricultural extension services are instrumental in organizing training programs, workshops, field demonstrations, and farmer field schools that provide practical exposure to organic farming techniques. These initiatives focus on areas such as organic input preparation, soil fertility management, pest control through biological methods, and integrated farming practices. In addition to technical training, extension services contribute to strengthening institutional and policy frameworks that support organic agriculture. Extension agents often collaborate with government bodies, research institutions, and non-governmental organizations (NGOs) to design and implement region-specific organic farming models suited to local agro-climatic conditions.

Furthermore, extension systems play an advocacy role by highlighting the needs and challenges of organic farmers to policymakers. They support the formulation of favorable policies, including subsidies, incentives, and financial assistance schemes that encourage farmers to adopt organic practices. Such coordinated efforts ensure that farmers receive not only technical knowledge but also institutional backing for sustainable agriculture.

7.6 Strengthening Organic Farming through Extension Services

Agricultural extension services are central to strengthening organic farming systems by integrating knowledge dissemination, technology transfer, and market facilitation. They bridge the critical gap between scientific research and practical field application, ensuring that farmers can effectively implement organic practices. Extension educators empower farmers by providing timely information, hands-on training, and continuous advisory support, which enhances their confidence and decision-making capacity. As a result, farmers are better equipped to improve soil health, optimize resource use, and maintain ecological balance while sustaining productivity (Adnan *et al.,* 2018).

With the growing global demand for organic products, the role of extension services becomes even more significant in transforming traditional agricultural practices into sustainable and profitable organic enterprises. Strengthening extension systems through capacity building, digital integration, and institutional support will be essential to ensure long-term agricultural sustainability and resilience.

8. Integration of Organic Farming with Agricultural Extension Services

The integration of organic farming with agricultural extension services represents a holistic and multi-dimensional approach to sustainable agricultural development. Organic farming is not merely a set of practices but a comprehensive system that requires coordinated efforts across training, diagnostics, certification, and market development to achieve long-term success (Addai *et al.,* 2024). Agricultural extension services play a pivotal role in facilitating this integration by guiding farmers through each stage of the organic farming process. They provide training and advisory services that equip farmers with knowledge on sustainable agricultural practices, including soil fertility management, organic pest control, and crop diversification. These services ensure that farmers are well-prepared to adopt and sustain organic farming systems. Another critical component of this integration is diagnostic support, which includes soil testing, residue analysis, and quality assessment. Extension agencies help farmers understand soil health parameters and ensure that their produce meets organic standards. This is essential for maintaining the integrity and credibility of organic products in the market.

9. Challenges in Promoting Sustainable Agriculture through Extension Services

Despite the significant contributions of agricultural extension services in advancing sustainable agriculture, several structural and operational challenges hinder their effectiveness. Addressing these constraints is essential to ensure that extension systems can deliver meaningful and long-lasting impacts at the grassroots level. One of the primary challenges is the limitation of financial resources. Many extension programs operate under constrained budgets, which restricts their ability to expand outreach, conduct regular training programs, and adopt modern technologies. Insufficient funding also affects the availability of demonstration units, field visits, and capacity-building initiatives, ultimately reducing the quality-of-service delivery.

Another critical issue is the shortage of trained and skilled extension personnel. The success of extension services largely depends on the technical expertise, communication skills, and field experience of extension agents. However, in many regions, there is a lack of adequately trained professionals who possess specialized knowledge in sustainable and organic farming practices. This gap limits the effective transfer of technology and reduces farmers' confidence in adopting new practices. In addition, inadequate rural infrastructure, including poor transportation networks, limited access to digital connectivity, and insufficient institutional support, hampers the efficient delivery of extension services. These infrastructural constraints make it difficult for extension personnel to reach remote areas and provide timely advisory services. Collectively, these challenges highlight the need for strengthening extension systems to effectively promote sustainable agriculture.

10. Strategies for Enhancing Extension Services in Sustainable Agriculture

To overcome existing challenges and maximize the effectiveness of extension services, a combination of strategic interventions is required. These strategies should focus on strengthening institutional capacity, improving service delivery, and fostering collaboration among stakeholders. Investment in extension education and infrastructure is crucial for improving the reach and quality of services. Increased funding can support the recruitment and training of skilled personnel, establishment of demonstration units, and integration of modern technologies into extension systems. Strengthening human resources will enhance the ability of extension agents to deliver accurate and timely information to farmers.

Adopting localized and context-specific approaches is equally important. Extension programs must be tailored to the agro-climatic conditions, socio-economic status, and cultural practices of farmers. Location-specific recommendations ensure that farmers receive practical and relevant solutions, thereby increasing the likelihood of adoption. Public-private partnerships (PPPs) offer a promising avenue for enhancing the scope and impact of extension services. Collaboration among government agencies, research institutions, non-governmental organizations (NGOs), and private sector entities can facilitate resource sharing, technological innovation, and wider outreach. Such partnerships can also improve access to markets, inputs, and financial services for farmers. The utilization of digital technologies has become increasingly important in modern extension systems. Mobile applications, online advisory platforms, and digital communication tools enable the rapid dissemination of information and provide real-time support to farmers. These technologies help bridge the gap between extension agents and farmers, particularly in remote areas.

Furthermore, incorporating participatory approaches ensures that farmers are actively involved in the planning and implementation of extension programs. By engaging farmers in decision-making processes, extension services can better address their specific needs, challenges, and aspirations. This participatory model fosters trust, enhances knowledge exchange, and promotes the sustainable adoption of agricultural innovations.

11. Future Aspects of Agricultural Extension in Organic Farming

The future of agricultural extension in organic farming will be shaped by the integration of advanced technologies, farmer-centric approaches, and supportive policy frameworks. As global demand for organic products continues to grow, extension services must evolve to address emerging challenges and leverage new opportunities for sustainable agricultural development.

11.1 Digitalization and ICT Integration

The adoption of Information and Communication Technologies (ICTs) is expected to revolutionize agricultural extension systems. Digital tools such as mobile-based advisory services, artificial intelligence (AI)-driven decision support systems, and remote sensing technologies will enable the delivery of precise, real-time recommendations to farmers. These innovations can assist in soil health monitoring, pest and disease forecasting, and efficient resource management (Sharma & Shivandu, 2024). Online learning platforms, mobile applications, and social media networks will further enhance knowledge dissemination by connecting farmers with experts, researchers, and market stakeholders. This digital transformation will make extension services more accessible, efficient, and responsive to farmers' needs.

11.2 Climate-Smart Organic Farming

In the context of climate change, future extension programs must prioritize climate-smart organic farming practices. Approaches such as agroecology, integrated pest management, crop diversification, and water conservation will play a critical role in enhancing resilience against climatic uncertainties (Altieri *et al.,* 2015). Extension personnel must be trained in climate adaptation and mitigation strategies to guide farmers in managing risks associated with extreme weather events. By promoting sustainable resource management, extension services can help ensure long-term agricultural productivity and environmental stability.

11.3 Strengthening Participatory Extension Approaches

Participatory extension models will gain greater prominence in the future, particularly in organic farming systems. Farmer-led initiatives such as Farmer Field Schools (FFS), participatory research, and community-based learning platforms will empower farmers to actively engage in innovation and decision-making processes. Strengthening farmer cooperatives, self-help groups, and producer organizations will further enhance collective learning, knowledge sharing, and bargaining power in organic markets. These approaches foster a sense of ownership among farmers and improve the sustainability of extension interventions.

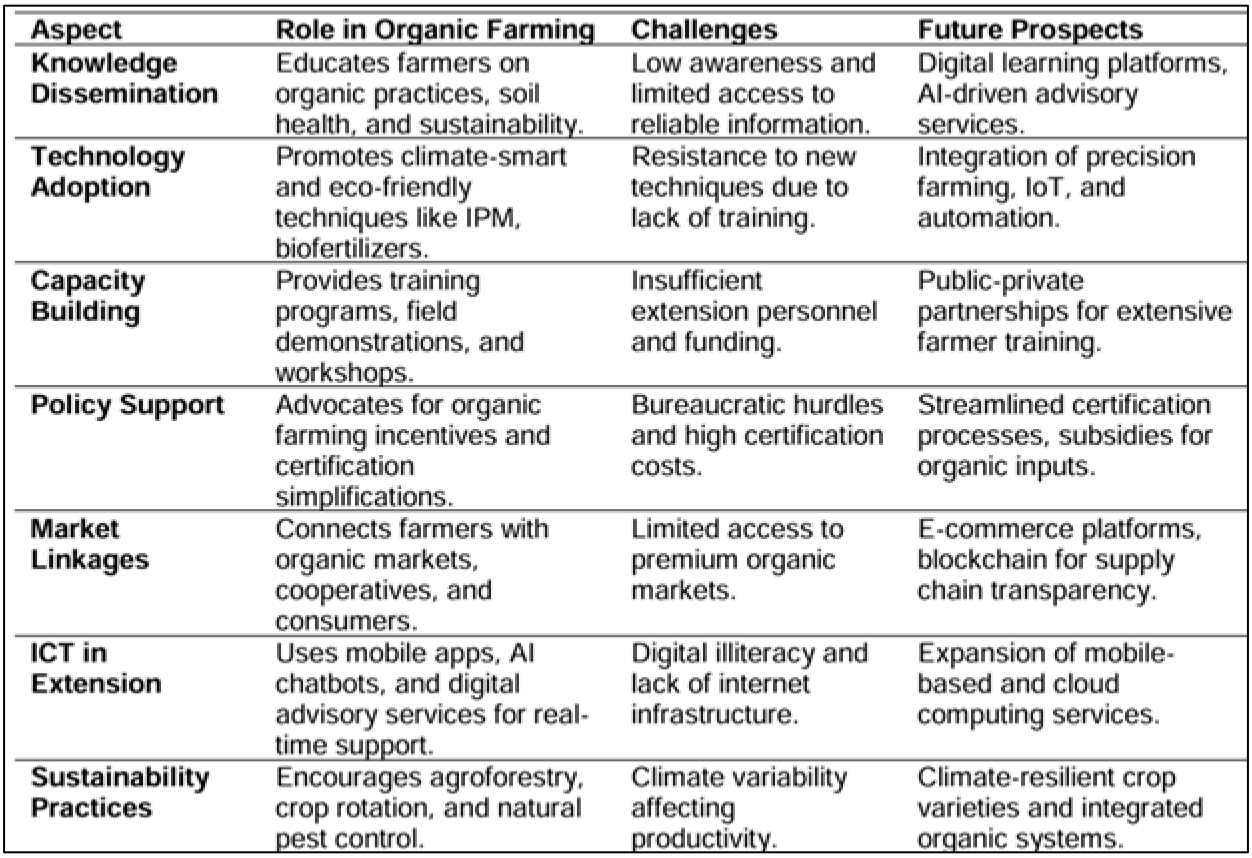
11.4 Simplification of Organic Certification and Market Linkages

Simplifying certification processes will be a key priority for promoting organic farming among smallholder farmers. Extension services should focus on expanding Participatory Guarantee Systems (PGS), which provide a cost-effective and accessible certification mechanism (Taranov & Kawabata, 2024). Additionally, strengthening organic value chains through direct market linkages, e-commerce platforms, organic fairs, and contract farming arrangements will enhance farmers' access to premium markets. These initiatives will improve income generation and incentivize farmers to adopt organic practices.

11.5 Policy Support and Institutional Frameworks

Supportive policy frameworks and strong institutional mechanisms will be essential for the future growth of organic farming. Governments, extension agencies, and research institutions must collaborate to design policies that provide financial incentives, subsidies, and technical support to organic farmers. Investments in research and development, capacity building of extension personnel, and infrastructure development will further strengthen extension systems. A well-coordinated institutional framework will ensure that extension services effectively promote sustainable and organic agriculture, contributing to food security, environmental conservation, and rural development.

Table 1: Key aspects of agricultural extension in organic farming



Aspect	Role in Organic Farming	Challenges	Future Prospects
Knowledge Dissemination	Educates farmers on organic practices, soil health, and sustainability.	Low awareness and limited access to reliable information.	Digital learning platforms, AI-driven advisory services.
Technology Adoption	Promotes climate-smart and eco-friendly techniques like IPM, biofertilizers.	Resistance to new techniques due to lack of training.	Integration of precision farming, IoT, and automation.
Capacity Building	Provides training programs, field demonstrations, and workshops.	Insufficient extension personnel and funding.	Public-private partnerships for extensive farmer training.
Policy Support	Advocates for organic farming incentives and certification simplifications.	Bureaucratic hurdles and high certification costs.	Streamlined certification processes, subsidies for organic inputs.
Market Linkages	Connects farmers with organic markets, cooperatives, and consumers.	Limited access to premium organic markets.	E-commerce platforms, blockchain for supply chain transparency.
ICT in Extension	Uses mobile apps, AI chatbots, and digital advisory services for real-time support.	Digital illiteracy and lack of internet infrastructure.	Expansion of mobile-based and cloud computing services.
Sustainability Practices	Encourages agroforestry, crop rotation, and natural pest control.	Climate variability affecting productivity.	Climate-resilient crop varieties and integrated organic systems.

Conclusion

As organic agriculture continues to gain global prominence due to its environmental sustainability, economic viability, and health benefits, the importance of a robust, efficient, and farmer-centric agricultural extension system becomes increasingly evident. Extension services serve as a critical bridge between research innovations and field-level implementation, ensuring that farmers are equipped with the knowledge, skills, and resources necessary to transition toward sustainable agricultural systems. The concept emphasized in *"Insights into Agricultural Extension"* underscores the vital role of knowledge dissemination, technology transfer, and capacity building in promoting resilient and eco-friendly farming practices.

A key dimension of organic farming lies in the adoption of climate-smart agricultural practices such as crop diversification, agroforestry, integrated pest management, and sustainable soil and water management. These approaches not only enhance farm productivity but also strengthen resilience against climate variability and environmental stress. Agricultural extension services must prioritize the promotion of such practices through participatory learning methods, including farmer field schools, on-farm demonstrations, and experiential training programs, thereby enabling farmers to make informed and context-specific decisions. In addition, the integration of Information and Communication Technologies (ICTs) into extension systems represents a transformative opportunity to improve outreach and efficiency. Digital tools such as mobile applications, online advisory platforms, and e-learning modules can provide real-time, location-specific information to farmers, thereby bridging knowledge gaps and enhancing decision-making capabilities. The use of advanced technologies, including artificial intelligence and remote sensing, further strengthens precision in organic farming practices and resource management. Policy support also plays a decisive role in accelerating the adoption of organic agriculture. The integration of organic farming into national agricultural policies, along with the provision of financial incentives, subsidies, and simplified certification mechanisms, can significantly encourage farmers to adopt sustainable practices. Strengthening Participatory Guarantee Systems (PGS) and streamlining certification processes will reduce barriers for small and marginal farmers.

Furthermore, enhancing market linkages and promoting farmer cooperatives are essential for ensuring the economic sustainability of organic farming. Extension services must facilitate direct connections between farmers and markets, support value addition, and encourage collective action to improve bargaining power and profitability. Looking ahead, the future of agricultural extension in organic farming depends on the adoption of farmer-led participatory approaches, climate-resilient technologies, and innovative digital solutions. A collaborative framework involving policymakers, researchers, extension professionals, and farmers is crucial to addressing existing challenges such as certification complexities, limited market access, and knowledge constraints. By strengthening extension systems and fostering an integrated approach, it is possible to achieve sustainable agricultural development that balances productivity, environmental conservation, and socio-economic well-being.

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CULTIVATION OF *PLEUROTUS ERYNGII*: SUSTAINABLE TECHNOLOGY AND NUTRITIONAL IMPORTANCE

Vijay Kumar*[1] and Ashok Chhetri[2]
[1]Department of Plant Pathology,
[2]Department of Fruit Science,
Multi Technology Testing Centre & Vocational Training Centre, College of Fisheries,
Central Agricultural University (Imphal), Lembucherra, Agartala- 799210, Tripura, India
*Corresponding author E-mail: vnarwal777@yahoo.com

1. Introduction

Mushroom cultivation represents a sustainable and eco-friendly biotechnological approach for converting agricultural wastes into high-value, protein-rich food. Among edible mushrooms, *Pleurotus eryngii*, commonly known as King Oyster mushroom or Kabul Dhingri, is highly valued for its superior culinary qualities, thick stipe, meaty texture, and extended shelf life. It is increasingly gaining popularity in subtropical and temperate regions due to its high economic potential and adaptability. *Nutritionally*, *Pleurotus eryngii* is rich in proteins, essential amino acids, vitamins, minerals, and dietary fiber while being low in fat, making it an excellent functional food. In addition to its dietary importance, its cultivation contributes significantly to environmental sustainability. According to Savoie and Largeteau (2011), mushroom cultivation enhances food security while efficiently converting lignocellulosic waste into edible biomass. Similarly, Carrasco *et al.* (2018) emphasized its role in circular economy systems by transforming agricultural residues such as straw, sawdust, and maize cobs into valuable products. Furthermore, *Pleurotus eryngii* exhibits strong bioremediation potential, helping detoxify polluted soils and water. The spent mushroom substrate (SMS) remains enzymatically active and can be utilized as a biofertilizer, contributing to sustainable agriculture (Philippoussis, 2009). From a socio-economic perspective, its cultivation offers low-cost, high-return opportunities for smallholders, landless farmers, and women, thus supporting rural livelihoods (Royse *et al.*, 2017). Additionally, cultivation reduces dependence on wild mushroom collection, aiding biodiversity conservation (Boa, 2004).

2. General Characteristics of *Pleurotus eryngii*

Pleurotus eryngii is distinguished from other oyster mushrooms by its thick, fleshy stipe and relatively smaller cap. It exhibits moderate growth compared to other *Pleurotus* species but is preferred due to its higher market value and longer shelf life. The fungus is saprophytic and efficiently degrades lignocellulosic substrates, making it suitable for cultivation on various agricultural wastes.

3. Cultivation Technology of *Pleurotus eryngii*

The cultivation of *Pleurotus eryngii* follows a systematic sequence involving pure culture preparation, spawn production, substrate preparation, spawning, incubation, and harvesting.

Although similar to other oyster mushrooms, this species requires slightly more controlled environmental conditions for optimal production.

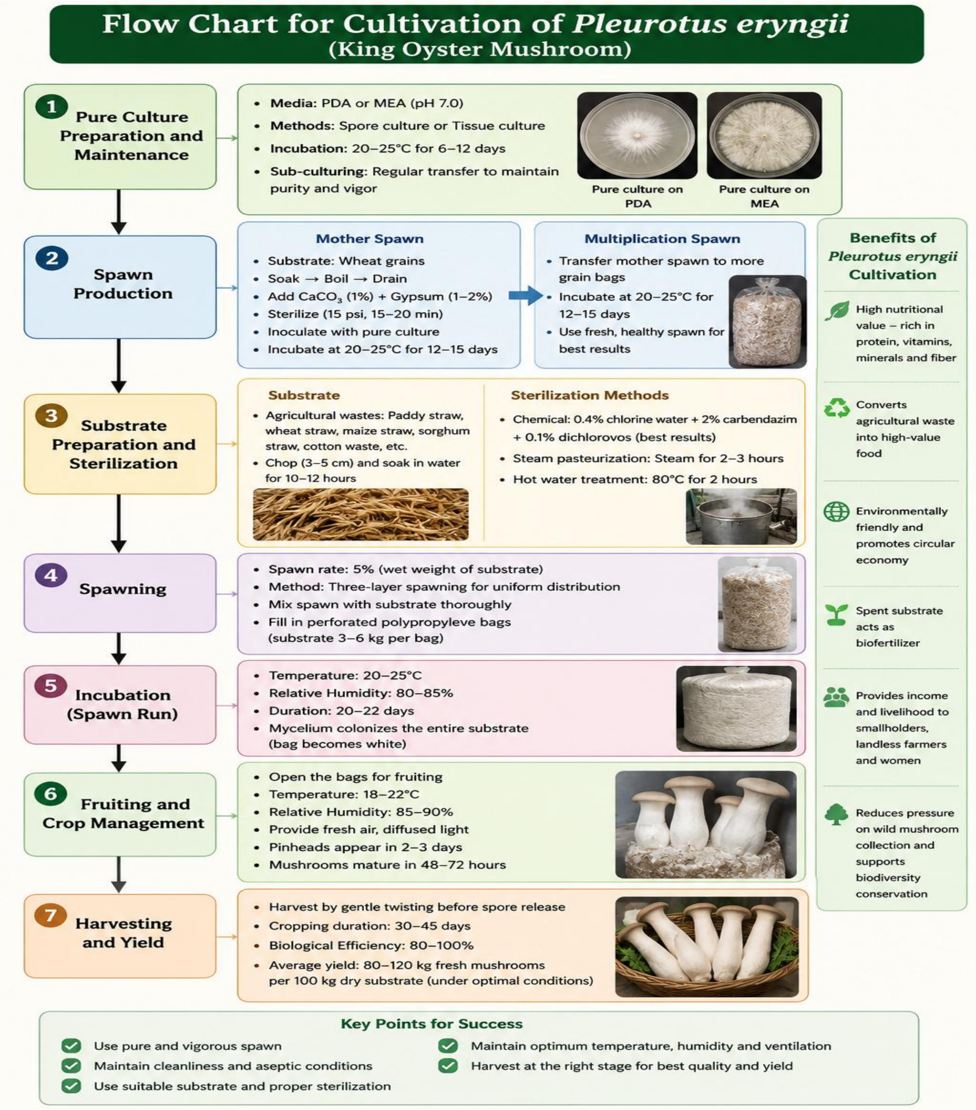
3.1 Pure Culture Preparation and Maintenance: The cultivation process begins with the preparation of pure culture on nutrient media such as Potato Dextrose Agar (PDA) or Malt Extract Agar (MEA). These media are prepared by dissolving respective components in water, adjusting pH to 7.0, and sterilizing at 15 psi for 15–20 minutes. Pure cultures are obtained using spore culture or tissue culture techniques. In tissue culture, a small piece of inner mushroom tissue is aseptically transferred onto the medium, ensuring genetic uniformity. Cultures are incubated at 20–25°C for 6–12 days. Regular sub-culturing is essential to maintain vigor and prevent degeneration (Moonmoon *et al.,* 2010; Chang & Miles, 1992).

3.2 Spawn Production: Spawn serves as the planting material and consists of actively growing mycelium on cereal grains such as wheat. Grains are soaked, boiled, and mixed with calcium carbonate and gypsum to maintain pH and prevent clumping. The grains are sterilized and inoculated with pure culture under aseptic conditions. After incubation at 20–25°C for about two weeks, the grains become fully colonized, forming mother spawn. Spawn is multiplied for cultivation; quality shows uniform white growth, no contamination, and firm grain texture (Moonmoon *et al.,* 2010).

3.3 Substrate Preparation and Sterilization: The success of *Pleurotus eryngii* cultivation largely depends on substrate quality. Common substrates include paddy straw, wheat straw, maize straw, sorghum straw, cotton waste, and supplemented substrates such as wheat straw with bran. Studies have shown that paddy straw provides the highest biological efficiency (88.4%), while maize straw supports faster colonization (Deora *et al.,* 2021; Philippoussis *et al.,* 2001; Zervakis *et al.,* 2001). Substrate sterilization is a critical step to eliminate competing microorganisms. Chemical sterilization using chlorine water, carbendazim, and dichlorovos has been reported as highly effective, yielding superior biological efficiency (Deora *et al.,* 2021; Mejia & Alberto, 2012). Alternatively, steam pasteurization and hot water treatment can also be used depending on the scale of cultivation.

3.4 Spawning: Spawning involves mixing spawn with the prepared substrate at an optimal rate of around 5% (wet weight), which has been found to provide the best results in terms of yield and colonization speed (Ram & Pant, 2004; Fan *et al.,* 2000). The three-layer spawning method is commonly used to ensure uniform distribution of spawn within the substrate. The spawned substrate is filled into perforated polypropylene bags and incubated under controlled conditions.

3.5 Incubation and Crop Management: The incubation phase is carried out at 20–25°C with relative humidity of 80–85%. During this period, the mycelium colonizes the substrate completely within 20–22 days. After full colonization, the bags are opened to initiate fruiting. Environmental conditions are then adjusted to promote fruit body development, typically maintaining temperatures of 18–22°C and relative humidity of 85–90%. Proper ventilation and diffused light are essential for uniform growth. Pinheads appear within 2–3 days, and mature mushrooms develop within 48–72 hours (Deora *et al.,* 2021; Gregori *et al.,* 2007).



Flow Chart for Cultivation of *Pleurotus eryngii*
(King Oyster Mushroom)

1 Pure Culture Preparation and Maintenance

- **Media:** PDA or MEA (pH 7.0)
- **Methods:** Spore culture or Tissue culture
- **Incubation:** 20–25°C for 6–12 days
- **Sub-culturing:** Regular transfer to maintain purity and vigor

Pure culture on PDA

Pure culture on MEA

2 Spawn Production

Mother Spawn

- Substrate: Wheat grains
- Soak → Boil → Drain
- Add $CaCO_3$ (1%) + Gypsum (1–2%)
- Sterilize (15 psi, 15–20 min)
- Inoculate with pure culture
- Incubate at 20–25°C for 12–15 days

Multiplication Spawn

- Transfer mother spawn to more grain bags
- Incubate at 20–25°C for 12–15 days
- Use fresh, healthy spawn for best results

3 Substrate Preparation and Sterilization

Substrate

- Agricultural wastes: Paddy straw, wheat straw, maize straw, sorghum straw, cotton waste, etc.
- Chop (3–5 cm) and soak in water for 10–12 hours

Sterilization Methods

- Chemical: 0.4% chlorine water + 2% carbendazim + 0.1% dichlorovos (best results)
- Steam pasteurization: Steam for 2–3 hours
- Hot water treatment: 80°C for 2 hours

4 Spawning

- Spawn rate: 5% (wet weight of substrate)
- Method: Three-layer spawning for uniform distribution
- Mix spawn with substrate thoroughly
- Fill in perforated polypropyleve bags (substrate 3–6 kg per bag)

5 Incubation (Spawn Run)

- Temperature: 20–25°C
- Relative Humidity: 80–85%
- Duration: 20–22 days
- Mycelium colonizes the entire substrate (bag becomes white)

6 Fruiting and Crop Management

- Open the bags for fruiting
- Temperature: 18–22°C
- Relative Humidity: 85–90%
- Provide fresh air, diffused light
- Pinheads appear in 2–3 days
- Mushrooms mature in 48–72 hours

7 Harvesting and Yield

- Harvest by gentle twisting before spore release
- Cropping duration: 30–45 days
- Biological Efficiency: 80–100%
- Average yield: 80–120 kg fresh mushrooms per 100 kg dry substrate (under optimal conditions)

Benefits of *Pleurotus eryngii* Cultivation

- High nutritional value – rich in protein, vitamins, minerals and fiber
- Converts agricultural waste into high-value food
- Environmentally friendly and promotes circular economy
- Spent substrate acts as biofertilizer
- Provides income and livelihood to smallholders, landless farmers and women
- Reduces pressure on wild mushroom collection and supports biodiversity conservation

Key Points for Success

- ☑ Use pure and vigorous spawn
- ☑ Maintain cleanliness and aseptic conditions
- ☑ Use suitable substrate and proper sterilization
- ☑ Maintain optimum temperature, humidity and ventilation
- ☑ Harvest at the right stage for best quality and yield

3.6 Harvesting and Yield: Harvesting is performed by gently twisting the fruiting bodies before spore release to maintain quality and shelf life. The cropping cycle lasts approximately 30–45 days under optimal conditions. The yield depends on substrate type, spawn quality, and environmental management. Biological efficiency can reach up to 90–100% under ideal conditions, with higher productivity achieved using optimized substrate and spawn rates (Deora *et al.*, 2021).

Conclusion

The cultivation of *Pleurotus eryngii* represents a sustainable and economically viable agricultural practice that integrates waste recycling, environmental conservation, and food production. Its high nutritional value, market demand, and adaptability make it an important crop for modern agriculture. With proper management of cultivation parameters, it offers significant potential for income generation, especially for small-scale farmers and rural communities. Furthermore, its role in circular economy systems, biodiversity conservation, and bioremediation highlights its importance in sustainable development.

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ROLE OF ARTIFICIAL INTELLIGENCE IN SMART SUSTAINABLE AGRICULTURE

S. G. Yadav
Department of Botany,
Shivaji Mahavidyalaya, Renapur -413527 Dist. Latur (MS) INDIA
Corresponding author E-mail: dryadavsg@gmail.com

Abstract

Agriculture is one of the most important sectors supporting human civilization and economic development. However, modern agriculture faces multiple challenges such as climate change, declining soil fertility, water scarcity, pest infestations, labor shortages, and increasing food demand due to rapid population growth. Traditional agricultural practices alone are insufficient to ensure sustainable food production and environmental conservation. In recent years, Artificial Intelligence (AI) has emerged as a revolutionary technology capable of transforming conventional agriculture into smart agriculture. Smart agriculture involves the integration of AI with digital technologies such as the Internet of Things (IoT), machine learning, robotics, drones, cloud computing, and remote sensing to improve agricultural productivity, efficiency, and sustainability. AI enables farmers to make accurate and data-driven decisions related to irrigation, fertilization, disease management, crop monitoring, and yield prediction. AI-based systems can analyze large volumes of agricultural data, automate farming operations, reduce wastage of resources, and improve crop quality. The application of AI in agriculture also supports climate-resilient farming and sustainable resource management. This paper discusses the concept of AI in smart agriculture, major technologies involved, applications, advantages, challenges, and future prospects. The study highlights the importance of AI-driven agriculture in achieving food security, environmental sustainability, and rural development. The paper is descriptive and theoretical in nature and aims to provide a comprehensive understanding of the transformative role of AI in modern agriculture.

Keywords: Artificial Intelligence, Smart Agriculture, Precision Farming, IoT, Machine Learning, Sustainable Agriculture, Crop Monitoring, Digital Farming.

1. Introduction

Agriculture has always played a crucial role in the survival and progress of human civilization. It is not only the primary source of food but also an important contributor to economic development, employment generation, and industrial growth. In developing countries like India, agriculture supports the livelihood of millions of people and contributes significantly to national income. Despite technological progress in many sectors, agriculture still faces numerous problems that affect productivity and sustainability.

The increasing global population has created tremendous pressure on agricultural systems to produce more food using limited natural resources. Simultaneously, climate change, soil degradation, water scarcity, pest outbreaks, and environmental pollution have emerged as serious threats to agricultural productivity. Traditional farming methods often rely heavily on manual labor, excessive chemical usage, and conventional irrigation techniques, which are becoming increasingly inefficient and unsustainable.

In this context, technological innovations are becoming essential for the modernization of agriculture. Artificial Intelligence (AI) has emerged as one of the most significant technological advancements capable of transforming the agricultural sector. AI refers to the ability of machines and computer systems to simulate human intelligence processes such as learning, reasoning, problem-solving, and decision-making. AI systems can analyze large volumes of data, identify patterns, and provide intelligent recommendations for various agricultural activities.

The integration of AI into agriculture has led to the development of smart agriculture, also known as digital or intelligent farming. Smart agriculture uses advanced technologies such as sensors, drones, robotics, machine learning, remote sensing, and IoT devices to collect and analyze agricultural data in real time. These technologies help farmers improve productivity, optimize resource utilization, minimize environmental impacts, and reduce operational costs.

AI-based smart agriculture is transforming traditional farming into a precise, efficient, and sustainable system. Farmers can now monitor crop health, detect diseases early, automate irrigation systems, predict weather conditions, manage pests effectively, and optimize harvesting schedules using AI-driven technologies. Moreover, AI supports climate-resilient agriculture by helping farmers adapt to changing environmental conditions.

The application of AI in agriculture is rapidly expanding across the world. Governments, research institutions, agricultural universities, and private companies are investing heavily in AI-driven agricultural technologies. In countries like India, AI has immense potential to improve the livelihoods of smallholder farmers and strengthen food security.

This paper aims to provide a descriptive and theoretical overview of the role of Artificial Intelligence in smart agriculture. The paper discusses major AI technologies, applications, benefits, challenges, and future opportunities associated with AI-driven agricultural systems.

2. Concept of Artificial Intelligence in Agriculture

Artificial Intelligence is a branch of computer science that focuses on developing machines and systems capable of performing tasks that normally require human intelligence. AI systems can learn from data, analyze information, recognize patterns, and make decisions with minimal human intervention. In agriculture, AI is used to improve farming operations by providing intelligent solutions based on data analysis and predictive modeling. AI technologies help farmers understand field conditions, monitor crop growth, optimize agricultural inputs, and improve productivity. The concept of AI in agriculture is closely associated with smart agriculture or precision farming. Smart agriculture involves the use of advanced digital technologies to monitor and manage agricultural activities more accurately and efficiently. AI acts as the central decision-making system in smart agriculture by analyzing data collected from various sources such as sensors, drones, satellites, weather stations, and mobile applications.

AI in agriculture mainly focuses on the following objectives:

- Improving crop productivity
- Conserving water and natural resources
- Reducing production costs
- Enhancing crop quality
- Minimizing environmental pollution
- Increasing farm profitability
- Supporting sustainable agriculture

The development of AI-based agricultural systems has become possible due to advancements in computing power, internet connectivity, cloud computing, and data analytics. Modern farms generate enormous amounts of data related to soil conditions, temperature, humidity, crop health, rainfall, and pest infestations. AI systems process this information and convert it into actionable recommendations for farmers. Thus, AI has become an essential component of modern agricultural systems aimed at increasing efficiency and sustainability.

3. Smart Agriculture and Its Components

Smart agriculture refers to technology-based farming systems that use digital tools and intelligent devices for agricultural management. It combines information technology with agricultural practices to create efficient and sustainable farming systems.

The major components of smart agriculture include:

3.1 Internet of Things (IoT)

The Internet of Things refers to interconnected devices capable of collecting and exchanging data through the internet. In agriculture, IoT devices include soil sensors, weather stations, smart irrigation systems, and automated machinery.

These devices continuously monitor field conditions and provide real-time information regarding:

Soil moisture, Temperature, Humidity, Nutrient levels, Crop growth

The collected data are analyzed using AI algorithms to support agricultural decision-making.

3.2 Machine Learning

Machine learning is a subset of AI that enables computer systems to learn from data and improve performance over time without explicit programming.

In agriculture, machine learning is used for:

- Disease identification
- Yield prediction
- Weather forecasting
- Weed detection
- Soil analysis

Machine learning models become more accurate as they process larger datasets.

3.3 Drones and Remote Sensing

Agricultural drones equipped with cameras and sensors capture aerial images of fields. AI analyzes these images to detect crop stress, disease symptoms, and irrigation requirements.

Remote sensing technologies provide valuable information regarding:

- Crop health
- Soil conditions
- Water availability
- Pest infestations

3.4 Robotics

AI-powered robots are increasingly used for planting, harvesting, spraying pesticides, and removing weeds. Agricultural robots reduce labor dependency and improve operational efficiency.

3.5 Cloud Computing

Cloud computing enables the storage and processing of agricultural data on remote servers. Farmers can access farm information through smartphones and computers from any location.

Cloud-based AI systems provide:

- Real-time monitoring
- Data storage
- Decision support
- Predictive analytics

Thus, smart agriculture integrates multiple technologies to create intelligent farming systems capable of improving productivity and sustainability.

4. Applications of AI in Smart Agriculture

Artificial Intelligence has numerous applications in agriculture that are transforming farming practices worldwide.

4.1 Precision Farming

Precision farming is one of the most important applications of AI in agriculture. It involves site-specific crop management based on field variability.

AI systems analyze data related to soil fertility, moisture levels, and crop conditions to optimize agricultural inputs such as fertilizers, pesticides, and water.

Precision farming helps in:

- Increase crop yields
- Reduce input costs
- Minimize environmental pollution
- Improve resource efficiency

4.2 Crop Monitoring

AI-powered crop monitoring systems continuously observe crop growth and field conditions. Drones, sensors, and satellite images are used to collect agricultural data.

AI algorithms analyze this information to detect:

- Nutrient deficiencies
- Water stress
- Disease symptoms
- Pest attacks

Early detection enables timely intervention and prevents crop losses.

4.3 Disease Detection

Plant diseases significantly affect agricultural productivity. AI-based image recognition systems can identify diseases at early stages by analyzing leaf images and crop patterns. Machine learning models trained on thousands of plant images can accurately diagnose diseases in crops such as, Rice, Wheat, Tomato, Cotton and Maize.

AI-based disease detection reduces excessive pesticide usage and improves crop quality.

4.4 Smart Irrigation

Water scarcity is a major agricultural challenge. AI-based irrigation systems optimize water usage by analyzing soil moisture levels, weather forecasts, and crop water requirements.

- Smart irrigation systems:
- Prevent over-irrigation
- Conserve water
- Reduce electricity consumption
- Improve crop growth

These systems are especially beneficial in drought-prone regions.

4.5 Weather Forecasting

Climate variability greatly influences agricultural productivity. AI models analyze meteorological data to provide accurate weather predictions.

Farmers receive information regarding:

- Rainfall
- Temperature
- Humidity
- Storms
- Drought conditions
- Weather forecasting helps farmers plan agricultural activities more effectively.

4.6 Yield Prediction

AI systems predict crop yields based on historical data, weather conditions, and field management practices.

- Yield prediction helps:
- Agricultural planning
- Market management
- Storage preparation
- Food supply estimation

4.7 Weed Management

AI-powered computer vision systems can differentiate weeds from crops. Automated sprayers apply herbicides only where needed.

This approach:

- Reduces chemical usage
- Protects the environment
- Lowers production costs

4.8 Livestock Management

AI technologies are also applied in livestock farming for monitoring animal health and productivity. Smart livestock systems use sensors and wearable devices to monitor:

- Body temperature
- Feeding behavior
- Movement patterns
- Milk production
- AI helps improve animal welfare and farm profitability.

5. Advantages of AI in Agriculture

The integration of AI into agriculture offers several advantages that contribute to sustainable farming and food security.

5.1 Improved Productivity: AI technologies optimize agricultural operations and increase crop yields through precise management.

5.2 Resource Conservation: AI reduces excessive use of water, fertilizers, and pesticides by enabling targeted applications.

5.3 Reduced Labor Dependency: Automation reduces dependence on manual labor and improves operational efficiency.

5.4 Early Detection of Problems: AI identifies diseases, pest infestations, and nutrient deficiencies before severe damage occurs.

5.5 Better Decision-Making: AI systems provide data-driven recommendations for agricultural management.

5.6 Environmental Protection: Reduced chemical usage and efficient resource management help minimize environmental pollution.

5.7 Climate Resilience: AI supports climate-smart agriculture by helping farmers adapt to changing environmental conditions.

6. Challenges of AI in Smart Agriculture

Despite its advantages, AI adoption in agriculture faces several challenges.

6.1 High Initial Cost: AI technologies such as drones, sensors, and robotics require significant investment, making them less accessible to small farmers.

6.2 Lack of Technical Knowledge: Many farmers lack awareness and technical skills required to operate AI-based systems.

6.3 Poor Internet Connectivity: Rural areas often have inadequate internet infrastructure, limiting smart agriculture adoption.

6.4 Data Management Issues: AI systems require large volumes of accurate data. Poor-quality data can reduce system effectiveness.

6.5 Privacy and Security Concerns: Agricultural data sharing raises concerns regarding ownership, privacy, and cyber security.

6.6 Small Land Holdings: Fragmented land holdings in countries like India make mechanization and AI implementation difficult.

6.7 Dependence on Technology: Excessive dependence on automated systems may create operational problems during technical failures.

Therefore, successful implementation of AI in agriculture requires supportive policies, infrastructure development, farmer training, and affordable technologies.

7. Role of AI in Sustainable Agriculture:

Sustainable agriculture aims to meet present food needs without compromising the ability of future generations to meet their own requirements. AI contributes significantly to sustainable agricultural development.

AI supports sustainability through:

- Efficient water management
- Reduced chemical usage
- Soil conservation
- Energy efficiency
- Climate adaptation
- Biodiversity protection

AI-driven precision farming minimizes wastage of agricultural inputs and reduces environmental degradation. Smart irrigation conserves water resources, while AI-based disease management reduces excessive pesticide application.

AI also promotes climate-resilient agriculture by helping farmers adapt to unpredictable weather patterns and environmental stresses. Thus, AI has become an important tool for achieving sustainable agricultural development and global food security.

8. Future Prospects of AI in Agriculture:

The future of AI in agriculture is highly promising. Rapid advancements in machine learning, robotics, IoT, cloud computing, and satellite technologies are expected to further revolutionize farming systems.

Future agricultural developments may include:

- Fully autonomous farms
- AI-powered agricultural robots
- Smart greenhouses
- Advanced climate prediction systems
- Real-time pest surveillance
- Precision breeding technologies

The development of affordable AI tools and mobile applications will enable smallholder farmers to access smart farming technologies. Governments and research institutions are increasingly investing in digital agriculture projects aimed at strengthening food security and agricultural sustainability.AI is expected to play a crucial role in addressing future agricultural challenges associated with population growth, climate change, and resource scarcity.

Conclusion

Artificial Intelligence has emerged as a transformative technology capable of revolutionizing modern agriculture. The integration of AI with smart agricultural systems has improved productivity, resource efficiency, sustainability, and decision-making processes. AI-based technologies such as machine learning, IoT, drones, robotics, and remote sensing are transforming traditional farming into intelligent and data-driven agriculture.

AI applications in precision farming, crop monitoring, disease detection, smart irrigation, weather forecasting, and livestock management demonstrate enormous potential for improving agricultural productivity and environmental sustainability. These technologies help farmers optimize agricultural inputs, reduce production costs, minimize environmental pollution, and improve crop quality.

Despite several challenges such as high costs, poor infrastructure, lack of technical knowledge, and data management issues, AI adoption in agriculture continues to expand globally. Governments, research institutions, and private organizations are actively promoting digital agriculture and smart farming technologies.

In countries like India, AI has tremendous potential to support smallholder farmers, improve rural livelihoods, and strengthen food security. Future advancements in AI and related technologies are expected to create highly efficient, climate-resilient, and sustainable agricultural systems capable of meeting the food demands of the growing global population.

Therefore, Artificial Intelligence is not merely a technological innovation in agriculture but a vital tool for achieving sustainable agricultural development and ensuring global food security in the twenty-first century.

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FLUDIOXONIL RESISTANCE IN BLUE MOLD PATHOGEN

Ramesh Baviskar

Department of Botany,

ICLES' Motilal Jhunjhunwala College, Vashi, Navi Mumbai, MS, India.

Corresponding author E-mail: baviskar_ramesh@yahoo.co.in

Abstract

Blue mold of pears, caused by *Penicillium expansum*, leads to significant post-harvest losses worldwide. Continuous subculturing of the sensitive isolate Pe-11 on fludioxonil increased resistance to this fungicide. However, when the pathogen was alternately cultured or treated with a mixture containing fludioxonil, polyram, and dithane Z-78, its growth was completely inhibited. In contrast, treatments with kocide and acrobat did not significantly reduce fungal growth in the first passages, though a decrease was observed by the 2nd, 3rd, 4th, and 5th passages. Notably, combining fludioxonil with polyram, dithane Z-78, kocide, and acrobat resulted in a marked reduction in the development of resistance. Among the various combinations tested, dithane Z-78 was found to be the most effective. *In vivo* experiments further confirmed that applying fludioxonil in combination with polyram, dithane Z-78, kocide, and acrobat lowered disease incidence, with dithane Z-78 showing superior performance. Furthermore, applying fludioxonil alongside the mentioned fungicides significantly reduced disease resistance by the 5th passage, with acrobat showing the highest efficacy in suppressing resistance.

Keywords: Blue Mold, Pear, *Penicillium expansum*, Fludioxonil Resistance, Fungicides.

Introduction

Since the late 19th century, fungicides have been crucial in managing fungal diseases in plants. Among temperate fruit crops, pear holds significant economic importance. However, continuous use of fungicides raises concerns about the potential development of resistance. This has led researchers to explore how repeated passage on agar media using fludioxonil alone, in combination with other fungicides (such as acrobat, polyram, kocide, and dithane Z-78), or in alternating patterns might influence the development of resistance. Additionally, multiple studies have reported the development of fungal resistance to systemic fungicides (Gangawane, 1981; More, 2009; Jagtap, 2010; Sable & Gangawane, 2012).

This study specifically targeted postharvest infections in pear fruit. Diseased fruits were collected from various regions, revealing five predominant pathogens: *Rhizopus stolonifer*, *Botrytis cinerea*, *Alternaria* sp., *Aspergillus niger*, and *Aspergillus flavus*. Among these, *Penicillium expansum* was found to be the most widespread and aggressive, causing scabs across multiple cultivars and locations. Given that fludioxonil is commonly recommended for pear disease management, its potential to induce resistance was extensively investigated. Despite the increasing use of fungicides, reports of resistance in plant pathogens remain limited across crops. Hence, this study aimed to evaluate whether *Penicillium expansum* could develop resistance to fludioxonil.

Materials and Methods

The study investigated the development of resistance in sensitive *Penicillium expansum* isolates through continuous and alternating treatment with fludioxonil, a fungicide with a distinct mode of action, either alone or in combination with other fungicides. Initially, the minimum inhibitory concentration (MIC) of fludioxonil was determined for 23 isolates. For in vitro analysis, agar plates were supplemented with a sub-lethal dose of fludioxonil (754.5 µg/ml) across five successive passages to evaluate resistance development. Control plates without fungicide were used for comparison. A 5 mm mycelial disc from a 10-day-old culture was placed in the center of each plate to initiate growth. After 10 days, linear growth was measured, and resistance development was assessed by the increasing percentage of isolates capable of growth at each passage. Fludioxonil was also alternated with acrobat, polyram, dithane Z-78, and kocide in combination treatments.

In vivo studies were conducted on pears using a tissue paper fruit-wrapping method. Fruits were treated by dipping in fludioxonil alone or in combination with other fungicides and then inoculated with the sensitive isolate. For subsequent passages, the inoculum was obtained from re-isolated pathogens from the previously infected fruit. This cycle was repeated up to the fifth passage to monitor resistance progression.

Results and Discussions

In *vitro* studies

This investigation employed the sensitive isolate Pe-11. For five successive passages, Pe-11 was cultured on potato dextrose agar (PDA) medium containing lethal doses (754.5 µg/ml) of fungicides, applied either individually or in alternation with other fungicides.

As shown in Table 1, continuous culturing of *Penicillium expansum* on fludioxonil for five passages resulted in increased fungal growth, with growth progressively rising with each passage. When fludioxonil was alternated with polyram, dithane Z-78, kocide, and acrobat, varied effects were observed. Alternation with polyram initially stimulated growth up to the second passage, but a decline was seen in the 3rd, 4th, and 5th passages. In contrast, dithane Z-78 and kocide showed a consistent suppressive effect, completely inhibiting growth across all passages. When alternated with acrobat, growth increased slightly in the second passage but declined in subsequent passages.

As indicated in Table 2, continuous exposure to fludioxonil alone consistently enhanced *P. expansum* growth over all five passages. However, when fludioxonil was combined with polyram, dithane Z-78, and kocide, the combination significantly inhibited fungal growth.

Notably, when fludioxonil was combined with acrobat, growth initially increased in the second passage but then gradually decreased in the 3rd, 4th, and 5th passages.

In *vivo* studies

The sensitive isolate (Pe-11) of *Penicillium expansum* was inoculated into pears after being dipped in a fungicide concentration. After 15 days, the percentage of the infection zone diameter was measured.

The influence of continuous and alternating passage on establishing fludioxonil resistance in *Penicillium expansum* on pear. Fludioxonil was altered with polyram, dithane Z-78, kocide, and acrobat for five successive passages.

Results indicated in Table 3 that treatment of pear fruits for 5 successive passages increased the growth significantly. Similarly, the infection was also increased when fludioxonil treatment was altered with polyram in the second passage; passage 3rd, 4th, and 5th decreased the growth of *P. expansum*. In dithane Z-78, kocide, and acrobat, altered with fludioxonil, decreased the infection of all five passages.

Polyram, dithane Z-78, kocide, and acrobat were combined with fludioxonil, and pears were treated for five consecutive passages. Results shown in Table 4 that continuous use of fludioxonil with polyram, dithane Z-78, kocide, and acrobat decreased infection or inhibited the *P. expansum* in all passages except the fludioxonil treatment, continuous infection by the pathogen increased across all five passages.

All of them agree that resistant mutants emerge due to spontaneous mutation under the selection pressure of a fungicide. High resistance may develop in the *Penicillium expansum,* causing blue mold in the pear. In the present finding, fludioxonil, acrobat, polyram, kocide, and dithane Z-78 are always used to manage blue mold and other fruit diseases (Patel, 1988; Dahiwale *et al.,* 2009; Baviskar & Suryawanshi, 2011).

Fungicide administration can potentially influence the establishment of resistance in plant pathogens. On agar plates and pear fruits, the effects of repeated exposure to *Penicillium expansum* (Pe-11 isolate) on fludioxonil were examined, either alone, in rotation, or in combination with other fungicides operating via distinct mechanisms.

In this investigation, the continuous passage of sensitive isolate on fludioxonil, five successive passages increased the growth significantly at the 5th passage. This indicates the development of fludioxonil resistance in the pathogen. But culturing of the isolate alternately or in a mixture with acrobat, polyram, kocide, and dithane Z-78 completely inhibited the growth of sensitive isolate (Pe-11) on the potato dextrose agar plates and the fruits. Fungicides used alternately should have different modes of action (Griffin,1981). The current study confirmed that using different specific site-inhibiting fungicides, such as acrobat, polyram, kocide, and dithane Z-78, reduces the likelihood of resistance mutations in *Penicillium expansum*. Edifenphos may be used against

Septoria nodorum and *Cercospora herpotrichoides*, two bacteria resistant to carbendazim (Horsten, 1979). To investigate potential new applications of fungicides, proposed mathematical models (Kable & Jaffery, 1980). The pathogen in this study likely developed resistance to fludioxonil, acrobat, polyram, kocide, and dithane Z-78 in combination, as previously shown in *Macrophomina phaseolina* (Anitha *et al.,* 1989).

Table 1: Effect of continuous and alternate passage and passage on the development of fludioxonil resistance in *Penicillium expansum* on agar plate

Sr. No.	Fungicides (µg/ml)	I	II	III	IV	V
1	Fludioxonil continuous (754.5 µg/ml)	13.15	23.12	25.62	41.23	46.32
2	Fludioxonil altered Polyram	12.50	19.30	15.00	13.20	10.20
3	Fludioxonil altered Dithane	12.75	12.00	08.00	04.60	03.21
4	Fludioxonil altered Kocide	12.85	20.25	16.23	15.65	11.30
5	Fludioxonil altered Acrobat	12.15	16.10	13.00	11.23	09.36

Table 2: Effect of continuous individual passage and passage on mixed fungicide on the development of fludioxonil resistance in *Penicillium expansum* on agar plate

Sr. No.	Fungicides (µg/ml)	I	II	III	IV	V
1	Fludioxonil continuous (754.5 µg/ml)	13.15	23.25	25.90	41.60	46.94
2	Fludioxonil + Polyram	12.65	08.95	07.52	05.65	02.94
3	Fludioxonil + Dithane	10.62	09.35	08.00	04.60	03.00
4	Fludioxonil + Kocide	11.76	09.98	06.88	05.82	03.90
5	Thiophanate methyl + Acrobat	13.00	14.33	11.84	11.10	06.33

Table 3: Effect of continuous and alternate passage and passage on the development of fludioxonil resistance in *Penicillium expansum* on pear.

Sr. No.	Fungicides (µg/ml)	I	II	III	IV	V
1	Fludioxonil continuous (754.5 µg/ml)	18.95	21.00	27.25	39.10	46.75
2	Fludioxonil altered Polyram	19.15	21.75	17.12	13.50	09.85
3	Fludioxonil altered Dithane	19.75	13.50	11.25	09.90	06.25
4	Fludioxonil altered Kocide	18.95	16.78	13.50	07.95	05.15
5	Fludioxonil altered Acrobat	19.13	15.95	14.55	10.95	07.75

a - PDI as a percentage of control

* Significance of p=0.05 and p=0.01 with Wilcoxon's (1939) sum rank

Test results are compared with the first passage to those of other passages

Table 4: Effect of continuous individual passage and passage on mixed fungicide on the development of fludioxonil resistance in *Penicillium expansum* on pear

Sr. No.	Fungicides (µg/ml)	I	II	III	IV	V
1	Fludioxonil continuous (754.5 µg/ml)	19.75	21.00	28.50	39.75	47.25
2	Fludioxonil + Polyram	16.00	10.95	09.21	06.95	05.25
3	Fludioxonil + Dithane	13.50	14.10	11.50	10.25	06.50
4	Fludioxonil + Kocide	14.75	12.95	11.25	09.50	07.00
5	Fludioxonil + Acrobat	13.50	09.25	06.75	05.50	03.50

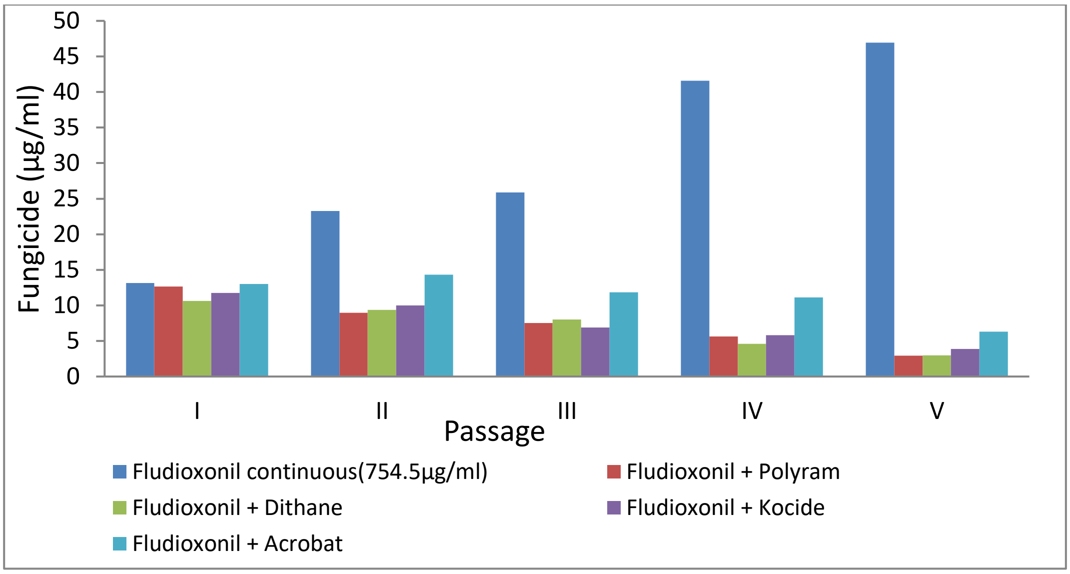

Figure 1: Effect of continuous and alternate passage and passage on the development of fludioxonil resistance in *P. expansum* on the agar plate

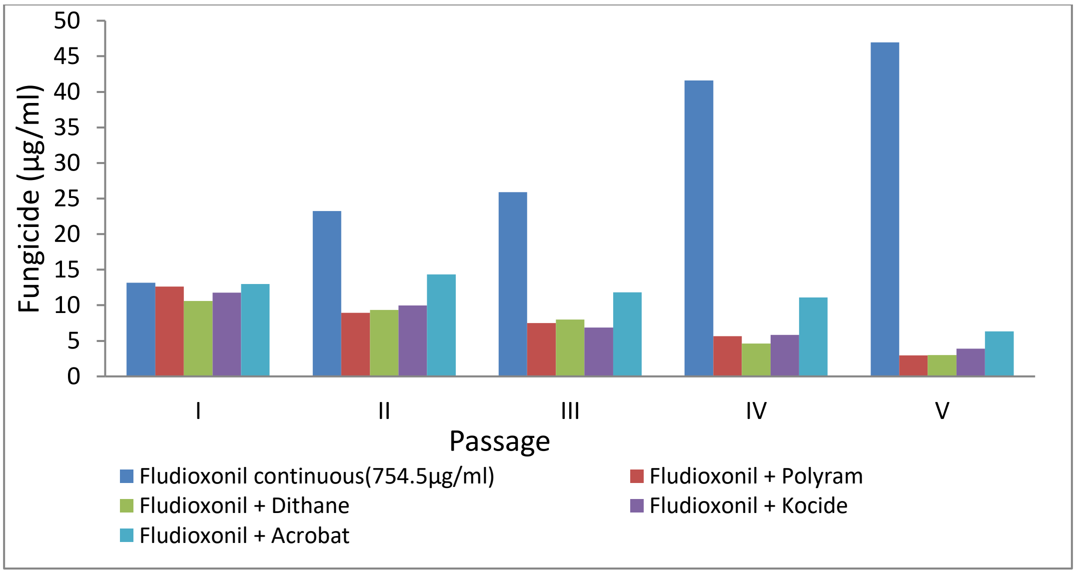

Figure 2: Effect of continuous individual passage and passage on mixed fungicide on the development of fludioxonil resistance in *P. expansum* on an agar plate

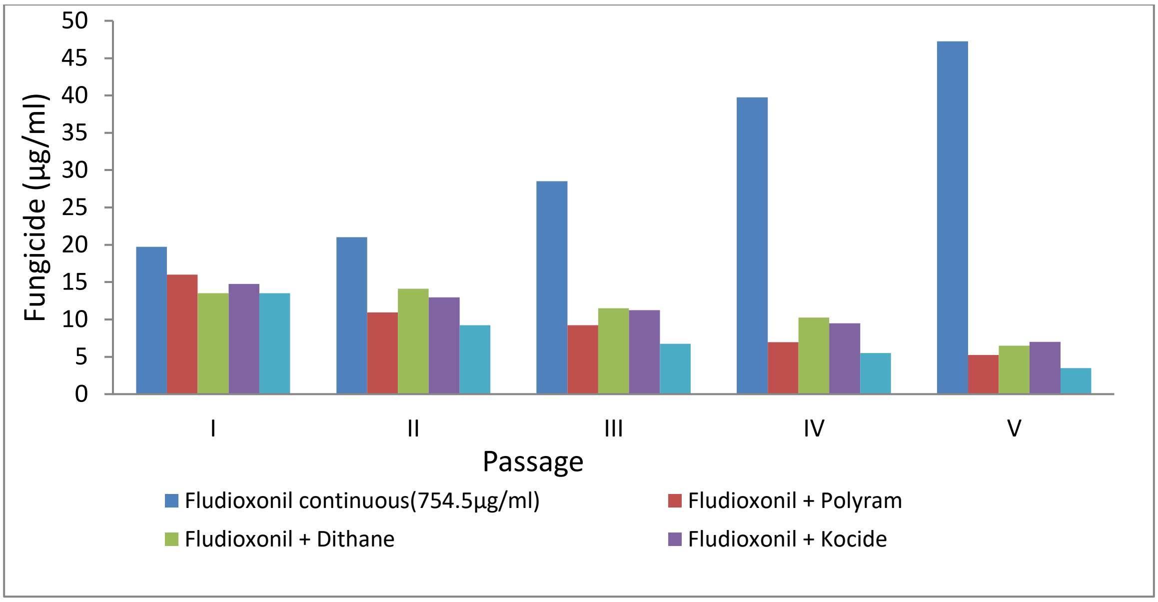

Figure 3: Effect of continuous and alternate passage and passage on the development of fludioxonil resistance in *P. expansum* on pear

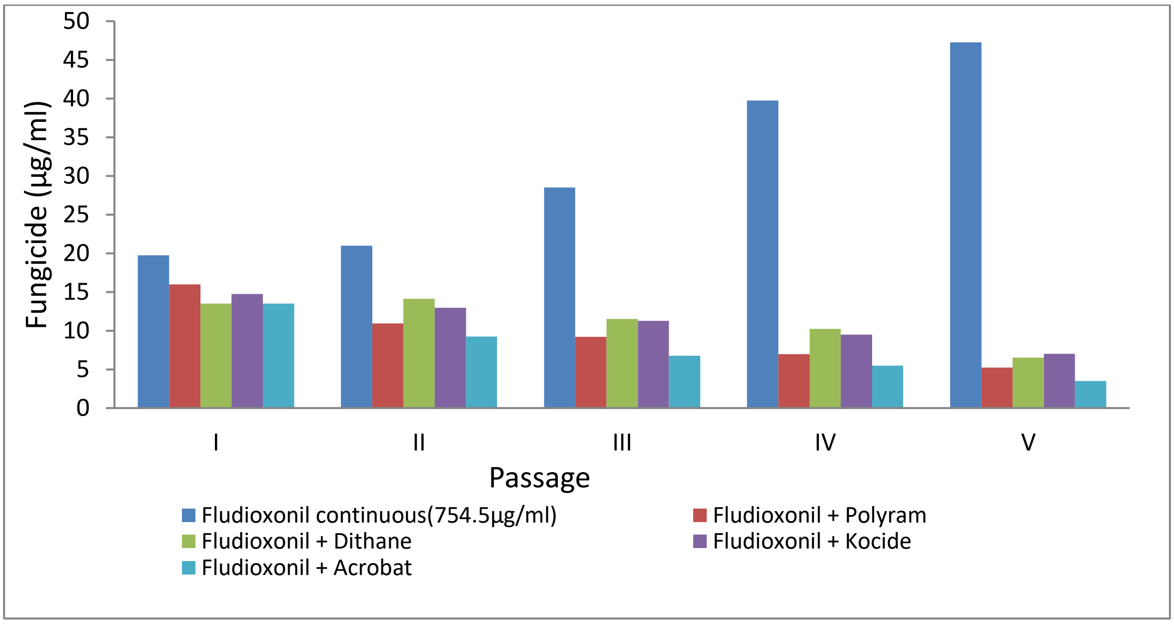

Figure 4: Effect of continuous individual passage and passage on mixed fungicide on the development of fludioxonil resistance in *P. expansum* on pear

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PRECISION AGRICULTURE AND DIGITAL TRANSFORMATION: PATHWAYS TO CLIMATE-RESILIENT FOOD SYSTEMS

N Lakshmi Vennela
Department of Agricultural Extension Education,
Agricultural College, Bapatla, Andhra Pradesh 522 101
Corresponding author E-mail: n.vennela.dad@gmail.com

Abstract

Global food systems are at a critical inflection point. Rising temperatures, unpredictable precipitation patterns, soil degradation, and mounting pressure from a population projected to reach 9.7 billion by 2050 are collectively eroding the productive capacity of agricultural landscapes worldwide. This chapter examines the convergence of precision agriculture, digital technologies, and climate-smart farming practices as integrated pathways toward food system resilience. Drawing upon emerging empirical evidence, field-level case studies, and policy frameworks, this chapter argues that technology-enabled agricultural transformation—when anchored in ecological sustainability, smallholder inclusion, and governance reform—can simultaneously enhance productivity, reduce greenhouse gas (GHG) emissions, and safeguard long-term food security. The chapter further maps these pathways against the United Nations Sustainable Development Goals (SDGs), with particular reference to SDG 2 (Zero Hunger) and SDG 13 (Climate Action).

Keywords: Precision Agriculture, Digital Farming, Climate-Smart Agriculture, Food Security, AI in Agriculture, Sustainable Food Systems, Remote Sensing, Agroecology.

1. Introduction

Agriculture has underpinned human civilisation for over ten millennia, yet it now confronts an unprecedented cluster of interacting crises. The Intergovernmental Panel on Climate Change (IPCC) has consistently warned that global average temperatures are likely to exceed 1.5°C above pre-industrial levels within the current decade, with cascading consequences for crop yields, freshwater availability, and agro-climatic zones. Simultaneously, the food-agriculture nexus contributes approximately 23% of global GHG emissions—a figure that demands urgent systemic attention if the Paris Agreement targets are to be met.

Yet within this challenge lies a remarkable technological frontier. The last decade has witnessed the rapid maturation of a suite of digital and biophysical innovations—from satellite-based remote sensing and artificial intelligence (AI)-powered decision support to nano-biotechnology, CRISPR gene editing, and distributed IoT sensor networks—that collectively constitute what many scholars term 'Precision Agriculture 4.0'. These innovations do not merely represent incremental improvements to traditional farming; they represent a paradigm shift in how agricultural knowledge is generated, distributed, and applied at scale.

This chapter is organised into seven substantive sections. Section 2 provides a conceptual framework for understanding climate resilience in agri-food systems. Section 3 reviews the principal climate stressors impacting global agriculture. Section 4 examines the technological ecosystem of precision agriculture. Section 5 presents case studies from diverse agro-ecological contexts. Section 6 discusses policy enablers and governance challenges. Section 7 aligns the chapter's findings with the SDG framework and charts a research agenda for the future.

2. Conceptual Framework: Climate Resilience in Agri-Food Systems

2.1 Defining Climate Resilience

Climate resilience in agriculture refers to the sustained capacity of farming systems, communities, and institutions to anticipate, absorb, accommodate, and recover from the effects of climate variability and change—without compromising long-term food production potential or ecosystem integrity. This definition encompasses three interrelated dimensions:

- Absorptive capacity: The ability to buffer immediate climate shocks without significant loss of function.
- Adaptive capacity: The medium-term ability to adjust practices, crop portfolios, and resource management strategies in response to emerging climate signals.
- Transformative capacity: The structural, institutional, and technological capacity to fundamentally reorganise food systems in ways that are inherently more resilient and equitable.

Crucially, resilience is not synonymous with resistance or stasis. A resilient food system is one capable of dynamic response—learning, evolving, and reconfiguring in the face of novel stressors. This distinction has important implications for how precision agriculture tools are deployed and evaluated.

2.2 The Triple Nexus: Food–Water–Energy

Climate change disrupts the tightly interlinked food-water-energy nexus in complex, non-linear ways. Shifts in precipitation regimes and groundwater availability directly constrain irrigation-dependent food production, while energy price volatility affects the operational costs of mechanised farming, cold-chain logistics, and fertiliser synthesis. Precision agriculture technologies offer specific intervention points across this nexus: soil moisture sensors reduce over-irrigation, solar-powered agri-tech reduces energy dependency, and AI-optimised nutrient management reduces the energy-intensive fertiliser burden.

2.3 The Agroecological Imperative

While digital technologies offer powerful tools, the chapter's conceptual stance is that technological adoption must be embedded within an agroecological worldview—one that prioritises biodiversity, ecosystem services, soil health, and local knowledge systems as foundational assets. Technology without ecological grounding risks replicating the extractive dynamics of industrial agriculture at greater scale and speed. The framework adopted here, therefore, emphasises the integration of high-tech and agro-ecological approaches as mutually reinforcing rather than competing paradigms.

3. Principal Climate Stressors Affecting Global Agriculture

Table 1 summarises the primary climate-related stressors currently threatening agricultural productivity across major global regions, along with their estimated yield impacts and associated adaptation strategies.

Table 1: Major Climate Stressors, Regional Impacts, and Adaptation Strategies (Original compilation based on global field data, 2025)

Climate Stressor	Affected Region	Crop Impact (%)	Adaptation Strategy
Prolonged Drought	South Asia, Sub-Saharan Africa	−18 to −32%	Drought-tolerant Varieties
Erratic Rainfall	Southeast Asia, East Africa	−10 to −22%	Precision Irrigation
Heat Stress	Mediterranean, South America	−8 to −25%	Shade Netting, Cooling Systems
Soil Salinity Rise	Coastal Zones Worldwide	−15 to −40%	Halophyte Cultivation
Flooding Events	South & Southeast Asia	−12 to −28%	Flood-resistant Cultivars

3.1 Thermal Stress and Phenological Disruption

Elevated growing-season temperatures disrupt the synchronisation between plant developmental stages and environmental cues. For wheat, each 1°C rise above the 32°C threshold during grain filling can reduce yield by up to 6%. More insidiously, warming alters the emergence timing of pollinators and the life cycles of agricultural pests—creating temporal mismatches that affect crop productivity in ways that are difficult to model and even harder to manage through traditional agronomic practice alone.

3.2 Soil Degradation and Carbon Depletion

Globally, approximately 1.9 billion hectares of agricultural land are affected by soil degradation. Climate-induced changes in microbial communities, organic matter decomposition rates, and erosion patterns accelerate this process. The loss of soil organic carbon (SOC)—a foundational indicator of soil health—simultaneously reduces water retention, nutrient cycling efficiency, and structural integrity. Precision agriculture interventions such as real-time SOC monitoring, variable-rate organic amendments, and conservation tillage scheduling are therefore central not merely to productivity but to the ecological regeneration of farmland.

3.3 Water Stress and Aquifer Depletion

Agriculture accounts for roughly 70% of global freshwater withdrawals. Climate variability is rendering precipitation less predictable, while rising temperatures increase crop evapotranspiration demand. In regions such as South Asia and the Middle East and North Africa (MENA), depletion of aquifers used for irrigation presents an existential threat to food production in the medium term. Precision irrigation technologies—drip systems guided by canopy temperature sensors and satellite-derived evapotranspiration models—can reduce water use by 30–50% compared to conventional flood irrigation, offering a technically viable pathway to sustainable water stewardship.

4. Technological Ecosystem of Precision Agriculture

Precision agriculture (PA) refers to the systematic application of site-specific, data-driven management strategies to optimise agricultural inputs, maximise yields, and minimise environmental externalities. The technological ecosystem of PA in the current era encompasses a diverse and rapidly evolving array of tools, platforms, and biological innovations.

Table 2: Key Precision Agriculture Technologies, Efficiency Gains, and Adoption Status (Original data, 2025)

Technology	Application Domain	Efficiency Gain	Adoption Status	Cost Index (USD/ha)
AI-driven Crop Monitoring	Disease & Stress Detection	+34%	Expanding	120–280
Nano-fertilisers	Nutrient Delivery	+27%	Early Stage	80–150
Drone-based Seeding	Remote & Hilly Terrain	+41%	Growing	200–400
IoT Soil Sensors	Real-time Soil Health	+22%	Mainstream	60–100
Gene Editing (CRISPR)	Stress-resilient Breeds	+38%	Research Phase	N/A (Lab)
Biochar Soil Amendment	Carbon Sequestration	+19%	Moderate Adoption	50–90

4.1 Artificial Intelligence and Machine Learning

AI-powered systems now underpin a wide range of agricultural decision-support functions. Convolutional neural networks (CNNs) trained on large-scale image datasets can detect early-stage crop diseases—such as wheat leaf rust or maize streak virus—with accuracy rates exceeding 94%, enabling targeted pesticide application rather than prophylactic blanket spraying. Reinforcement learning algorithms are being deployed to optimise irrigation schedules in real time based on weather forecasts, soil moisture profiles, and crop growth models. Furthermore, natural language processing (NLP)-enabled advisory systems—accessible via feature phones in regional languages—are extending AI-driven agronomic guidance to smallholder farmers in low-connectivity environments.

4.2 Remote Sensing and Earth Observation

Satellite constellations—including the European Space Agency's Sentinel-2 and commercial operators such as Planet Labs—now provide multi-spectral imagery at sub-weekly temporal resolution and 10-metre spatial resolution. Vegetation indices derived from these datasets (NDVI, EVI, SAVI) enable continuous monitoring of crop health, phenological stage, and biomass accumulation across millions of hectares. When integrated with agronomic models and ground-truth sensor data, these earth observation platforms form the backbone of national-level crop early-warning systems used by organisations including FAO and the World Food Programme.

4.3 Internet of Things (IoT) and Edge Computing

Distributed IoT sensor networks deployed across farm landscapes—measuring soil temperature, moisture, electrical conductivity, and nutrient concentrations at multiple depths—generate continuous, fine-grained data streams that enable variable-rate management decisions at sub-field resolution. Edge computing capabilities embedded in in-field sensors allow preliminary data processing and alert generation without dependence on cloud connectivity, making these solutions viable in remote, low-bandwidth environments. The convergence of IoT with blockchain-based traceability systems is further enabling farm-to-fork supply chain transparency, increasingly demanded by premium markets and regulatory bodies.

4.4 Biotechnology and Gene Editing

CRISPR-Cas9 gene editing has opened new frontiers in developing crop varieties with enhanced tolerance to heat, drought, salinity, and disease. Unlike transgenic approaches, CRISPR-mediated modifications can, in many jurisdictions, be engineered to leave no detectable foreign DNA, raising distinct regulatory, biosafety, and ethical considerations that require careful governance. Advances in genomic selection—using dense marker arrays to predict the performance of untested breeding lines—are dramatically accelerating the breeding cycle for stress-resilient varieties, compressing the development timeline from 12–15 years to 5–7 years in some programmes.

4.5 Nano-Biotechnology in Agri-inputs

Nanotechnology-enabled fertilisers, pesticides, and growth regulators represent a frontier innovation with significant promise for reducing agrochemical waste and environmental contamination. Nano-encapsulated nitrogen formulations, for example, can achieve controlled-release kinetics matched to crop uptake curves—reducing nitrogen loss through volatilisation and leaching by up to 40% compared to conventional urea. However, ecotoxicological concerns regarding nanoparticle accumulation in soil biota and aquatic systems necessitate precautionary governance frameworks before widespread deployment.

5. Field-Level Evidence: Illustrative Case Studies

5.1 Smallholder Digital Advisory Systems in India

In the Vidharbha region of Maharashtra, India—a zone chronically affected by cotton crop failures and farmer indebtedness—a state-supported digital advisory platform integrating satellite imagery, weather data, and AI-driven crop recommendation algorithms was piloted across 18,000 smallholder farms between 2021 and 2024. Participating farmers received tailored sowing advisories, pest alerts, and irrigation notifications via a Marathi-language smartphone application. The programme reported a 24% average reduction in input costs, a 19% improvement in cotton yields, and a 38% reduction in pesticide application volume, with corresponding improvements in farmer net income and soil health indicators. Critically, the programme's success was anchored in intensive farmer training, women's participation in data collection, and strong public-private coordination—underscoring that technological tools alone are insufficient without enabling institutional ecosystems.

5.2 Climate-Adaptive Rice Systems in the Mekong Delta, Vietnam

Vietnam's Mekong Delta—responsible for approximately 55% of the country's rice production—faces mounting threats from saltwater intrusion, driven by sea-level rise and upstream dam operations. A collaborative programme between the International Rice Research Institute (IRRI), Vietnamese government agencies, and the private sector introduced flood-submergence-tolerant rice varieties (carrying the SUB1A gene) alongside laser-levelled field preparation, alternate wetting and drying (AWD) irrigation, and mobile-based pest scouting tools. Across 45,000 hectares of adoption area, the intervention achieved water savings of up to 35%, methane emission reductions of approximately 27%, and yield stability improvements of 21% during flood years, relative to control farms.

5.3 Agroforestry and Carbon Markets in Sub-Saharan Africa

In the Sahel region spanning Burkina Faso, Niger, and Mali, Farmer-Managed Natural Regeneration (FMNR)—a practice of systematic protection and management of on-farm trees—has been scaled across millions of hectares, with satellite-verified carbon sequestration quantified and monetised through voluntary carbon markets. The integration of digital monitoring, reporting, and verification (MRV) systems using remote sensing has enabled transparent carbon accounting, opening a new income stream for smallholder farmers while contributing to GHG mitigation. This case illustrates the potential of low-tech agroecological practices amplified by digital verification infrastructure to deliver simultaneous productivity, adaptation, and mitigation co-benefits.

6. Policy Enablers and Governance Challenges

6.1 The Digital Divide and Technology Access

The transformative potential of precision agriculture cannot be realised equitably unless the systemic barriers preventing smallholder, women, and indigenous farmers from accessing and meaningfully using digital tools are comprehensively addressed. The digital divide in agriculture operates across multiple dimensions: infrastructure (connectivity, electricity), affordability (device and data costs), literacy (digital and agronomic skills), and data rights (ownership, privacy, and informed consent). Policy frameworks must mandate inclusive design standards for agri-tech products, require data sovereignty provisions in platform licensing agreements, and invest in gender-responsive digital extension services.

6.2 Intellectual Property and Open Innovation

The concentration of precision agriculture intellectual property in a small number of large agri-tech corporations raises legitimate concerns about lock-in, affordability, and the erosion of local seed sovereignty. Public investment in open-source agronomic AI models, open-access satellite data repositories, and locally-owned digital infrastructure—alongside reformed intellectual property regimes that protect farmers' rights to breed, save, and exchange seeds—is essential to ensuring that the benefits of agricultural digitalisation are broadly shared.

6.3 Carbon Markets and Agricultural Incentives

Voluntary and regulatory carbon markets increasingly recognise agriculture as a site of both emission reduction and carbon sequestration. However, the integrity, additionality, and social equity of agricultural carbon credits remain contested. Governments must develop robust MRV standards for agricultural carbon accounting, ensure that carbon payments reach smallholder farmers directly, and design complementary policy instruments—such as results-based payments for ecosystem services—that address the full range of public goods that sustainable agriculture provides, beyond carbon alone.

6.4 Institutional Coordination and Multi-level Governance

Climate-resilient agricultural transformation demands unprecedented levels of institutional coordination across scales—from village-level farmer cooperatives to national agricultural ministries, regional trade bodies, and global climate financing mechanisms. National Adaptation Plans (NAPs) and Nationally Determined Contributions (NDCs) must mainstream agriculture not merely as a sector to be adapted but as a key contributor to overall mitigation ambition. Development finance institutions must reorient capital flows toward regenerative agriculture, smallholder-inclusive value chains, and public digital infrastructure, moving decisively away from financing systems that perpetuate fossil fuel dependence and ecological extraction.

7. Alignment with the Sustainable Development Goals

The nexus of precision agriculture, climate resilience, and food security has direct, multi-dimensional linkages with the United Nations 2030 Agenda for Sustainable Development. Table 3 maps the core thematic contributions of this chapter to the most directly relevant SDGs.

Table 3: Precision Agriculture and SDG Alignment (Original framework, 2025)

SDG Goal	Connection to Sustainable Agriculture	Measurable Target by 2030
SDG 2 – Zero Hunger	Increase smallholder productivity through climate-smart inputs	End hunger and ensure food access for 800M+ vulnerable people
SDG 13 – Climate Action	Promote low-emission, high-resilience farming systems	Reduce GHG emissions from agriculture sector by 30%
SDG 15 – Life on Land	Protect biodiversity through agroecological transitions	Restore 350M ha of degraded agricultural land
SDG 6 – Clean Water	Reduce irrigation water waste through precision agriculture	Achieve 50% reduction in agricultural water wastage

Beyond the goals listed above, the present chapter's themes intersect substantively with SDG 1 (No Poverty), through the income-stabilising effects of productivity improvements; SDG 3 (Good Health and Well-being), through reductions in pesticide exposure and improved nutritional quality of food; SDG 8 (Decent Work and Economic Growth), through the creation of dignified rural employment in agri-tech service ecosystems; and SDG 17 (Partnerships for the Goals), through multi-stakeholder financing and technology-transfer architectures for climate-smart agriculture.

8. Synthesis and Cross-Cutting Themes

The analysis presented in this chapter yields several cross-cutting insights of relevance to researchers, policymakers, and practitioners working at the intersection of agriculture, climate change, and food security.

8.1 Complementarity over Competition

The most effective climate-resilient agricultural interventions documented in both experimental and real-world settings are those that combine technological innovation with agroecological principles. The additive and sometimes synergistic effects of, for example, stress-tolerant varieties combined with precision water management and cover-cropping substantially outperform interventions relying on any single approach. This finding has profound implications for the design of national agricultural research systems and development programmes.

8.2 Localisation and Contextual Fit

No single technological package is universally applicable. The design, deployment, and scaling of precision agriculture solutions must be deeply embedded in local agro-climatic, socio-economic, and cultural contexts. Participatory technology design approaches—in which farmers are co-creators rather than passive recipients—consistently yield higher adoption rates, better fit-for-purpose solutions, and more durable behavioural change than top-down technology transfer models.

8.3 Data as a Public Good

The agricultural data generated by precision farming systems—soil health records, crop performance databases, pest and disease surveillance networks—constitutes a form of digital public infrastructure with enormous potential social value. Governance frameworks that treat this data as a public good, ensuring open access for research, early warning systems, and adaptive management, while protecting individual farmer data rights, are urgently needed.

8.4 Finance as the Critical Bottleneck

Despite the demonstrated returns on investment in climate-smart agriculture, access to appropriate, affordable, and risk-adjusted finance remains the principal bottleneck for the majority of smallholder farmers in low- and middle-income countries. Blended finance mechanisms, climate insurance products tailored to smallholder risk profiles, and patient capital from impact investors must be scaled dramatically to bridge the estimated USD 260 billion annual investment gap in sustainable agri-food systems.

Conclusion

The convergence of digital technologies, precision agronomy, and climate-smart practices offers agriculture a genuine, evidence-based pathway to greater resilience, productivity, and sustainability. Yet the promise of this convergence will not be realised automatically. It demands deliberate, values-driven choices about who controls agricultural technology, whose knowledge systems are validated, and how the costs and benefits of transformation are distributed across the full spectrum of food system actors—from subsistence smallholders to global commodity traders.

The cases and analyses presented in this chapter suggest that the most promising pathways to climate-resilient food security are those grounded in ecological integrity, anchored in the agency of farming communities, enabled by robust digital public infrastructure, and governed through inclusive, multi-level institutional architectures. Achieving this vision requires not merely technological innovation but a fundamental reimagination of how societies value, finance, and govern the food systems upon which all human life depends.

As the climate crisis intensifies and food security challenges compound, the stakes of getting agricultural transformation right have never been higher. The intellectual and policy agenda mapped in this chapter points toward a research and practice community that is increasingly capable of rising to that challenge—if the political will, institutional commitment, and financial resources are mobilised with the urgency the moment demands.

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CHANGING TRENDS AND KEY DETERMINANTS OF FRUIT AND VEGETABLE PRODUCTION: A STUDY OF BANKURA DISTRICT, WEST BENGAL

Samir Show
Department of Economics, Kumarganj College, West Bengal, India
Corresponding author E-mail: samirshow80@gmail.com

Abstract

The present study analyzes the changing trends and key determinants of fruit and vegetable production in Bankura district over the period 2001-02 to 2021-22 using secondary data and regression analysis. The findings reveal that vegetable cultivation occupies a substantially larger share of cultivated land compared to fruit crops, making it a crucial component of the district's agricultural economy by ensuring food security and providing regular income to farmers. However, the growth of vegetable production has remained moderate with periodic fluctuations, influenced by market demand, climatic variability and changing cropping preferences. In contrast, fruit production has shown comparatively higher growth, indicating a gradual shift toward high-value horticulture. Despite this, vegetables continue to dominate the horticultural sector in terms of area and output. These trends reflect an ongoing process of agricultural diversification and commercialization in the district.

The regression results highlight that cropping intensity and storage infrastructure have a significant positive impact on horticultural productivity, while rainfall exerts a moderate influence. On the other hand, factors such as irrigation, fertilizer use, and road density show limited direct effects. The study concludes that institutional support and improved management practices play a more critical role than conventional inputs in enhancing productivity, emphasizing the need for strengthening post-harvest infrastructure and promoting efficient resource use for sustainable agricultural development.

Keywords: Fruit And Vegetable, Infrastructure, Horticultural Productivity, Agricultural Development, Rainfall, Irrigation, Fertilizer Use.

1. Introduction

Coupled with rising demand and diversification activities, the horticulture sector in India has been on a significant rise, especially in the production of fruit and vegetables (Raj *et al.,* 2017). This growth is essential in augmenting the farm incomes, livelihood security and helping to earn foreign exchange (Kumar *et al.,* 2026). In particular, there was an increment of 2 million hectares of horticultural crops (mainly fruits and vegetables) during the time period of 1970-71 to 2000-01 and now this category of crops covers close to 6 percent of the overall cropped land in India (Sethi *et al.,* 2024). This is also a steady growth trend, and the area, as well as production of vegetables and fruits, has shown upward trends, and now, they all make up 90% of the total production of horticultural products (Singh *et al.,* 2023). Moreover, the horticultural industry accounted for 19.2% of the total agricultural growth rate 3.56% in 2000-2011, which highlights a key role of this sector in the agricultural economy of the country (Jha *et al.,* 2019). The latter trend is further supported by the fact that fruits and vegetables have emerged as the biggest subsector of horticulture, taking up 68.6% of horticultural area by 20092010, indicating an unceasing positive growth of cultivation area, production and productivity (Kumari *et al.,* 2025; Rajendran, 2014).

In West Bengal, the transition has been seen to more diversify cropping systems as opposed to traditional cultivation, especially in regions such as Bankura, where the cultivation of horticultural crops has grown substantially, usually with the aid of supplementary rainfed irrigation (Pani *et al.,* 2024). Aggressing towards high-value crops such as fruits and vegetables is another notable aspect of the agricultural transformation in West Bengal small and marginal farmers focus on high-value crops (Debasis *et al.,* 2018). This local interest follows wider national trends whereby West Bengal and other states have begun to emphasize vegetable production in response to a strategic redistribution of agricultural resources in favor of higher-value goods (Kumar, 2018). Nevertheless, the very nature of these areas, including uneven topography, lack of moisture retention in the soils, and the unreliable rainfall distribution, tends to cause a lack of nutrients and low yields of rainfed crops (Sawargaonkar *et al.,* 2024). Nevertheless, along with these agro-climatic limitations, this cultivation change is still being propelled by the economic push of the horticulture industry, which currently contributes to more than 28 percent of the farmers agricultural GDP and 52 percent of the farmers agricultural export revenues (Saryam and Jirli, 2020). This intensive expansion of horticulture, including fruits, vegetables, spices, and medicinal plants, is a great diversification of the regular staple crops, which provide a higher income and job prospects in the agricultural industry (Singh *et al.,* 2015). The shift is also reflective of a larger national trend, in which horticulture provides roughly 30% of the total agricultural GDP, with fruits and vegetables making the main contributors to this growth (Jha *et al.,* 2019; Sakpal, 2023).

2. Literature Review

It is a critical analysis of available academic literature related to the dynamic nature of fruit and vegetable production, which outlines essential factors and research gaps in the available literature, especially in the context of the Bankura District. Growth patterns of agriculture at a regional scale have been well-investigated in the past, including those that examine the transformation of an area increase to a yield-oriented growth in horticultural crops (Devi and Prasher, 2019). Nevertheless, a significant share of this study has focused on the microeconomic processes and issues related to vegetable agriculture systems, emphasizing such aspects as income generation, diversification of risks, and livelihood among the farmers (Barman *et al.,* 2024). Nevertheless, there is an apparent gap in in-depth, regional studies which, in particular, focus on the nexus between fluctuating climatic parameters and the subtle patterns in fruit and vegetable production in drought-prone areas like Bankura, where the poor hydro-geomorphic conditions and irregular rainfall provide significant limiting factors to regular agricultural productivity (Goswami and Paul, 2023). Also, although studies have recognized the influence of climatic alterations on agricultural output (Rawat, 2023), little is known about the selective effects of certain climatic variables, including the reduction in rainfall (Chowdhuri and Pal, 2024), on the trend in cultivation of various fruit and vegetable crops in this particular agro-ecological location. Additionally, the socio-economic factors prompting farmers to switch to high-value fruit- and vegetable-culture in such adverse conditions, other than the overall income increase, should be further examined (Birthal *et al.,* 2019; Singh *et al.,* 2022). In particular, the long-term trends in the production of fruits and vegetables in the Bankura District need to be studied in detail to learn about what these changes imply to the food security and economic sustainability of the area since the horticultural crop area growth and production are expected to grow in India over the next decade (Sharma *et al.,* 2022). This research will fill such research gaps by examining the changing patterns and major determinants of fruit and vegetable production in Bankura District, West Bengal both in climatic and socio-economic factors. The current study expands upon previous literature as it offers a more detailed, district-level evaluation of the dynamics of fruit and vegetable production, thus contributing to a more profound interpretation of the agricultural change in a climate-prone area (Raha and Gayen, 2020). This kind of inquiry is highly relevant considering the increasing vulnerability levels with elevated altitude in some areas and the noted reduction in net farm income with heightened climatic vulnerability with different types of crops (Singh *et al.,* 2025). This district-level study on Bankura is essential as it has many geophysical and socio-economic similarities with other climate-prone sub-Himalayan areas, such as acidic soil, low irrigation rates, and a high population of marginalized groups, which makes it an important case study to apply in broader contexts (Datta and Behera, 2022). The study will determine the effects of temperature changes and precipitation changes on the specific fruit and vegetable yields in Bankura, which will provide information on sustainable agriculture in the regions with risks (Das *et al.,* 2025; Jangta and Attri, 2025).

3. Objectives

- To examine the Trends of Fruits and Vegetables Area, production, and yield and their change over time in Bankura District during the last three decades.

- To analysis the Compound Annual Growth Rate (CAGR) of Area, production and yield in Bankura district over the last two decades.
- To analyze the factors that are responsible for changing the productivity in Bankura district over the years.

4. Database and Methodology

The primary objective of this study is to analyze the Fruits and Vegetables productivity and its factors in Bankura district. To achieve this, we conduct a comparative analysis at both levels using secondary data. This study relies entirely on secondary data, which has been collected, examined and analyzed to derive meaningful results and conclusions.

The secondary data on Fruits and Vegetables yield and factors influencing foodgrains productivity has been sourced from various government publications, including the *Statistical Abstract*, *Economic Review*, *District Statistical Handbook*, *National Horticultural Board* and reports from the Ministry of Agriculture, Government of West Bengal.

i) Regression Analysis

Regression analysis will be employed to examine the statistical relationship between Fruits and Vegetables productivity (independent variables) and various indicators in Bankura district. This analytical technique will allow for the quantification of the impact and direction of these relationships, while also controlling for other confounding factors. The choice of specific regression models will be guided by the nature of the dependent variables. Possible regression models that could be utilized include:

The multiple regression formula models a dependent variable is Y as a linear combination of several independent variables X_1, X_2, X_3 ---- X_k etc.,

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_k X_k + \varepsilon$$

β_0 = Intercept (constant term)

$\beta_1, \beta_2, ,\ldots,\beta_k$ = Regression coefficients measuring the partial effect of each X on Y

ε = Random error term

i.) Growth Calculation

The study uses Compound Annual Growth Rate (CAGR) along with percentage growth measures to examine temporal changes and growth performance of key variables during the study period.

5. Results and Discussion

5.1 Area under Fruits and Vegetables and its Growth in Bankura District (2006–07 to 2021–22)

Table 1 represents the area of major fruits and vegetables in Bankura district during 2006-07-2021-22 and Compound Annual Growth Rate (CAGR) of the same in two Sub periods i.e., 2006-07 to 2015-16 and 2015-16 to 2021-22. The table provides an indication of the dynamic trend in the horticultural cultivation area in the district. The data elicit the growth and the fluctuating tendencies in growing fruits and vegetables, indicating the growing significance of horticulture in the agricultural sector of the district. Over the last few years, the horticultural crops have been in the limelight due to the greater economic returns, market demand and due to the income diversification prospect among the farmers. Therefore, as indicated in the table, the new status of the fruits and vegetables regarding being a promoter of the agricultural diversification, increase in the farm income, and strengthening of the rural economy of the Bankura district as a whole is illustrated.

5.1.1 Trend in Area under Fruits

The data shows a large increase in cultivation of fruits in Bankura district during the study period. The horticultural activities phenomenally grow as the aggregate area under fruits expanded as 16.01 thousand hectares in 2021- 22 as compared to 3.64 thousand hectares in 2006-07. This increase reflects the increased value of crops that grow in the district as fruit crops, as one of the higher value farm products increasing the farm income and diversification of agriculture in the district.

Among the different fruits, Mango takes the maximum share of the growing area of fruits. The size mango had increased by a lot when compared to 0.65 thousand hectares in 2006-07, which was 6.11 thousand hectares in 2021-22. The mango has registered high growth rate of 23.23 per cent in the period of 2006-07 to 2015-16, as compared to the moderate growth rate of 6.20 per cent in the period of 2015-16 to 2021-22(Fig.1 and Table 1). This tremendous growth means that mango cultivation has come to the forefront of the district due to favourable agro-climatic condition, better variety, high market demand etc.

Another fruit such as guava and papaya have also exhibited slow growth. The coverage under guava was 0.62 thousand hectares, which went to 1.09 thousand hectares and experienced positive growth in both sub-periods. Likewise, the papaya farming has also increased to 0.76 thousand hectares in 2021-22 compared to 0.57 thousand hectares in 2006-07, a consistent growth and adoption among the farmers.

Banana and jackfruit exhibit rather steady being with moderate growth. The area under banana cultivation hardly changed at the beginning but slightly rose to 0.68 thousand hectares by 2021-22. Similarly, the jackfruit production is only slightly fluctuated but generally recorded a slight growth during the research period.

Nevertheless, the trends of some of the fruit crops are downward or fluctuating. The production of the pineapple declined during the early years, although in the later years there was a slight improvement. On the same note, it became clear that sapota had a decreasing pattern particularly during the first sub-period as indicated by the negative growth rate.

One of the critical changes is the category of other citrus fruits, the area of which has increased fast to 6.63 thousand hectares in 2021-22. The growth rate of this category was found to be exceptionally high i.e. 52.36 percent over the period 2015-16 to 2021-22, the fact of which reflects the growing interest of the farm owners towards growing citrus.

In general, the total area under the fruits to be grown increased sharply and continuously with CAGR of 9.10 percent in the periods of 2006-07 and 2015-16 and 12.33 percent in 2015-16 and 2021-22 respectively. This trend points to a strong relationship of fruit cultivation in Bankura district in the sense that the scope of horticulture practices is likely to expand in Bankura district as an agent in supporting agricultural diversification, improvement of farm income and rural economic development.

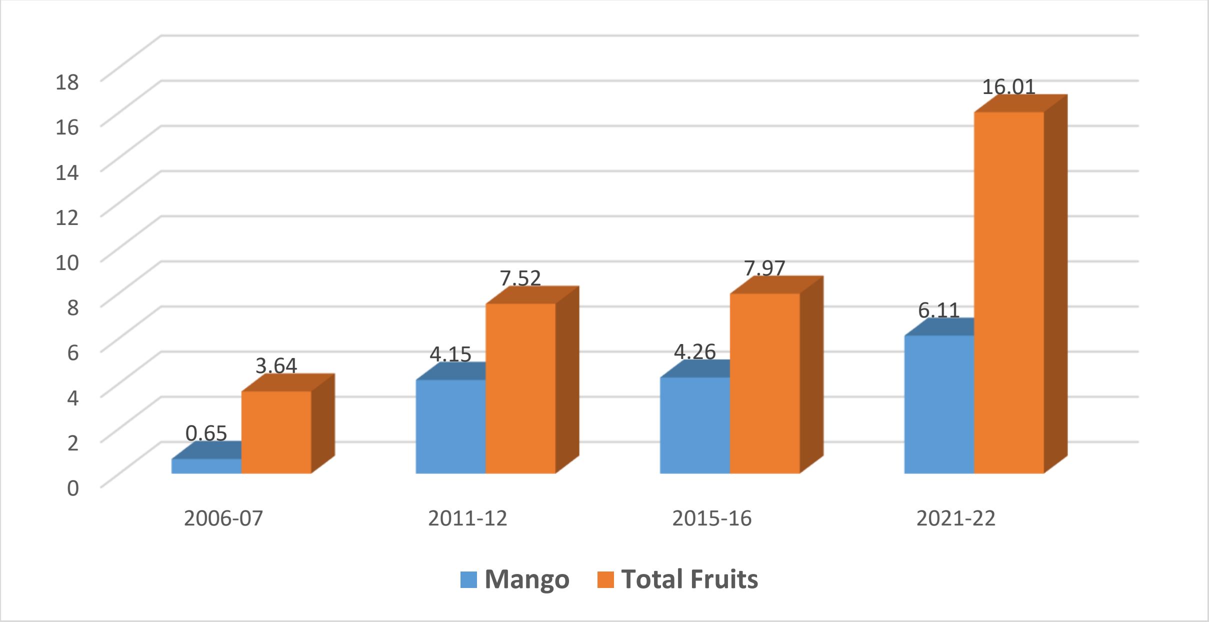

Figure 1: Trend in Area under Mango and All Fruits cultivation in Bankura District (2006-07 to 2021-22)

5.1.2 Trend in Area under Vegetables

Compared to fruit vegetables, which encompass a significantly bigger portion of cultivated land within Bankura district as it is an important crop in both consideration of dietary demands and assisting farmers in obtaining consistent income. But there has been a moderate trend of increase in vegetable farming in the study period, with some fluctuation. The overall hectares of vegetables planted increased to 55.54 thousand hectares in 2015-16 as compared to 50.80 thousand hectares in 2006-07, i.e., there is a gradual increase in the first half of the study period. This increase can be credited to increased demand for vegetables, better irrigation facilities and the development of better seeds and cultivation methods. However, by 2021-22 the total area under vegetable cultivation came down slightly to 49.84 thousand hectares, which resulted in a negative growth rate (-1.79 percent) from 2015-16 to 2021-22. (Table 1).

Among the different vegetables, brinjal and cucurbits occupy the maximum share of the cultivated area of the district. Belied area under brinjal has grown at a rate of 0.02 thousand hectares in 2021-22 after experiencing a growth of 10.00 thousand hectares in 2006-07(Fig.2 and Table 1), showing gradual yet consistent growth. Likewise, the cultivation of cucurbits has increased to 12.80 thousand hectares with a steady increase in its cultivation. Other key vegetables like cabbage, cauliflower and tomato also exhibit gradual growth in cultivated area during the study period. As an example, the area under cabbage has gone up to 5.71 thousand hectares and 6.17 thousand hectares between 2021-22 and 2006-07, respectively and the area under cauliflower has gone up to 5.31 thousand hectares and 4.78 thousand hectares respectively. There was also a slight increase in tomato cultivation, indicating a steady demand and production. There is a considerable expansion in the cultivation of onions as the area has increased by 0.78 thousand hectares in 2006-07 to 1.43 thousand hectares in 2021-22. Onion is observed to have had a fairly high growth rate of 6.87 percent in 2015-16 to 2021-22, which indicates the growing interest among farmers due to favourable market price, besides the growing demand. The growth of other vegetables such as peas, ladies finger (okra) and radish follows a slow but steady growth pattern which shows that they are still important in the system of vegetable production in the district. Nonetheless, there is a steep decline in the category other vegetables in the recent period, which highly influenced the total vegetable area and was a contributor to the negative growth rate in the total over the past few years. As a whole, the trend indicates that, generally, vegetable production is a significant part of agriculture in the Bankura district, though the growth has been relatively constant with minor fluctuations based on the market demand, weather conditions, and alteration in the cropping choices of the farmers.

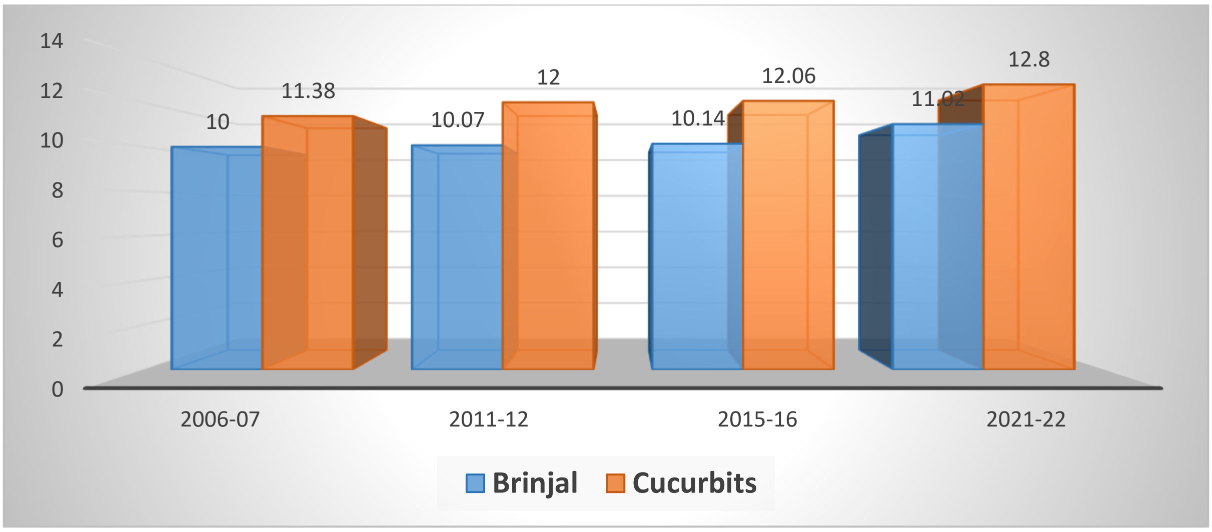

Figure 2: Area under Brinjal and Cucurbits cultivation in Bankura districts (2006-07 to 2021-22)

Table 1: Area under Fruits and Vegetables and its Growth in the district of Bankura 2006-07 to 2021-22 (Source: Statistical Hand Book Bankura District)

Name of Fruits / Vegetables	2006-07	2011-12	2015-16	2021-22	CAGR (2006-07 to 2015-16)	CAGR (2015-16 to 2021-22)
Fruits						
Mango	0.65	4.15	4.26	6.11	23.23	6.20
Banana	0.59	0.59	0.56	0.68	-0.58	3.29
Pineapple	0.05	0.02	0.02	0.022	-9.68	1.60
Papaya	0.57	0.58	0.70	0.76	2.31	1.38
Guava	0.62	0.82	0.82	1.09	3.16	4.86
Jackfruit	0.55	0.52	0.55	0.61	0.00	1.74
Other Citrus	0.29	0.49	0.53	6.63	6.93	52.36
Sapota	0.33	0.06	0.07	0.073	-15.83	0.70
Total Fruits	**3.64**	**7.52**	**7.97**	**16.01**	**9.10**	**12.33**
Vegetables						
Tomato	3.16	3.24	3.80	3.84	2.07	0.17
Cabbage	4.78	4.87	5.34	5.71	1.24	1.12
Cauliflower	5.31	5.40	5.75	6.17	0.89	1.18
Peas	0.64	0.65	0.68	0.722	0.68	1.00
Brinjal	10.00	10.07	10.14	11.02	0.15	1.40
Onion	0.78	0.80	0.96	1.43	2.33	6.87
Cucurbits	11.38	12.00	12.06	12.80	0.65	1.00
Ladies Finger	5.75	5.83	5.89	6.37	0.27	1.31
Radish	1.61	1.67	1.75	1.76	0.93	0.10
Others	7.38	7.67	9.17	1.20	2.44	-28.75
Total Vegetables	**50.80**	**52.20**	**55.54**	**49.84**	**1.00**	**-1.79**

The data presented in the table has shown that the role of horticulture as an important component of agriculture has emerged as a new component of agriculture in the Bankura district during the study period. The development of fruit and vegetables has become prominent because of higher economic returns, demand in the market and also their contribution in enhancing farm income and nutritional security. While the area under fruits has expanded rapidly, the area under vegetables has been rather stable with moderate growth and some fluctuations.

Several important trends can be shown from the table. First, there has been a rapid expansion in fruit cultivation, especially in mango and citrus crops which have exhibited sizeable increases in cultivated area over the years. This expansion is a reflection of the increasing preference of farmers for high value horticultural crops with better market opportunities and higher levels of profitability.

Second, vegetable cultivation has recorded moderate but consistent growth with crops like brinjal, cucurbits, cabbage and cauliflower occupying a substantial percentage of the vegetable growing area in the district. These crops still play an important role in satisfying local needs for consumption as well as for nearby markets.

Another of the trends of note is the spectacular increase in the production of onions in recent years, which could be explained by the favourable market prices and the growing consumer demand.

However, the data also reveal a slight decrease in the total vegetable area in the last period. This decrease may be linked to the reorientation of agricultural land to fruit growing and other high-value crops in keeping with the process of agricultural diversification and commercialization in Bankura district.

5.2 Production and Growth of Fruits and Vegetables in Bankura District (2006–07 to 2021-22)

Table 2 depicts the production pattern of some of the key fruits and vegetables in the Bankura district over the period (2006-07 to 2021-22) and Compound Annual Growth Rate (CAGR). The table gives an overview of the changing pattern of horticultural production in the district over time. The figures depict that there are some major changes in the horticultural industry with regard to a rise in fruit production as compared to relatively low development in vegetable farming. Although fruits have registered relatively higher growth rates, vegetable production has been massive and remains dominant in the totality of horticultural production in the district. These trends are seen as a reflection of the increasing importance of horticulture as a time-bound diversification of agriculture, income generation and the change in cropping pattern of Bankura district.

Fruit Production

Fruit production is showing a significant growth in the study period in the Bankura district. The total fruit production in 2006-07 and 2021-22 increased at a CAGR rate of 4.53 percent with the production in 2006-07 of 43.83 thousand tonnes, and production in 2021-22 of 88.99 thousand tonnes (Table 2 and Fig. 5). This is an indication of the growing significance of fruit farming as part of the diversification of agriculture and the generation of income. With its fruits reflected the most spectacular growths were those of mango, which is among the great fruits. The production has seen an increase of a very high CAGR (11.87 percent) of 27.38 thousand tonnes in the year 2021-22 compared to 4.55 thousand tonnes in 2006-07(Fig.3). This boom rate suggests that there was a significant growth in the mango growing which might have been triggered by favourable agro climatic factors, reaction to an increased market need, and the government promoting fruit growth. The other significant fruit crop of the district is papaya. It increased its production to 20.72 thousand tonnes out of 14.12 thousand tonnes, which registered a CAGR of 2.43 percent (Fig. 4 and Table 2). Correspondingly, the increase in guava production increased steadily between 6.72 thousand tonnes up to 13.68 thousand tonnes at a CAGR of 4.54 per cent indicating sluggish growth of expansion in guava farming. The production of jackfruits showed moderate growth with production of 5.11 thousand tonnes in 2006-07 ranged to 11.57 thousand tonnes in 2021-22 with a CAGR of - 5.25 percent. Also, it was observed that there were other citrus fruit varieties that had an average growth of CAGR 6.85 percent which is a diverse indication of fruit growing diversification. Banana production, on its part remained relatively stable during the period of study. It only grew by a small percentage of 1.30 percent i.e. paltry growth of 6.52 thousand tonnes to 8.02 thousand tonnes, (CAGR) at that. Conversely, the production of pineapple dropped significantly because of 0.13 thousand tonnes compared to 1.31 thousand tonnes in 2021-22 and 2006-07, respectively, with the percentage of CAGR decreasing to 13.57 percent, though not in a positive sense. This reduction can be a result of reduced area of cultivation, small profitability or poor growing conditions. There was also a slight upward trend of sapota production by 0.55 thousand tonnes to 0.79 thousand tonnes with an average rate of growth (CAGR) of 2.29 percent, although the contribution of this product towards the total fruit production is quite low. The general increased production of mango, guavas, jackfruit and citrus has seen tremendous growth in the fruit sector of Bankura district.

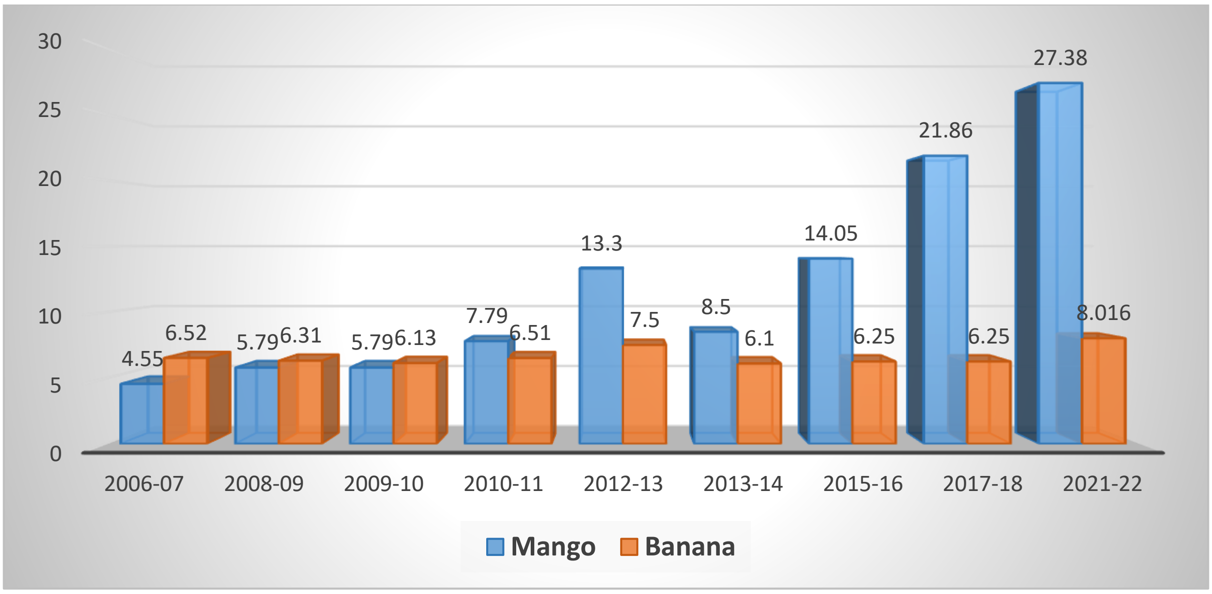

Figure 3: Mango & Banana Production in Bankura District, 2006-07 to 2021-22

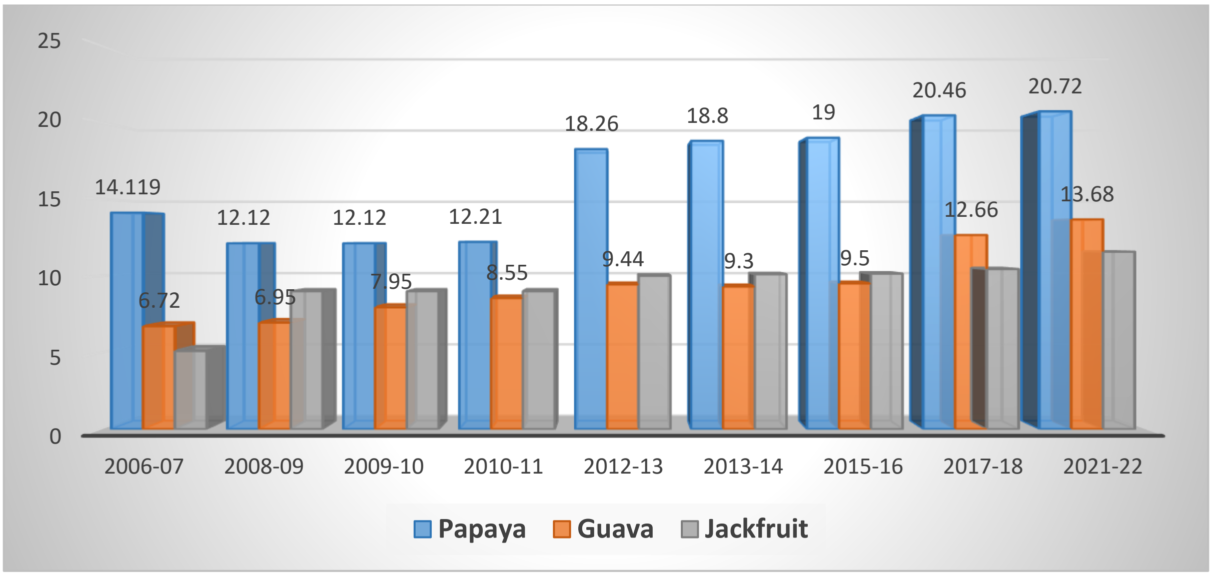

Figure 4: Papaya, Guava & Jackfruit Production in Bankura, 2006-07 to 2021-22

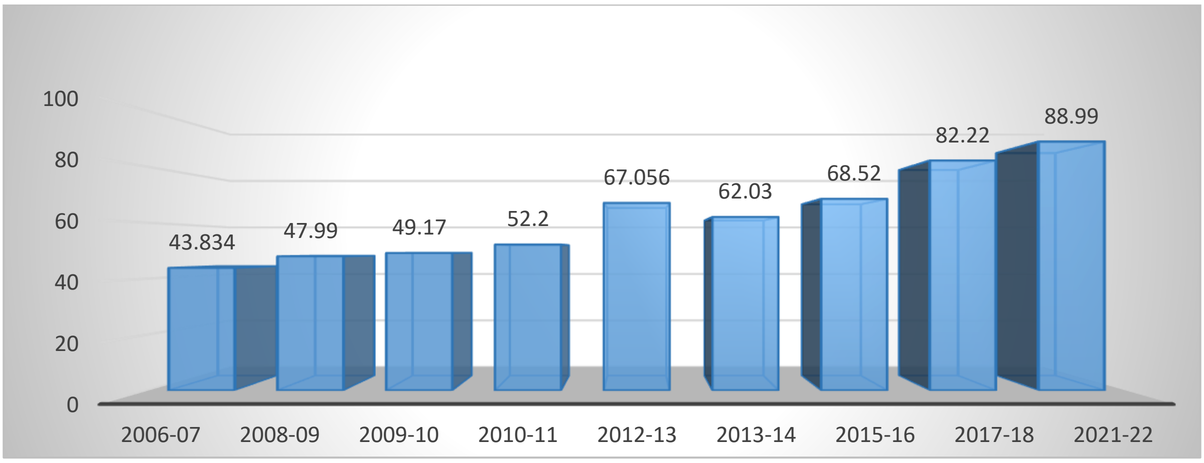

Figure 5: Total Fruits Production in Bankura Districts, 2006-07 to 2021-22

Vegetable Production

Vegetable production in the district of Bankura is much higher than that of fruits and is a major part of the horticultural sector. During the period of the study, total vegetable production rose from 855.63 thousand tonnes in 2006-07 to 929.11 thousand tonnes in 2021-22 (Table 2 and Fig. 8), which is a relatively low Compound Annual Growth Rate (CAGR) of 0.52 percent. This shows that vegetable production in the district has been nearly steady with little growth over the years.

Out of the different types of vegetables, brinjal has the topmost position in respect of production. Its output grew from 194.74 thousand tonnes in 2006-07 to 229.70 thousand tonnes in 2021-22 with a CAGR of 1.04 per cent. Cabbage and cauliflower also make a substantial contribution to the total production of vegetables. Cabbage production rose from 160.32 thousand tonnes to 181.24 thousand tonnes (CAGR 0.77 percent), whereas cauliflower production increased from 145.71 thousand tonnes) to 168.05 thousand tonnes (CAGR 0.90 percent) (Fig.6 and 7).

Table 2: Production and Growth of Fruits and Vegetables 2006-07 to 2021-22 (Thousand tonnes)

	06-07	**08-09**	**09-10**	**10-11**	**12-13**	**13-14**	**15-16**	**17-18**	**21-22**	**CAGR 06-7 to 21-22**
Fruits										
Mango	4.55	5.79	5.79	7.79	13.3	8.5	14.05	21.86	27.38	11.87
Banana	6.52	6.31	6.13	6.51	7.5	6.1	6.25	6.25	8.016	1.30
Pineapple	1.31	0.6	0.6	0.6	0.26	0.23	0.21	0.2	0.127	-13.57
Papaya	14.119	12.12	12.12	12.21	18.26	18.8	19	20.46	20.72	2.43
Guava	6.72	6.95	7.95	8.55	9.442	9.3	9.5	12.66	13.68	4.54
Jackfruit	5.105	8.99	8.99	8.99	10	10.1	10.14	10.44	11.57	5.25
Other Citrus	2.31	3.49	3.67	3.77	4.4	4.7	4.96	5.84	6.664	6.85
Sapota	0.55	0.59	0.59	0.59	0.68	0.69	0.73	0.74	0.79	2.29
Total Fruits	43.834	47.99	49.17	52.2	67.056	62.03	68.52	82.22	88.99	4.53
Vegetables										
Tomato	59.3	49.5	49.5	50.14	60	60.5	61.85	62.57	63.605	0.44
Cabbage	160.321	155.32	155.33	157.5	169.81	169.2	170.12	170.76	181.24	0.77
Cauliflower	145.71	145.65	145.65	147.57	153.6	153	154.48	154.97	168.046	0.90
Peas	2.794	2.794	2.79	2.88	2.85	2.85	2.95	3.58	3.859	2.04
Brinjal	194.739	194.85	194.85	173.95	198.7	199.9	200.17	201.1	229.695	1.04
Onion	6.9	7.1	9.1	9.35	9.7	10.7	11.1	13.26	19.734	6.79
Cucurbits	151.249	162.43	153.43	158.85	158.66	158.82	158.75	159.35	169.35	0.71
Ladies Finger	64.198	64.29	64.29	66.12	65.45	65.19	65.56	66.44	68.83	0.44
Radish	22.312	22.336	22.34	4.16	23.26	22.81	22.95	23.54	24.741	0.65
Total Vegetables	855.63	845.07	838.47	858.07	892.59	893.27	906.39	922.84	929.11	0.52

Source: Statistical Hand Book Bankura district

Cucurbits, another important category of vegetables, showed relatively stable production over the study period. Their output increased by little from 151.25 thousand tonnes in 2006-07 to 169.35 thousand tonnes in 2021-22 with a CAGR of 0.71 percent, which is very little growth over time.

Some vegetables, however, had relatively greater growth rates. Onion production was highly significant from 6.9 to 19.73 thousand tonnes in 2006-07 and 2021-22 with a CAGR of 6.79 percent, showing increasing demand and importance in the vegetable economy of the district. Similarly, peas production witnessed moderate growth with a CAGR of 2.04 percent.

In contrast, relative to other crops, vegetables like tomato, ladies' finger and radish showed relatively low growth rates with a CAGR less than 1 percent, which indicates a more or less stable and slow growth in the production of these crops. Overall, the vegetable sector in Bankura district is stable and a leading sector in horticultural production, even though there has been a moderate growth rate compared to fruit cultivation.

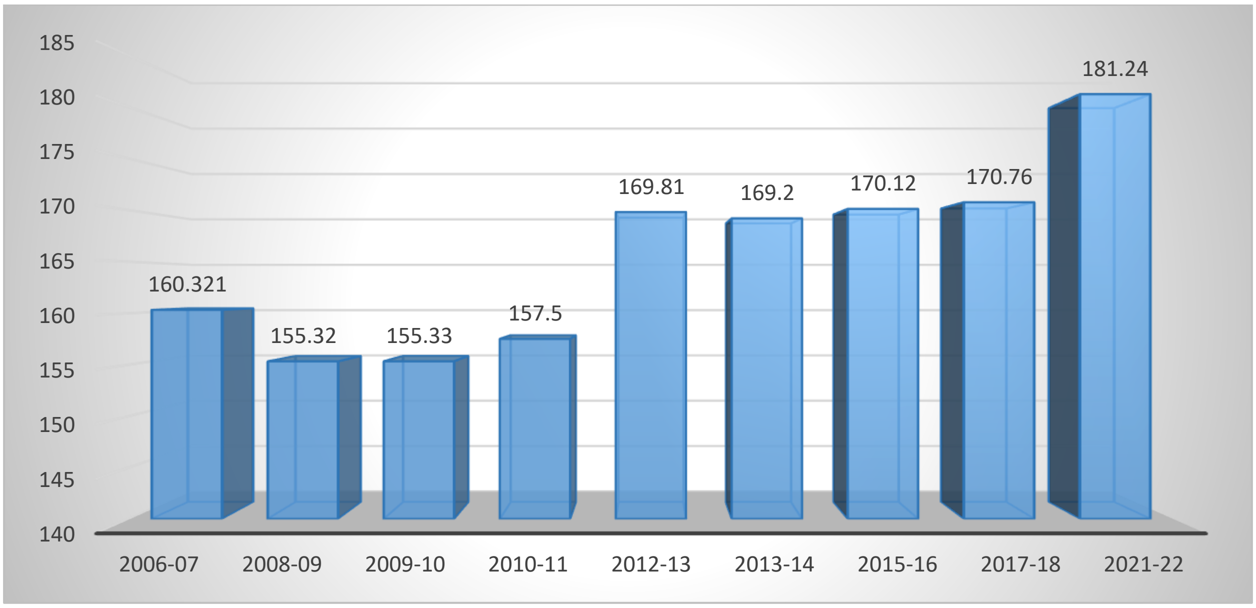

Figure 6: Cabbage Production in Bankura, 2006-07 to 2021-22

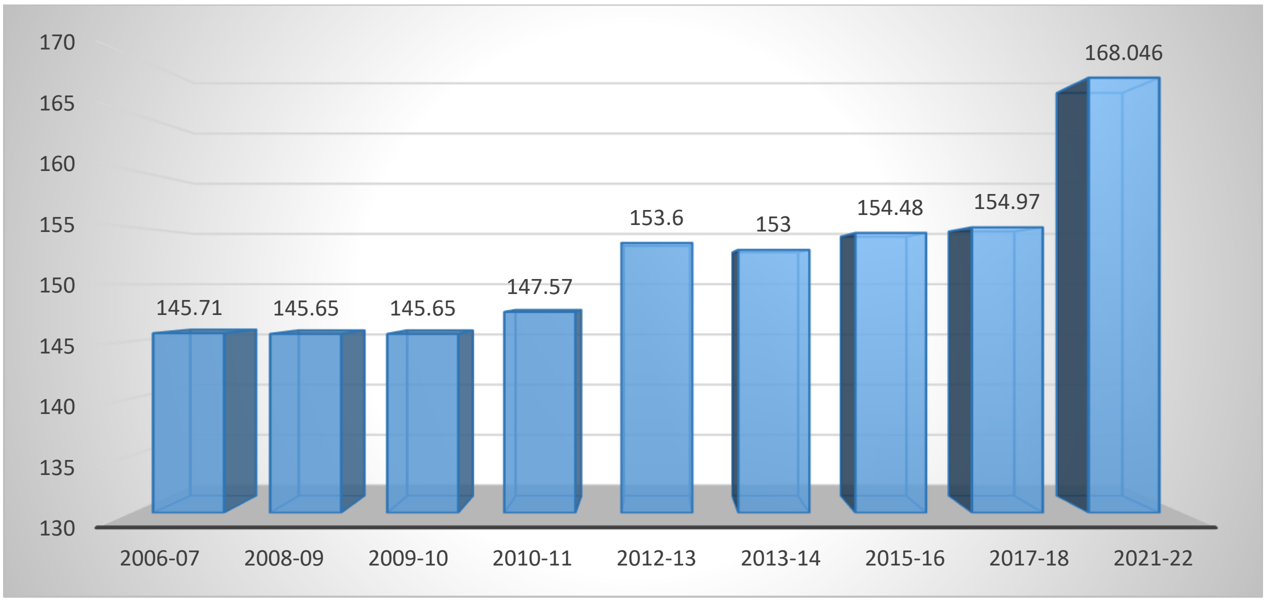

Figure 7: Cauliflower Production in Bankura, 2006-07 to 2021-22

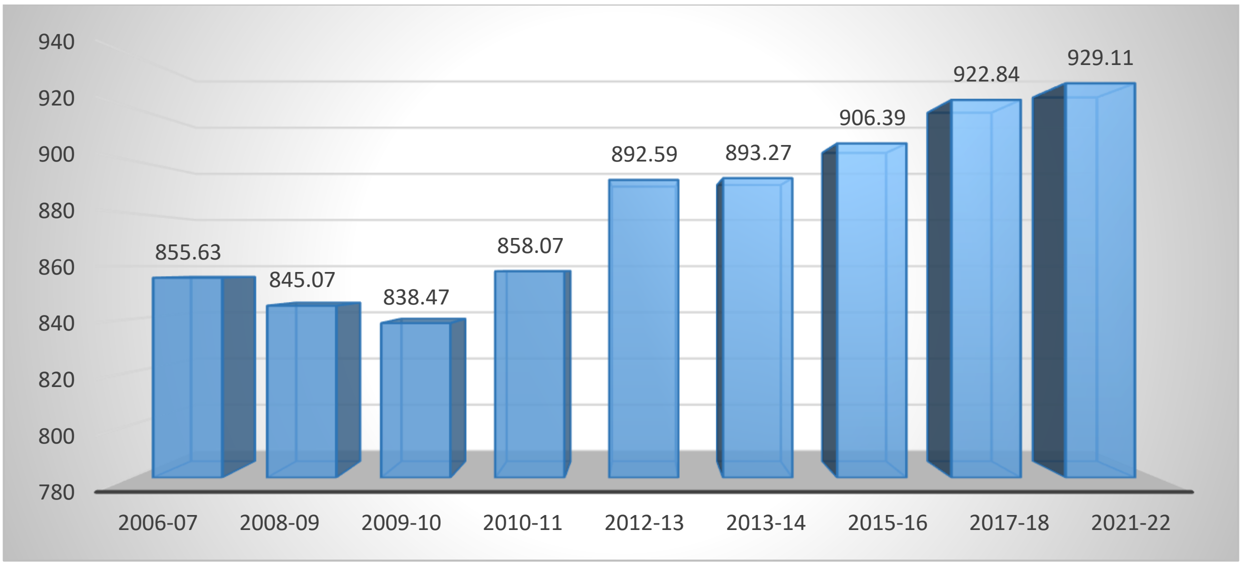

Figure 8: Total Vegetables Production in Bankura, 2006-07 to 2021-22

Overall, as seen in Table 2, it shows growth in horticultural production in Bankura district over the period of study and the consumption of fruits has growth rates that are higher compared to vegetables. Fruit cultivation, especially mango and citrus crops, has grown rapidly as a sign of the growing diversification of agriculture. In contrast, it can be said that vegetable production has been quite stable with very slight increases, with some crops such as onion and brinjal increasing. These trends point to a gradual change in the horticultural sector in Bankura district, with growing importance to fruit cultivation along with the traditional importance given to vegetables.

5.3 Productivity of Fruits and Vegetables in Bankura District (2007–08 to 2021–22)

This table-3 shows the productivity of the Bankura district of major fruits and vegetables in 2007-8 and 2021-22 and their Compound Annual Growth Ratio (CAGR). The statistics demonstrate the dynamics of horticultural output of the territory in the district during the period studied and contribute to the evaluation of the performance and efficiency of various fruits and vegetables.

The table shows different trends in productivity of various crops, which invoke different approaches towards the cultivation, adoption of technology, production and agro-climate conditions. It also facilitates interesting knowledge on the general growth trend of the horticultural sector within the Bankura district, which indicates areas that must be improved and crops whose productivity has either stagnated or reduced.

Fruit Productivity

The trend of productivity of fruits differs significantly from that of the crops. Papaya was also one of the top fruits to achieve relatively high productivity in the period of time, when it grew into 21,263 kg per hectare in 2007-08, to 27,267 kg per hectare in 202122, and with a CAGR of

1.67. This shows that the papaya production has been on a steady growth, perhaps as a result of improved varieties and the management practice of the crop.

There were some observable variations in the yields of mangoes throughout the years. It has experienced a decreasing trend in the initial years but has been on an increasing trend since then, with an increase in the amount of yeast between 3,525 kg per hectare in 2007- 08 and 4,478 kg per hectare in 2021-22, with a CAGR of 1.61 percent. This enhancement implies the slow improvement of the orchard management and practices of cultivation.

The productivity of guava also improved with the change from 9,929 to 12,473 kg per hectare of guava with a CAGR of 1.53 percent. On the same note, the productivity of sapota also increased by moderate values in the study period as it increased from 9586 kg per hectare to 10822 kg per hectare with a CAGR of 0.81 percent.

The productivity of bananas saw a comparatively steady improvement with slight growth by 10,712 to 11,634 kg/ha, with the CAGR being 0.55 percent. There was also a slight improvement in the productivity of jackfruits, as the yield had risen to 18,951 kg per hectare compared to the previous level of 17, 288kg per hectare with the CAGR of 0.61 percent.

Conversely, the productivity of pineapples dropped tremendously in the course of the research. It lowered to a minimum of 15, 000 kg/ha in 2007-08 to 5, 773 kg/ha in 2021-22(negative CAGR of -6.17 percent). Other citrus fruits registered a similar downward trend and their productivity decreased by a huge margin and showed a negative CAGR of 13.32 percent.

The trend of the average productivity of total fruits revealed a downward pattern, whereby the productivity decreased to 5,558 kg per hectare in 2021-22, respectively 9873kg per hectare in 2007-08. This decrease can be attributed to variations in production, alterations in the territory of cultivation, and a differentiation of orchard production.

The table presents the productivity levels of major fruits and vegetables in Bankura district from 2007-08 to 2021-22, measured in kilograms per hectare, along with their Compound Annual Growth Rate (CAGR). The data illustrate the changes in horticultural productivity in the district over the study period and help assess the performance and efficiency of different fruit and vegetable crops.

The table reveals varying trends in productivity across different crops, reflecting differences in cultivation practices, technological adoption, crop management, and agro-climatic conditions. It also provides important insights into the overall growth pattern of the horticultural sector in Bankura district, highlighting areas of improvement as well as crops where productivity has remained stagnant or declined.

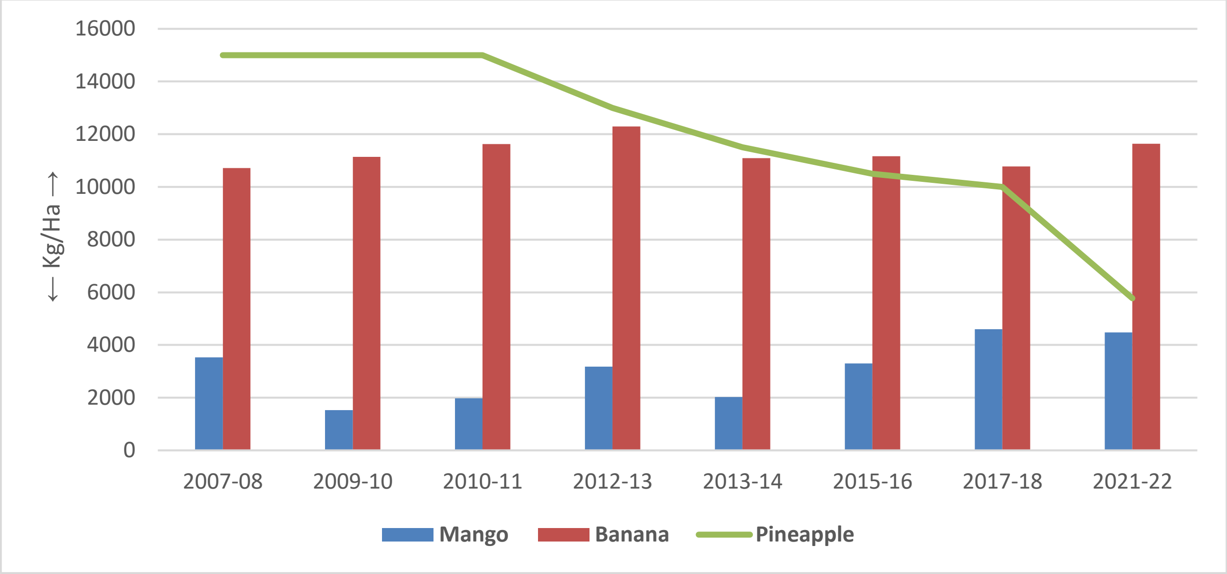

Figure 9: Mango, Banana and Pineapple Productivity (Kg/Ha), 2007-08 to 2021-22

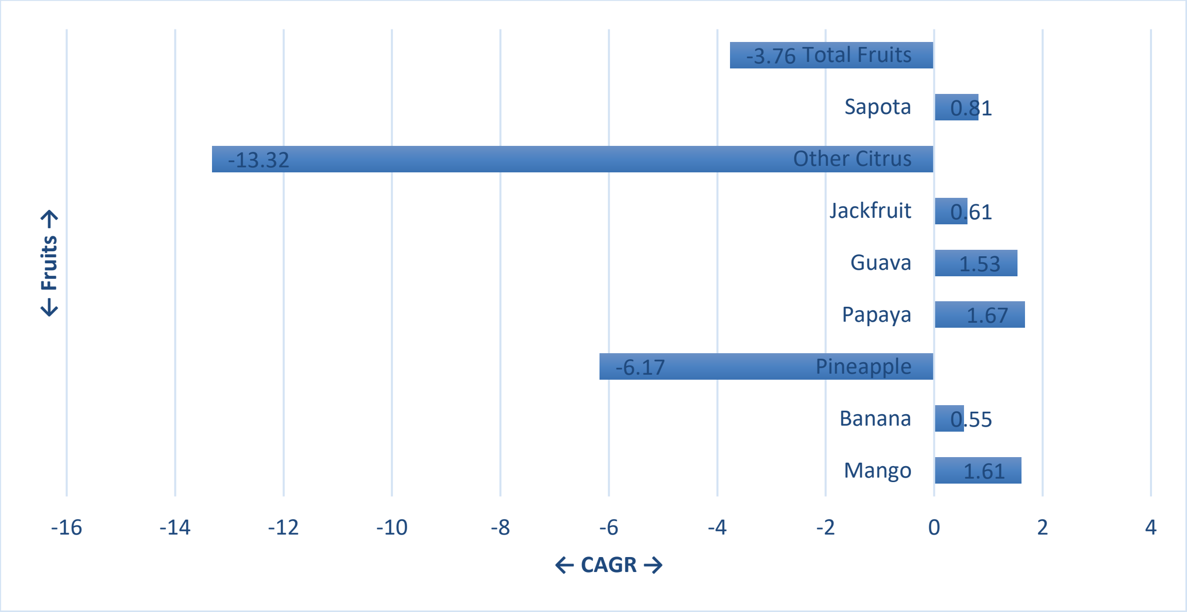

Figure 10: CAGR of Fruits in Bankura districts, 2007-08 to 2021-22

Vegetable Productivity

The trends of productivity of vegetable crops in the Bankura district tended to have more consistent isotope trends as compared to fruits. The total productivity of vegetables rose to 18, 642 kg per hectare in 2021-22 as compared to 16,447 kg per hectare in 2007-08 with a CAGR of 0.84 percent, which shows a slow progression of vegetable growth (Table 3 and Fig. 12).

Onion was the only vegetable that had a high productivity in 2021-22, as it reached 13771 kg per hectare as compared to 8987 kg per hectare in 2007-08, which had a CAGR of 2.89et cetera. This indicates a growing productivity in onion farming and possibly better methods of farming.

Table 3: Productivity Fruits and Vegetable Production per hectare (Kg/Ha), CAGR, 2007-08 to 2021-22

	07-08	09-10	10-11	12-13	13-14	15-16	17-18	21-22	CAGR 07-8 to 21-22
Fruits									
Mango	3525	1524	1972	3174	2024	3298	4592	4478	1.61
Banana	10712	11145	11625	12295	11091	11161	10776	11634	0.55
Pineapple	15000	15000	15000	13000	11500	10500	10000	5773	-6.17
Papaya	21263	21263	21421	28106	27647	27143	28417	27267	1.67
Guava	9929	10461	10556	11376	11481	11585	12918	12473	1.53
Jackfruit	17288	17288	17288	18519	18364	18436	18982	18951	0.61
Other Citrus	8575	7646	7694	8627	9216	9358	9419	1005	-13.32
Sapota	9586	9833	9833	9714	9857	10429	10571	10822	0.81
Total Fruits	9873	6945	7151	8575	7912	8597	9322	5558	-3.76
Vegetables									
Tomato	15615	15615	15669	16000	16133	16276	16380	16555	0.39
Cabbage	32428	32428	32474	32040	31805	31858	31858	31718	-0.15
Cauliflower	27429	27429	27429	26995	26842	26866	26905	27236	-0.05
Peas	4359	4359	4431	4318	4318	4338	5188	5345	1.37
Brinjal	19505	19505	20250	19654	19714	19741	19716	20843	0.44
Onion	8987	11519	11835	11687	11889	11563	13531	13771	2.89
Cucurbits	13704	12915	13183	13167	13158	13163	13051	13223	-0.24
Ladies Finger	11181	11181	11361	11169	11144	11131	11166	10805	-0.23
Radish	13876	13458	11243	13368	13109	13114	13299	14089	0.10
Others	5263	5551	5032	5805	5762	6375	7226	6250	1.15
Total Vegetables	16447	16313	14519	16318	16283	16320	16465	18642	0.84

Source: Statistical Handbook Bankura District

The growth in peas productivity was also moderate as the productivity increased to 5345 kg per hectare out of 4359 kg per hectare, having a CAGR of 1.37 per cent. On the same note, other vegetables increased by a notable margin, also with a CAGR of 1.15 percent.

Some of the vegetables were rather stable in terms of productivity. A good example is the fact that tomato productivity rose at a CAGR of 0.39 percent, with a resultant increase in tomato production by 15,615 kg per hectare to 16,555 kg per hectare and brinjal tomatoes with a resultant growth of 20,843 kg per hectare to 19,505 kg per hectare.

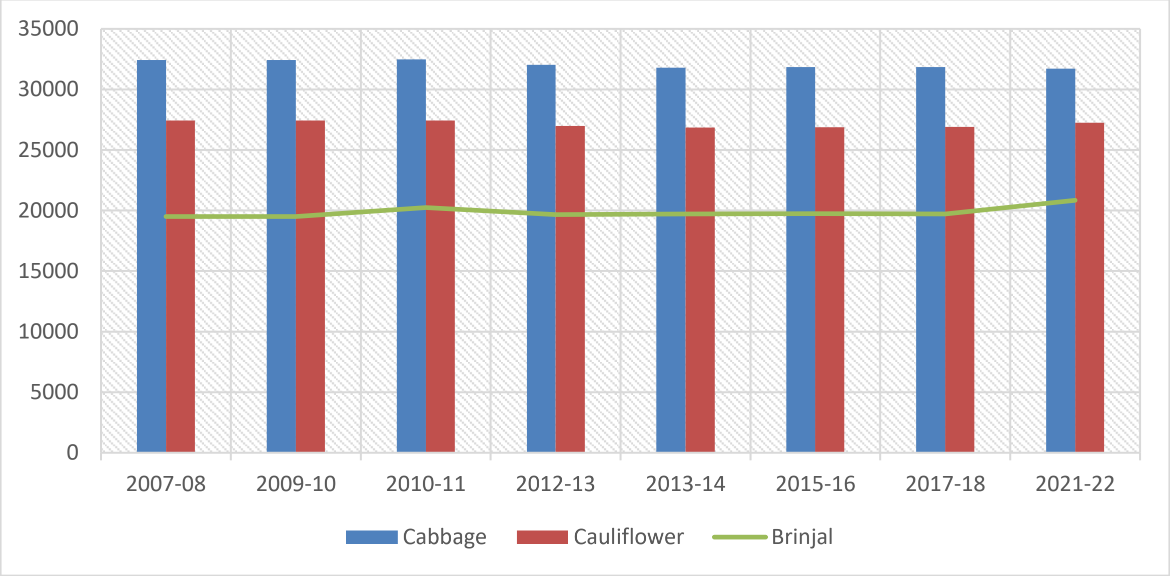

Figure 11: Cabbage, Cauliflower and Brinjal productivity (Kg/Ha) in Bankura District, 2007-08 to 2021-22

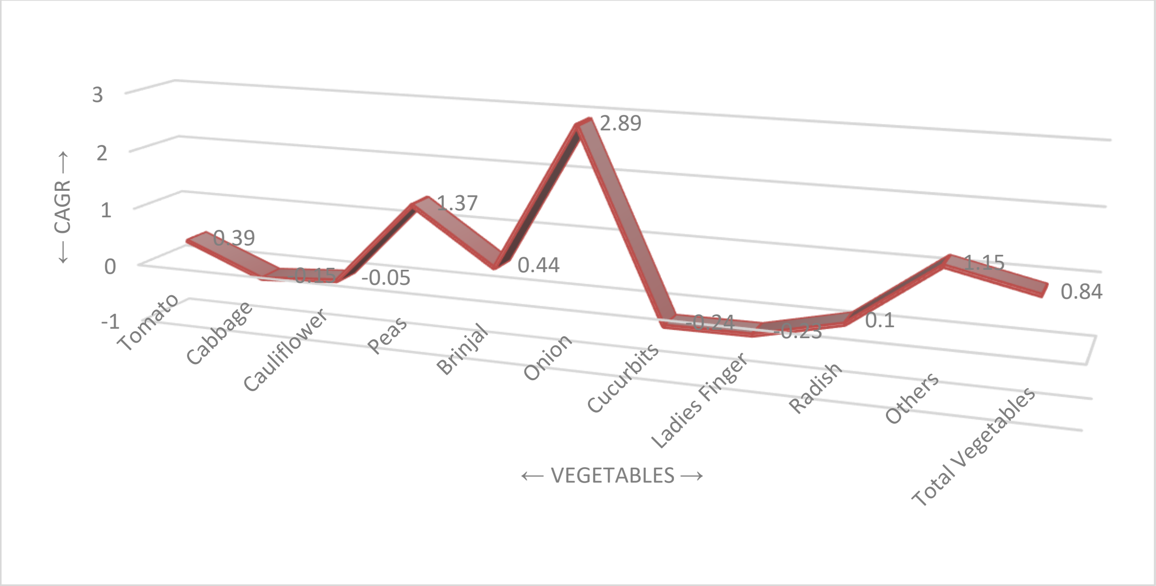

Figure 12: CAGR of Vegetables in Bankura District, 2007-8 to 2021-22

On the other hand, there were slight decreases in the productivity of some vegetables. Cabbage and cauliflower had an insignificant negative growth, a CAGR of -0.15 percent and -0.05 percent. Likewise, cucurbits and ladies' fingers also revealed a slight fall in productivity, indicating no improvement in the yield.

In general, the table shows inconsistent changes in the horticultural production in Bankura district. Some of the fruit crops like papaya, mango and guava have registered moderate rates of growth, whereas others like the pineapple and citrus fruits have registered significant losses. Conversely, vegetable yields were quite constant with smooth increases in production, especially on the crops of onion and peas. These trends indicate that even though the horticultural cultivation has increased in the district, productivity growth in various crops has not been uniform, which means that technological assistance should be enhanced, more varieties should be developed, and the management of crops should be advanced to ensure the horticultural sector continues to achieve productivity improvement.

5.4 Factors Influencing Fruits and Vegetable Productivity in Bankura District

Table 4 shows the output of a regression model that investigates the relation among different agricultural and infrastructural variables and their impact on the fruit and vegetable production in Bankura district between the years 2001-02 and 2021-22. Overall, the model is very good with an R^2 of 0.76, which means that approximately 76 percent of the variance in the yield is accounted for by the variables that it includes. A reasonably good fit is also verified based on the number of predictors since the adjusted R^2 was 0.66. Further, the F-value (7.69) indicates that the model is statistically significant at the 1% level, meaning that the variables collectively explain a lot.

The intercept (5780.82) is not only positive but also significantly high at the 1 per cent level, which suggests a strong and statistically quality base level of fruits and vegetables production in the district even at a constant of all the explanatory variables. This implies that there exist other background factors, say, natural soil fertility, handicraft farming experience, or even good agro-climatic conditions that help bring a high starting point of productivity in Bankura.

The Cropping Intensity Coefficient is positive (24.905) and significant at the 5 percent level, and thus it plays a significant role in optimizing the horticultural production. This means that when the number of crops planted on the same land in a year increases, the fruits and vegetables produced will increase by a measure. The outcome is an increase in how well land is utilized, multiple systems of crop production, and may be the increase in the scheduling of irrigation and the planned production of crops. It also signals a transition towards more productive and efficient agriculture, which makes the most of scarce land resources.

The relationship between storage house beneficiaries and storage house is also positive and statistically significant (coefficient = 2.560) at the 5% level. This highlights the significance of post-harvest infrastructure in the productivity of agriculture. Availability of storage facilities helps farmers to minimize losses related to spoilage and post-harvest on commodities that are perishable, such as fruits and vegetables. In addition, it enables farmers to bypass inconvenient sales and store fruits and sell them at a better age when the market conditions are more favorable, thus enhancing yield realisation in addition to income stability indirectly.

The coefficient of Annual Rainfall (0.532) is positive and significant at the 10% level, which shows that it has a moderate but significant effect on the productivity. This implies that rainfall is still supportive in the growth of crops, particularly in an area such as Bankura, which is partially reliant on monsoon rains in its agriculture sector. Sufficient rainfall in adequate amounts and at the right time can increase soil moisture and help avoid irrigation, thereby supporting crop growth. Nevertheless, the lower level of significance also suggests that rainfall is not the determining factor, likely because of greater reliance on additional irrigation and improved irrigation practices.

Table 4: Percentage of Irrigated Area, Fertilizer Use Per Hectare, Storage house beneficiaries, Road Density and Annual Rainfall in Relation to Fruits and Vegetables Yield in Bankura, 2001-02 to 2021-22

Variables	Coefficients	Standard Error	t Stat	P-value
Intercept	5780.82	1593.671	3.627	0.0027***
Cropping Intensity	24.905	10.3423	2.408	0.0303**
Storage house beneficiaries	2.560	2.922075	2.105	0.050**
Road Density	228.234	492.8406	0.463	0.650
Fertilizer use per hactare	4.689	9.846082	0.476	0.641
% Irrigated Area	4.573	15.40082	0.296	0.770
Annual Rainfall(mm)	0.532	0.344762	2.045	0.084*
R Square = 0.76 Adjusted R Square = 0.66 Observations = 21 F Value= 7.69 Model Significant 1 % level				

*** Indicates coefficient significant at 1 percent level,

** Indicate coefficient significant at 5 percent level, * Indicates coefficient significant at10 percent level.

Conversely, some variables turned out to be insignificant statistically and their independent actions on the yield of fruits and vegetables were not substantial within the framework of this model:

The positive but statistically insignificant impact is exhibited by the Road Density (coefficient = 228.234, p = 0.650). Even with the generally better access to the market and supply of inputs through better road infrastructure, its direct impact on yield does not seem to have much impact. This implies that roads are vital in marketing and distribution, but do not have a significant impact on productivity in the field.

The use of fertilizers on a hectare (coefficient = 4.689, p = 0.641), too, is not significant, meaning that the higher the level of fertilizers applied to various hectares, the higher the yield in this scenario. This may be because of unbalanced or inefficient fertilizer application, decreasing soil responsiveness, or already adequate application levels. It can also be used to demonstrate the weight of integrated nutrient management as opposed to the weight of fertilizer utilization.

Correspondingly, the percentage of irrigated area (4.573 coefficient, p = 0.770) is also positive, but it is so meaningless that it is somewhat an unexpected outcome. This result seems to imply that the simple increase in the coverage of irrigation cannot ensure an increase in the productivity of fruits and vegetables. Some of the possible reasons could be inefficient water use or an inappropriate choice of crops to be planted under the irrigation or sufficient rainfall that diminishes the marginal contribution of irrigation. It can also show that the management and quality of irrigation systems are more important than their size.

Conclusion

The current paper analyzes how the trends of production of fruit and vegetables in Bankura district of West Bengal vary and what are the primary determinants of its production during the period between the years 2001-02 and 2021-22. Using secondary data and regression analysis, however, the category "other vegetables" shows a sharp decrease in the recent period, which significantly affected the total vegetable area and contributed to the negative growth rate in the overall total in recent years. All in all, the trend indicates that in general, vegetable production is a significant part of agriculture in the Bankura district but has grown in a fairly stable manner with slight fluctuations based on the market demand, weather and alterations in the cropping habits of the farmers.

The area of vegetable cultivation occupies a significantly greater portion of the cultivated land in comparison with fruit crops, which form an important crop in consideration of the dietary requirements and aid farmers to get regular earnings in the district of Bankura. Nevertheless, the general trend of extended vegetable farming throughout the process of study has been average, with few variations.

The data demonstrates some remarkable changes in the horticultural sector, particularly the growth in fruit production in comparison with rather stable development in the vegetable cultivation. Although fruits have registered a relatively higher growth rate, the vegetable production in the district is really enormous and is still reigning supreme in the total horticultural output in the district. These trends are seen as a reflection of the increasing importance of horticulture as a time-bound diversification of agriculture, income generation and the change in cropping pattern of Bankura district

The paper finds the contribution of factors like concerns on the intensity of cropping, irrigation, application of fertilizers, rainfall, density of roads and inventory on storage as determinants of horticultural abundance. The findings indicate that production is greatly increased by cropping intensity and storage facilities, whereas rainfall is moderately important. On the contrary, irrigation, the use of fertilizer, and the density of roads have little direct influence. The research underscores the increasing significance of institutional and management aspects compared with the conventional inputs in influencing the outcomes of agriculture.

Of the variables, the positive and significant effect of cropping intensity is evident, which indicates that multiple cropping and enhanced land use lead to an increase in yields. In the same manner, storage facilities are important aspects because better infrastructures in the form of post-harvest storage minimize loss and lead to efficiency. The moderate impact of rainfall is also positive, indicating that it is still significant in a monsoon-based agricultural system.

Another contrasting aspect is the statistically insignificant road density, fertilizer use, and irrigation. These factors are typically significant to the world of agriculture; however, in this situation, their direct effect on yield seems to be minimal. This could be as a result of inefficient use, diminishing returns or the increased significance of management practices and infrastructure over traditional inputs.

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E-AGRICULTURE AND SMART FARMING TECHNOLOGIES

Akshyaika Jena[1], Chinmayee Patra*[2], Abhiram Dash[1] and Ameesha Rani Das[1]

[1]Department of Agricultural Statistics, College of Agriculture,
Odisha University of Agriculture and Technology, Bhubaneswar
[2]Department of Agricultural Statistics, College of Agriculture,
Odisha University of Agriculture and Technology, Chiplima
*Corresponding author E-mail: chinmayee6395@gmail.com

Abstract

Agriculture is undergoing a major transformation due to rapid advancements in Information and Communication Technology (ICT), Artificial Intelligence (AI), Internet of Things (IoT), robotics, drones, cloud computing, and data analytics. Traditional farming systems are gradually shifting toward digital and smart agriculture to improve productivity, resource-use efficiency, sustainability, and profitability. E-Agriculture refers to the application of digital technologies, communication systems, and internet-based services in agriculture for knowledge dissemination, farm management, market access, and decision-making. Smart farming technologies involve the integration of advanced tools such as sensors, automation systems, GPS, drones, machine learning, and precision agriculture techniques to optimize agricultural operations. These technologies help farmers monitor crops, manage resources efficiently, reduce production costs, and improve agricultural sustainability. In India, several initiatives by the Indian Council of Agricultural Research (ICAR), government agencies, and private organizations are promoting digital agriculture and smart farming practices. This chapter discusses the concept of e-agriculture, components of smart farming, major technologies used in agriculture, applications, benefits, challenges, Indian initiatives, and future prospects of digital agriculture.

1. Introduction

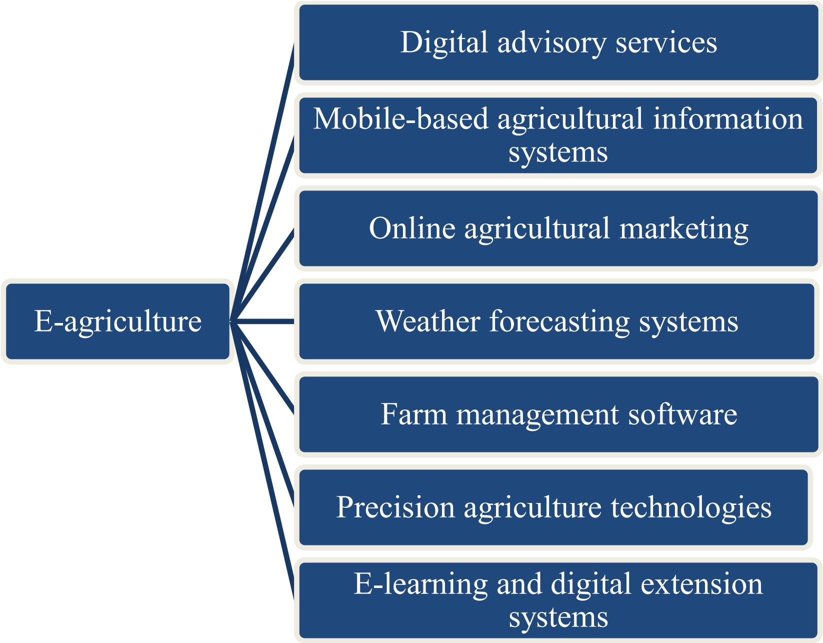
Agriculture is the backbone of the Indian economy and supports the livelihood of a large proportion of the population. However, the agricultural sector faces several challenges, such as climate change, declining land holdings, labour shortages, water scarcity, low productivity, and market uncertainties. Traditional agricultural practices alone are no longer sufficient to meet the growing food demand of the increasing population. The rapid development of Information and Communication Technology (ICT) has created new opportunities for agricultural modernization. The use of digital technologies in agriculture has led to the emergence of concepts such as e-agriculture, digital agriculture, precision agriculture, and smart farming.

E-agriculture refers to the use of ICT tools and digital technologies for agricultural development and rural empowerment. It includes internet-based advisory systems, mobile applications, digital marketplaces, weather forecasting systems, online extension services, and decision support systems. Varshney and Singh explained that ICT initiatives in India are playing an important role in agricultural knowledge dissemination, e-extension services, digital learning, market intelligence, and automation in agriculture.

Smart farming refers to the application of advanced technologies such as AI, IoT, drones, robotics, remote sensing, and automation for efficient farm management. Smart farming enables real-time monitoring and data-driven decision-making, helping farmers improve productivity and sustainability. According to Mehta et al., smart agriculture combines sensors, controllers, automation systems, and ICT tools to improve agricultural efficiency and precision. The integration of e-agriculture and smart farming technologies is transforming conventional agriculture into a modern, sustainable, and technology-driven sector.

2. Concept of E-Agriculture

E-agriculture is a broad term that refers to the use of digital technologies and ICT in agriculture and rural development. It includes:



The Food and Agriculture Organization recognizes e-agriculture as an important tool for improving agricultural productivity, communication, and rural livelihoods. Tiwari highlighted that India has witnessed significant growth in ICT-based agricultural initiatives such as e-Choupal, Bhoomi, Gyandoot, Village Information Centres, and digital agricultural knowledge networks. E-agriculture helps bridge the information gap between research institutions, extension agencies, and farmers.

3. Smart Farming Technologies

Smart farming involves the use of advanced digital technologies for precise and efficient farm management. The major smart farming technologies include:

3.1 Internet of Things (IoT)

IoT refers to interconnected devices and sensors that collect real-time data from agricultural fields. IoT devices monitor: Soil moisture

- Temperature
- Humidity
- Crop health
- Water availability
- Livestock movement

These sensors help farmers make informed decisions regarding irrigation, fertilization, and crop management. ICAR launched an e-Crop based smart farming facility using IoT and AI technologies to improve precision farming and farmer income.

3.2 Artificial Intelligence (AI)

AI technologies analyze agricultural data and provide predictive recommendations. Applications of AI include:

- Crop disease detection
- Yield prediction
- Weather forecasting
- Pest monitoring
- Precision irrigation

AI helps farmers improve productivity while reducing input costs and environmental impacts. Recent AI-driven agricultural projects in India are focusing on genomics, drone-based monitoring, and precision farming technologies.

3.3 Drones and Remote Sensing

Drones are increasingly used in agriculture for aerial monitoring and precision spraying. Drone technologies help in:

- Crop health monitoring
- Disease detection
- Weed mapping
- Precision pesticide application
- Yield estimation

Remote sensing technologies provide satellite-based crop information for large-scale agricultural management.

3.4 Geographic Information System (GIS)

GIS technologies help analyze spatial data related to soil, land use, water resources, and crop distribution. GIS-based systems support:

- Land suitability analysis

- Crop planning
- Precision nutrient management
- Water resource management

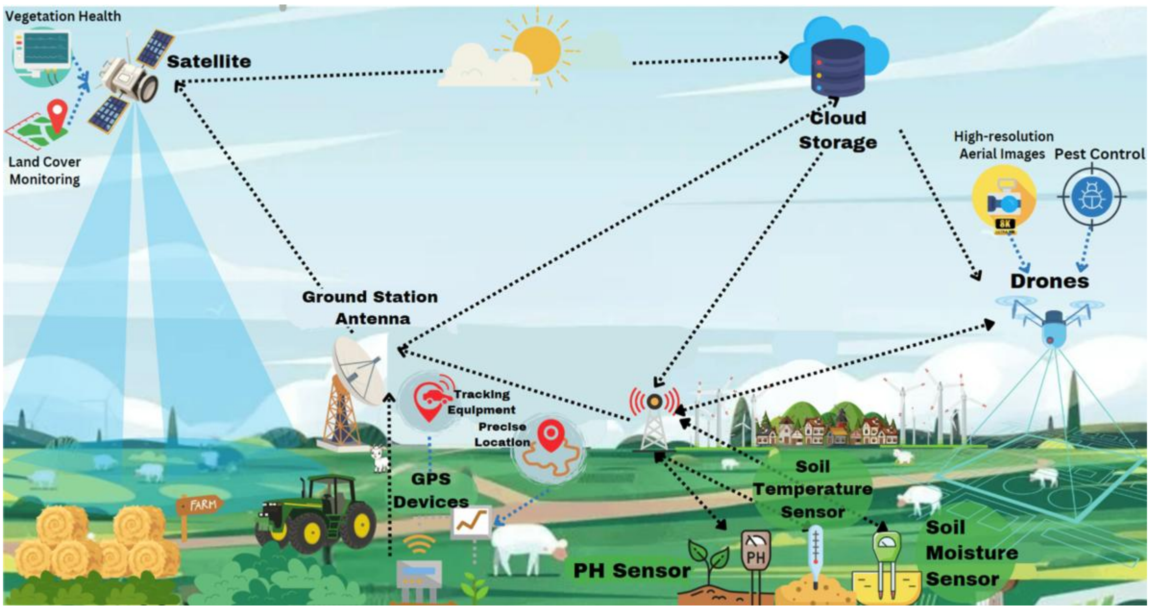


Figure 1: Overview of GIS application in agriculture

(Source: https://assets.cureusjournals.com/)

3.5 Robotics and Automation

Agricultural robots are used for:

- Automatic planting
- Harvesting
- Spraying
- Weeding
- Sorting and grading

Automation reduces labour dependency and improves operational efficiency. Jha et al. reported that automation technologies are transforming modern agricultural systems and improving farm productivity.

3.6 Cloud Computing and Big Data

Cloud computing enables storage and processing of large agricultural datasets. Big data analytics helps analyze:

- Weather data
- Soil data
- Crop performance
- Market trends
- Pest outbreaks

Wolfert et al. emphasized that big data technologies are becoming essential components of smart farming systems.

4. Applications of E-Agriculture and Smart Farming

4.1 Precision Agriculture

Precision agriculture involves site-specific management of crops using digital technologies.

It helps optimize:

- Fertilizer application
- Irrigation scheduling
- Pest management
- Seed placement

Zhang et al. described precision agriculture as a modern farming approach that improves productivity and input-use efficiency.

4.2 Smart Irrigation Systems

Smart irrigation systems use sensors and weather data to determine the exact water requirement of crops. Benefits include:

- Water conservation
- Reduced energy use
- Improved crop growth
- Prevention of waterlogging

These systems are particularly important in drought-prone regions.

4.3. Digital Agricultural Advisory Services: Mobile applications and online platforms provide farmers with:

- Weather forecasts
- Pest alerts
- Market prices
- Crop management recommendations

Digital advisory systems improve farmers' access to scientific information.

4.4. Online Agricultural Marketing: E-agriculture supports digital marketplaces where farmers can sell agricultural produce directly. Examples in India include:

- eNAM (National Agriculture Market)
- Agri-market mobile applications
- Online input purchasing platforms

These platforms improve market access and reduce middleman exploitation.

4.5. Smart Greenhouse Farming: Smart greenhouse systems use automation technologies to control temperature, humidity, light, and irrigation. These systems improve:

- Crop productivity

- Resource efficiency
- Quality of produce

4.6. Livestock Monitoring: Smart sensors and wearable devices monitor animal health, feeding behaviour, and milk production. These technologies support precision livestock farming and improve animal welfare.

5. Indian Initiatives in E-Agriculture and Smart Farming

India has launched several initiatives to promote digital agriculture and smart farming practices.

5.1 Digital Agriculture Mission

The Government of India launched the Digital Agriculture Mission to promote AI, IoT, drones, and digital databases in agriculture. The mission aims to improve agricultural efficiency and farmer services.

5.2 eNAM (National Agriculture Market)

eNAM is an online agricultural marketing platform that integrates agricultural markets across India. It helps farmers access better prices and transparent marketing systems.

5.3 ICAR Smart Farming Initiatives

The Indian Council of Agricultural Research has developed several smart farming technologies. ICAR-CTCRI launched an e-Crop-based smart farming facility integrating AI and IoT technologies for precision farming. ICAR-CIAE has also developed smart mechanization tools and digital machinery recommendation systems for farmers.

5.4 Mobile-Based Agricultural Apps

Several mobile applications are helping Indian farmers access agricultural information. Examples include:

- Kisan Suvidha
- Meghdoot
- eNAM app
- IFFCO Kisan app
- Plantix

These applications provide weather information, pest management advice, and market intelligence.

5.5 Smart Farming Research and Innovation: Indian institutions such as IITs and agricultural universities are researching AI-driven agriculture, drone technologies, and IoT-based crop monitoring systems.

6. Benefits of E-Agriculture and Smart Farming

- **Increased Productivity:** Digital technologies improve crop management and enhance agricultural output.

- **Efficient Resource Utilization:** Smart systems optimize the use of water, fertilizers, pesticides, and energy.
- **Reduced Production Cost:** Automation and precision technologies reduce labour and input costs.
- **Improved Decision-Making:** Real-time data helps farmers make accurate and timely decisions.
- **Better Market Access:** Digital platforms improve farmers' connectivity with markets and consumers.
- **Environmental Sustainability:** Precision farming reduces excessive chemical use and environmental pollution.

7. Challenges in E-Agriculture and Smart Farming

Despite several advantages, adoption of digital agriculture faces multiple challenges.

- **High Initial Investment:** Advanced technologies such as drones and sensors require significant investment.
- **Lack of Digital Literacy:** Many farmers lack the technical skills to use digital tools effectively.
- **Poor Internet Connectivity:** Rural regions often face inadequate internet infrastructure.
- **Small Land Holdings:** Small and fragmented farms create difficulties in technology adoption.
- **Data Privacy and Security Issues:** Digital agriculture systems involve large-scale data collection and management. Chetri et al. observed that ICT accessibility and information flow significantly influence farmers' adaptive capacity to climate risks in India.

Figure 2: Smart Farming: The future of agricultural industry

(Source: https://worldbusinessoutlook.com)

8. Future Prospects of Smart Farming

The future of agriculture is increasingly becoming technology-driven. Emerging technologies likely to shape future agriculture include:

- Autonomous tractors and robots
- AI-powered farm advisory systems
- Blockchain-based traceability systems
- Satellite-based crop monitoring
- Smart climate forecasting systems
- Fully automated greenhouses

Agriculture technologies, integrating AI, IoT, cloud computing, and robotics, are expected to transform agricultural production systems globally. India is also rapidly expanding smart farming research and digital agricultural infrastructure to improve sustainability and food security.

Conclusion

E-agriculture and smart farming technologies are revolutionizing modern agriculture by integrating digital tools, automation systems, and data-driven decision-making into farming practices. Technologies such as AI, IoT, drones, GIS, robotics, cloud computing, and mobile applications are improving productivity, resource-use efficiency, sustainability, and market access. In India, government initiatives, ICAR programs, digital agricultural platforms, and research institutions are playing a major role in promoting smart agriculture. Although challenges such as high costs, poor digital literacy, and infrastructure limitations exist, continuous technological advancements and policy support are expected to accelerate the adoption of digital agriculture. The integration of e-agriculture and smart farming technologies has immense potential to ensure sustainable agricultural development, improve farmer livelihoods, and strengthen food security in the future.

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About Editors

Dr. Samir Show is an Assistant Professor & HOD, Department of Economics at Kumarganj College under the University of Gour Banga, with more than 20 years of experience in teaching at the School and undergraduate levels. He has a Ph.D. and M.Sc. in Economics from Vidyasagar University and an MBA from Mizoram University. He has passed UGC-NET and SET (WB) as well. His areas of interest are rural development, agricultural economics and interdisciplinary studies. Dr. Show has written more than 30 research papers in renowned journals (Scopus Index) and has given talks at national and international conferences. His two books, namely 'Crop Diversification and Rural Development in India' and 'Sustainable Rural Development through Agricultural Diversification,' has been published. He has also worked in academic administration, serving as Bursar, IQAC Coordinator, Examination Coordinator, NSS Programme Officer and Project Supervisor under NEP 2020.

Dr. Swatilekha Mohanta obtained her B.Sc. (Ag.), M.Sc. (Ag.) in Nematology, and Ph.D. from the College of Agriculture, OUAT, Bhubaneswar, in 2008, 2010, and 2015, respectively. She qualified ASRB–NET in Nematology in 2014 and possesses over 11 years of teaching and research experience. Since February 2015, she has been serving as Assistant Professor (Nematology) at the College of Agriculture, OUAT, Chiplima. Dr. Mohanta has published 15 research papers, one book, an ICAR–JRF objective book, practical manuals, training manuals, and several popular articles. She received the Young Academician Award in Agriculture Science from Sabujeema in 2021, the Best Teacher Award from SAAST in 2024, and the Excellence in Teaching Award from ISASTR in 2025. She has guided four M.Sc. students and currently supervises five postgraduate scholars in the field of nematology.

Dr. Sagar A. Vhanalakar is Associate Professor, Coordinator (B.Sc. Wing), and Head, Department of Zoology at Shri Mouni Vidyapeeth's Karmaveer Hire Arts, Science, Commerce and Education College, Gargoti, Kolhapur, Maharashtra, India. He earned his Ph.D. from Shivaji University, Kolhapur, in 2010. Dr. Vhanalakar has 16 years of teaching and 20 years of research experience, with research interests in aquaculture and fisheries, limnology, and biodiversity. He has published 50 research papers, 15 book chapters, 16 books, and edited 18 books. He holds two international patents and has presented papers at over 75 conferences. He also served as IQAC Coordinator, contributing to the institution's NAAC 'A' Grade accreditation. Dr. Vhanalakar actively participates in social awareness programs, women SHG guidance, and environmental conservation activities.

Dr. Abhiram Dash is an Agricultural Scientist and presently heads the Department of Agricultural Statistics, College of Agriculture, OUAT, Bhubaneswar. He obtained his B.Sc. (Ag.) and M.Sc. (Ag.) in Agricultural Statistics from Odisha University of Agriculture and Technology and earned his Ph.D. in Agricultural Statistics from Visva-Bharati, Santiniketan, West Bengal. He possesses over 14 years of teaching and research experience. Dr. Dash has published more than 60 research papers, 11 book chapters, 4 books, 7 practical manuals, 21 lecture notes, one research manual, and 3 research compendiums. He has guided numerous postgraduate and Ph.D. scholars and organized training programs on APP development, Big Data Analysis, and Artificial Intelligence in Agriculture. His expertise includes statistical modelling, time series forecasting, experimental design, Artificial Neural Networks, and Machine Learning applications in agriculture.

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