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AGRICULTURAL FUTURES:

SMART FARMING AND NEXT-GENERATION AGRICULTURE

VOLUME II

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PREFACE

Agriculture is undergoing a profound transformation driven by technological innovation, environmental challenges, changing food demands, and the need for efficient resource management. *Agricultural Futures: Smart Farming and Next-Generation Agriculture* explores this transformation and presents emerging approaches that are reshaping agricultural production, sustainability, and rural development. The book brings together contemporary perspectives on the integration of science, technology, data, and innovative management practices in agriculture. Smart farming represents a shift from conventional, input-intensive approaches toward knowledge-based, precise, connected, and resource-efficient agricultural systems. Technologies such as artificial intelligence, Internet of Things, remote sensing, geographic information systems, drones, robotics, automation, satellite imagery, sensors, big data analytics, and digital platforms are creating new opportunities for monitoring crops, optimizing inputs, improving productivity, and strengthening decision-making. At the same time, climate change, soil degradation, water scarcity, biodiversity loss, and increasing production costs demand agricultural systems that are resilient and environmentally responsible.

This volume examines important dimensions of next-generation agriculture, including precision farming, digital agriculture, sustainable crop production, smart irrigation, protected cultivation, agricultural biotechnology, soil and water management, climate-smart practices, farm mechanization, agri-entrepreneurship, and emerging digital solutions. It also highlights the importance of integrating indigenous knowledge, scientific research, farmer participation, and institutional support to ensure that technological advancement remains inclusive and accessible.

The contributions in this volume provide valuable insights for researchers, academicians, students, agricultural professionals, policymakers, entrepreneurs, extension workers, and progressive farmers. By presenting diverse scientific and applied perspectives, the book seeks to encourage interdisciplinary collaboration and innovative thinking.

We hope *Agricultural Futures: Smart Farming and Next-Generation Agriculture* serves as a useful academic and professional resource, inspiring readers to explore emerging technologies and sustainable practices that can strengthen food security, enhance farmer livelihoods, conserve natural resources, and build a resilient agricultural future.

- Editors

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DIGITAL TRANSFORMATION IN AGRICULTURE: SMART FARMING TECHNOLOGIES, AGRIBUSINESS OPPORTUNITIES AND ADOPTION CHALLENGES

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Abstract

Digital transformation is reshaping agriculture by integrating artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), remote sensing, geographic information systems, crop modelling, digital platforms, and other data-driven technologies into farm and agribusiness decision-making. This chapter synthesizes recent evidence on digital and climate-smart agriculture to examine how smart-farming technologies are being applied, the agribusiness opportunities they create, and the factors that constrain their adoption. The evidence demonstrates applications in precision irrigation, crop-yield forecasting, soil and greenhouse-gas monitoring, pest and disease management, crop mapping, climate-risk assessment, autonomous farm management, digital advisory services, traceability, and agribusiness resilience. AI/ML is increasingly integrated with remote sensing, sensors, crop models, and decision-support systems to strengthen prediction and resource-use efficiency, while IoT enables real-time monitoring and satellite and UAV technologies extend digital intelligence from individual fields to broader landscapes. At the same time, technological performance alone does not guarantee successful adoption. High costs, inadequate connectivity, limited digital skills, financing constraints, data limitations, interoperability challenges, weak institutional support, and unequal access remain important barriers. From an agribusiness perspective, digital transformation creates opportunities for precision-agriculture services, digital advisory platforms, agri-finance, data-enabled services, smart supply chains, climate-risk management, and technology-enabled entrepreneurship. The chapter proposes an integrated pathway linking digital technologies with decision-making, value creation, institutional support, and sustainability outcomes. The future of smart farming will therefore depend not only on technological advancement, but also on the development of affordable, interoperable, inclusive, and farmer-centred digital ecosystems.

Keywords: Digital Agriculture, Smart Farming, Artificial Intelligence, Machine Learning, Internet Of Things, Agriculture 4.0, Agribusiness, Technology Adoption.

1. Introduction

Agriculture is rapidly transitioning toward data-driven, connected, and adaptive farming systems, supported by advances in artificial intelligence (AI), machine learning (ML), Internet of Things (IoT), remote sensing, crop modelling, and digital decision-support technologies (Mandour *et al.,* 2026; Mgana *et al.,* 2025). These technologies are increasingly being applied to crop management, irrigation, soil monitoring, climate-risk assessment, pest and disease management, and resource optimization (Hamdouni, 2026; Ramu *et al.,* 2025).

Smart farming is also evolving from isolated technological applications toward integrated digital ecosystems that combine sensing, data processing, prediction, and decision-making (Guo *et al.,* 2026). AI and remote sensing are being used for crop-yield and climate-risk prediction (Aboulhosn *et al.,* 2026; Reddy *et al.,* 2025), while IoT-based systems enable real-time monitoring of soil, weather, crops, and production environments (Ramu *et al.,* 2025; Pelekamoyo *et al.,* 2026). The integration of crop models with machine learning and digital technologies is further strengthening climate-adaptive agricultural decision-making (Devkota *et al.,* 2025; Mgana *et al.,* 2025).

The transformation extends beyond farm production to the broader agribusiness ecosystem, creating opportunities in precision-agriculture services, digital advisory systems, smart supply chains, digital finance, traceability, and technology-enabled entrepreneurship (Saxena *et al.,* 2025; Liu & Li, 2025). Digital agricultural platforms can connect farm-level information with crop monitoring, irrigation management, and production recommendations, thereby supporting more efficient and differentiated agricultural services (Raksapatcharawong & Veerakachen, 2025). Integrated digital systems can additionally enhance traceability, quality monitoring, and supply-chain transparency (Safeer *et al.,* 2025).

Despite these opportunities, digital transformation remains uneven across agricultural systems. High investment costs, inadequate connectivity, limited digital skills, financing constraints, data limitations, and weak institutional support continue to restrict adoption, particularly among smallholders (Ramu *et al.,* 2025; Antwi-Agyei *et al.,* 2025). Education, access to credit, extension services, climate information, and training can substantially influence adoption and farm-level outcomes (Bibi, 2025; Mahama *et al.,* 2025). Recent evidence further highlights the importance of targeted financial incentives and capacity building in overcoming barriers to climate-smart technology adoption (Sainath *et al.,* 2026).

Against this background, this chapter examines digital transformation in agriculture through the lens of smart-farming technologies, agribusiness opportunities, and adoption challenges. It synthesizes recent evidence to identify major digital technologies, their agricultural and business applications, emerging value-creation opportunities, and the technological, financial, institutional, and human-capital conditions required for effective, inclusive, and scalable adoption.

2. Evidence Base and Analytical Approach

This chapter draws on a structured body of recent research on digital and climate-smart agriculture to synthesize major technological developments, agricultural applications, agribusiness opportunities, and adoption challenges. The evidence covers key aspects of each study, including the agricultural sector, crop or commodity, geographic context, climate-related challenge, digital innovation, technologies or models used, methodological approach, major findings, outcomes, barriers, and research gaps.

For the synthesis, the evidence was organized into seven broad domains: (i) artificial intelligence and machine learning, (ii) IoT and sensor-based systems, (iii) remote sensing, GIS and UAV technologies, (iv) crop modelling and digital decision-support systems, (v) digital platforms and agricultural advisory services, (vi) traceability and integrated digital systems, and (vii) emerging Agriculture 5.0 and agentic AI approaches. These domains were examined across their major applications in agricultural production, resource management, climate adaptation, monitoring, and decision-making.

A second layer of synthesis focused on the agribusiness implications of digital transformation, particularly opportunities related to precision-agriculture services, digital advisory systems, smart supply chains, digital finance, traceability, and technology-enabled entrepreneurship. Recurring constraints were also examined, including technology costs, digital infrastructure, financing, technical skills, data availability, interoperability, extension support, and institutional capacity. Thus, the chapter adopts a thematic and integrative approach, linking technological innovation with agricultural value creation, resilience, sustainability, and the practical conditions required for effective and scalable adoption.

3. Digital Technologies Driving Smart Farming

Smart farming is increasingly defined by the integration of digital technologies for sensing, analysis, prediction and decision-making. Recent research demonstrates applications across crop production, irrigation, soil management, climate-risk assessment, crop monitoring, disease management and resource optimization. The technology landscape is broad, but its major components increasingly operate as interconnected systems rather than isolated tools.

3.1 Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning (ML) have become important components of smart farming because they can identify complex relationships among climatic, soil, crop and management variables. Applications in the evidence include yield prediction, irrigation optimization, soil-moisture and soil-carbon prediction, crop-stress detection and climate-risk assessment, using models such as Random Forest, XGBoost, LightGBM, CatBoost, neural networks and ensemble-learning approaches (Mandour *et al.,* 2026; Ray *et al.,* 2026; Elmotawakkil *et al.,* 2025).

Table 1: Major Digital Technologies and Their Contribution to Smart Farming

Technology Domain	Principal Applications	Representative Technologies	Primary Contribution
Artificial Intelligence and Machine Learning	Yield prediction, irrigation and resource optimization, soil assessment, stress and disease detection, climate-risk analysis	Random Forest, XGBoost, LightGBM, CatBoost, ANN, CNN, LSTM, SHAP	Converts complex agricultural data into predictive and decision-support information
Internet of Things and Smart Sensors	Real-time soil, weather, crop and greenhouse monitoring	Soil-moisture and environmental sensors, Arduino-based systems, sensor networks	Provides continuous information for timely farm management
Remote Sensing and GIS	Crop mapping, drought assessment, soil and landscape monitoring	Sentinel-2, Landsat, MODIS, Google Earth Engine, NDVI, GIS	Provides spatial intelligence from field to landscape scale
UAVs and Computer Vision	Crop-health assessment, disease detection, yield estimation and targeted management	UAV imagery, multispectral data, vegetation indices, computer vision	Enables high-resolution and site-specific monitoring
Crop Modelling and Decision Support	Yield, water, nutrient and climate-adaptation planning	APSIM, APSIM-NG, DSSAT, AquaCrop	Supports scenario analysis and climate-responsive decisions
Digital Platforms and Advisory Systems	Crop monitoring, farm recommendations and digital extension	Mobile applications, satellite-enabled platforms, AI-based advisory systems	Connects digital intelligence with farm-level decisions
Blockchain and Integrated Systems	Traceability, quality monitoring and secure information management	Blockchain, smart contracts, edge computing, computer vision	Strengthens transparency, quality assurance and value-chain coordination
Agriculture 5.0 and Agentic AI	Automation, intelligent interaction and integrated decision-making	Multi-agent AI, advanced deep learning, LLM-based systems	Moves smart farming toward increasingly autonomous agricultural systems

The evidence also demonstrates the practical value of these models. Ray *et al.* (2026) reported $R^2 = 0.86$ for ensemble machine-learning prediction of soil-organic-carbon responses, while Elmotawakkil *et al.* (2025) reported NSE = 0.94 for CatBoost-based soil-moisture prediction. Such applications illustrate the transition from descriptive monitoring toward predictive and increasingly prescriptive agriculture, where digital systems support both risk identification and management decisions.

3.2 Internet of Things and Smart Sensors

IoT technologies provide the continuous data layer required for responsive smart farming. Sensors can monitor soil moisture, environmental conditions and crop-related variables and connect these observations with irrigation, nutrient and greenhouse-management decisions (Ramu *et al.,* 2025). In a 2026 study, an Arduino-based IoT greenhouse system improved soil-moisture stability, nutrient retention and tomato growth while reducing resource wastage (Pelekamoyo *et al.,* 2026).

However, the value of IoT depends on the surrounding digital ecosystem. High implementation costs, connectivity constraints, digital-literacy limitations and interoperability problems remain important barriers. This means that successful IoT deployment requires affordable devices, reliable connectivity, compatible systems and appropriate technical support rather than hardware alone.

3.3 Remote Sensing, GIS and UAV-Based Intelligence

Remote sensing and GIS expand agricultural intelligence beyond individual field observations by providing spatially extensive information for crop classification, drought monitoring, soil assessment, biomass estimation and land-use planning. Sentinel-2, Landsat, MODIS and Google Earth Engine are among the platforms represented in the evidence (Poortinga *et al.,* 2019; Khan *et al.,* 2025; Hummatov *et al.,* 2025).

The integration of remote sensing and machine learning further strengthens this capability. Banerjee *et al.* (2025) combined Sentinel-2 imagery, Google Earth Engine and Random Forest and reported 94% classification accuracy for agricultural landscape assessment in Madhya Pradesh, India. UAV-based observations provide a complementary high-resolution approach for crop monitoring and yield assessment, although broader implementation requires reliable ground observations and validation across different production environments.

3.4 Crop Modelling and Digital Decision-Support Systems

Crop simulation models provide a process-based foundation for understanding crop responses to climate and management conditions. Models such as APSIM, APSIM-NG and AquaCrop are increasingly being integrated with machine learning and climate scenarios to support yield, irrigation, nutrient and adaptation decisions (Devkota *et al.,* 2025; Pinto *et al.,* 2026; Baluch *et al.,* 2025).

The key advantage of these hybrid approaches is the combination of process-based understanding with data-driven prediction. They can help evaluate alternative management scenarios and identify context-specific adaptation strategies. Their operational use nevertheless depends on appropriate calibration, uncertainty assessment, data quality and validation across agroecological conditions.

3.5 Digital Platforms, Blockchain and Emerging Agriculture 5.0

The development of smart farming is increasingly moving toward integrated digital platforms that connect multiple technologies with practical farm decisions. The Farmdee-Mesook platform, for example, combines satellite information, crop simulation, AI and a mobile application to support crop monitoring, irrigation scheduling, fertilizer management and pest management (Raksapatcharawong & Veerakachen, 2025).

Blockchain and integrated digital systems extend these capabilities into agricultural value chains. Safeer *et al.* (2025) combined IoT sensors, edge computing, computer vision and Ethereum blockchain to support real-time quality monitoring, traceability and fraud detection in saffron production. This illustrates how smart farming can increasingly connect production decisions with downstream quality and market functions.

At the leading edge of this transition is Agriculture 5.0 and agentic AI. Murad *et al.* (2026) developed an integrated system combining soil and weather sensors, multiple AI architectures, disease imagery and an LLM-powered chatbot for rice management. The study reported up to 96% accuracy for soil prediction and 98.5% for disease detection. These developments suggest a progression from isolated analytical tools toward coordinated systems capable of sensing, interpreting and supporting multiple agricultural decisions.

3.6 Cross-Technology Synthesis

The evidence indicates that the greatest potential of smart farming lies in technology convergence. AI and ML provide analytical intelligence; IoT supplies continuous field-level data; remote sensing provides spatial information; crop models contribute process-based simulation; and digital platforms translate information into operational recommendations. Blockchain can strengthen trust and traceability, while Agriculture 5.0 introduces increasingly automated forms of human–machine interaction.

Accordingly, the evolution of smart farming can be understood as a movement from data collection → information generation → prediction → decision support → intelligent action. The central challenge is no longer simply whether digital technologies can perform technically, but whether they can be integrated into affordable, reliable and farmer-relevant systems. This provides the foundation for the next section, which examines how these technologies translate into agribusiness value and emerging business opportunities.

4. Applications and Agricultural Value Creation

The value of smart farming extends beyond technology deployment to the improvement of production efficiency, climate resilience, crop health, and environmental performance. Digital tools increasingly connect farm-level data with management decisions, allowing agricultural resources and risks to be managed with greater precision. The evidence shows applications ranging from precision irrigation and crop modelling to disease surveillance, soil-carbon assessment, and climate-risk management.

4.1 Precision Production and Resource Management

One of the most immediate contributions of smart farming is the more precise allocation of agricultural resources. Digital irrigation systems, sensors, crop models and AI-based optimization can support decisions on water, nitrogen and planting management according to crop requirements and environmental conditions (Zhang *et al.,* 2026; Devkota *et al.,* 2025).

Table 2: Major Applications of Smart Farming and Their Agricultural Value

Application Area	Digital Approaches	Agricultural Value Created	Illustrative Evidence
Precision production and resource management	AI/ML, IoT, sensors, crop models, smart irrigation	Improved yield, water-use efficiency, nutrient-use efficiency and resource allocation	Zhang *et al.* (2026); Hasbi *et al.* (2026); Devkota *et al.* (2025)
Climate-risk management and resilience	Remote sensing, climate information, AI, crop models, digital platforms	Early warning, climate adaptation, improved resilience and risk-informed planning	Khan *et al.* (2025); Huang *et al.* (2026); Baluch *et al.* (2025)
Crop health, pest and disease management	AI, computer vision, remote sensing, species-distribution models	Earlier detection, targeted intervention and improved crop protection	Ablormeti *et al.* (2025); Murad *et al.* (2026)
Soil and carbon management	ML, hyperspectral sensing, remote sensing, digital monitoring	Soil diagnostics, carbon assessment, resource efficiency and environmental monitoring	Ray *et al.* (2026); Novais *et al.* (2026); Yeggina *et al.* (2026)
Agricultural platforms and decision support	Mobile platforms, AI, crop models, satellite data	Farm-specific recommendations and integrated management	Raksapatcharawong & Veerakachen (2025)
Supply-chain and quality management	IoT, computer vision, blockchain, edge computing	Traceability, quality control, transparency and reduced information asymmetry	Safeer *et al.* (2025)

The evidence demonstrates measurable benefits from such approaches. Zhang *et al.* (2026) reported that integrated precision management for maize increased yield by more than 20%, water productivity by more than 31%, and economic returns by more than 15%, while reducing irrigation and nitrogen inputs. Hasbi *et al.* (2026) similarly reported a 42.4% increase in cassava yield and 34% improvement in water-use efficiency using semi-automated drip irrigation combined with optimized planting timing.

These findings suggest that smart farming can create value not simply by increasing output, but by improving the efficiency with which scarce resources are converted into agricultural output.

4.2 Climate-Risk Management and Resilience

Digital technologies are increasingly being used to strengthen agricultural resilience under drought, rainfall variability, heat stress and other climate-related risks. Satellite observations, climate information services, crop models and AI-based prediction can support drought monitoring, early warning, adaptation planning and climate-responsive management (Khan *et al.,* 2025; Baluch *et al.,* 2025; Huang *et al.,* 2026).

Huang *et al.* (2026) identified digitalization and technology integration, particularly when combined with financial support and climate-resource management, as important pathways for improving agricultural resilience. Similarly, Baluch *et al.* (2025) demonstrated the use of integrated crop modelling and machine learning for drought-risk and irrigation planning under future climate scenarios. The evidence therefore indicates that digitalization should be viewed as an enabling component of resilience systems, rather than as a stand-alone climate adaptation intervention.

4.3 Crop Health, Pest and Disease Management

Smart farming technologies are also changing crop protection from predominantly reactive management toward earlier detection and targeted intervention. Remote sensing, AI, computer vision and spatial modelling can identify crop stress, disease risk and potential pest outbreaks before damage becomes widespread (Ablormeti *et al.,* 2025; Hussain *et al.,* 2025).

Ablormeti *et al.* (2025), for example, used MaxEnt species-distribution modelling and GIS to map the future suitability of *Agroathelia rolfsii* under alternative climate scenarios, achieving an AUC of 0.999. Hussain *et al.* (2025) developed a machine-learning framework for rapid plant-stress detection, highlighting the potential of AI for climate-resilient crop protection.

Emerging agentic-AI systems further extend this capability by integrating sensing, disease imagery and predictive models into coordinated decision-support environments (Murad *et al.,* 2026).

4.4 Soil, Carbon and Environmental Management

Digital agriculture is increasingly expanding into soil intelligence, carbon management and environmental monitoring. Machine learning, hyperspectral sensing and remote sensing can support soil-property estimation, soil-carbon assessment, ecosystem monitoring and climate-smart land management (Ray *et al.,* 2026; Novais *et al.,* 2026).

Ray *et al.* (2026) demonstrated the use of ensemble machine learning and SHAP analysis for predicting soil-organic-carbon responses, achieving $R^2 = 0.86$. Novais *et al.* (2026) used a cloud-based hyperspectral platform and machine learning for digital soil diagnostics, reporting $R^2 = 0.80$ for clay prediction and $R^2 = 0.63$ for soil-organic-carbon prediction.

Remote sensing can also support landscape-scale environmental monitoring. Yeggina *et al.* (2026), for instance, integrated satellite imagery, soil observations and socio-economic information to assess carbon stocks, soil health and ecosystem conditions in regenerative agricultural systems.

4.5 Integrated Farm and Value-Chain Management

An important emerging direction is the extension of smart farming beyond individual production decisions toward integrated farm and value-chain management. Digital platforms can combine satellite data, crop models, AI and mobile applications to provide field-specific recommendations for irrigation, fertilization, crop monitoring and pest management (Raksapatcharawong & Veerakachen, 2025).

Similarly, the combination of IoT, computer vision, edge computing and blockchain can connect production monitoring with downstream quality and traceability functions. Safeer *et al.* (2025) demonstrated this integration in saffron production, where the system supported real-time quality assessment, anomaly detection and traceability.

This expansion is important from an agribusiness perspective, because digital value creation can continue beyond the farm through quality differentiation, information sharing, traceability and supply-chain coordination.

5. Adoption Challenges and Constraints

The adoption of smart-farming technologies is influenced by a combination of economic, infrastructural, technical, institutional, and human-capital factors. Across the evidence, high technology costs, inadequate rural connectivity, limited digital literacy, financing constraints, weak extension systems, interoperability problems, and limited farmer participation repeatedly emerge as barriers to wider adoption (Ramu *et al.,* 2025; Izuogu *et al.,* 2025; Antwi-Agyei *et al.,* 2025).

5.1 Economic and Financial Constraints

Cost remains one of the most consistent barriers to smart-farming adoption. High implementation costs are reported for IoT systems, digital livestock technologies and other Agriculture 4.0 applications, while limited budgets constrain adoption among smallholders (Ramu *et al.,* 2025; Horváthné Kovács & Zörög, 2025). This suggests that technological performance must be accompanied by economic feasibility, particularly where farmers have limited access to credit or investment capital.

Table 3: Major Adoption Challenges in Smart Farming

Adoption Challenge	Evidence From the Literature	Implication For Adoption	Priority Response
Technology cost and financing	High implementation costs and limited budgets are repeatedly identified as barriers, particularly for smallholders (Ramu *et al.,* 2025; Izuogu *et al.,* 2025)	High upfront investment can prevent farmers from acquiring sensors, platforms, equipment and digital services	Affordable technologies, service-based models, targeted financing and supportive investment mechanisms
Digital infrastructure and connectivity	Rural connectivity, bandwidth and infrastructure limitations restrict access to digital services and real-time systems (Ramu *et al.,* 2025; Mollel *et al.,* 2025)	Poor connectivity limits the practical use of cloud systems, digital advisory and sensor-based technologies	Improved rural connectivity, appropriate digital infrastructure and locally suitable delivery systems
Digital literacy and technical capacity	Digital illiteracy, skill shortages and inadequate training are identified across studies (Izuogu *et al.,* 2025; Mollel *et al.,* 2025)	Farmers may be unable to operate technologies or interpret digital recommendations effectively	Farmer training, extension integration, technical support and user-centred interfaces
Data and interoperability	Interoperability, data-security and data-integration challenges recur in digital farming systems (Ramu *et al.,* 2025)	Fragmented systems reduce the effectiveness of integrated smart-farming platforms	Interoperable standards, appropriate data governance and better system integration
Extension and institutional support	Weak extension systems, limited institutional capacity and inadequate policy support constrain scaling (Antwi-Agyei *et al.,* 2025; Vetri *et al.,* 2025)	Technologies may remain pilot-scale without institutional mechanisms for diffusion and support	Stronger extension, coordinated policy, capacity building and public–private collaboration

Affordability and the digital divide	Low affordability, poor infrastructure and limited digital access particularly affect smallholder farmers (Mollel *et al.,* 2025)	Benefits of digital agriculture may be concentrated among better-resourced farmers	Inclusive technology design, affordable access and targeted support for underserved users
Farmer participation and usability	Limited farmer participation in technology development and perceived complexity can reduce adoption (Izuogu *et al.,* 2025)	Technologies that do not reflect users' needs may have low acceptance or continued use	Participatory design, locally relevant applications and simpler interfaces
Uncertain economic returns	Concerns about cost, uncertain benefits and adoption complexity are reported in livestock and other digital applications (Horváthné Kovács & Zörög, 2025)	Farmers may delay investment when economic benefits are unclear	Demonstration trials, profitability assessment, service models and evidence of return on investment

5.2 Infrastructure and Digital Connectivity

Digital technologies depend on reliable connectivity and supporting infrastructure. Rural connectivity limitations, bandwidth constraints and inadequate infrastructure can restrict access to digital advisory systems, cloud-based services and connected sensing technologies (Ramu *et al.,* 2025; Mollel *et al.,* 2025). Infrastructure gaps are therefore not simply technical limitations; they can determine whether smart farming is practically accessible.

5.3 Digital Literacy and Human Capacity

The effectiveness of digital agriculture depends heavily on users' ability to operate technologies and interpret information. Digital illiteracy, skill shortages and inadequate training have been identified as important constraints, particularly in smallholder contexts (Izuogu *et al.,* 2025; Mollel *et al.,* 2025). Strengthening extension services and providing practical training are therefore important complements to technological deployment.

5.4 Institutional Support, Participation and Inclusion

Adoption is also shaped by the broader institutional environment. Weak extension systems, limited climate-information infrastructure, inadequate policy implementation and human-resource constraints can hinder scaling (Antwi-Agyei *et al.,* 2025). In addition, limited farmer participation in technology development can reduce the relevance and acceptability of digital tools (Izuogu *et al.,* 2025). This highlights the importance of farmer-centred and participatory technology development.

5.5 A Broader Adoption Perspective

Overall, the evidence suggests that the principal challenge is not whether smart-farming technologies can function technically, but whether they can be made affordable, accessible, understandable and institutionally supportable. Digital transformation is therefore more likely to scale when technological innovation is combined with infrastructure, finance, skills, extension, participatory design and supportive institutions (Mollel *et al.,* 2025; Izuogu *et al.,* 2025; Antwi-Agyei *et al.,* 2025).

6. Research Gaps and Future Research Agenda

Although digital agriculture research has expanded rapidly, several important gaps remain. A recurring concern is the limited validation of technologies across locations, seasons, crops, and production environments. Many studies identify promising model performance but also call for broader field-scale, multi-location, or multi-season validation before technologies can be scaled reliably (Ray *et al.,* 2026; Hasbi *et al.,* 2026; Banerjee *et al.,* 2025).

A second gap concerns the scalability and economic feasibility of digital technologies. High implementation costs, limited financing, infrastructure constraints, and uncertain benefits recur across studies, particularly in smallholder settings (Ramu *et al.,* 2025; Izuogu *et al.,* 2025; Horváthné Kovács & Zörög, 2025). This indicates a need for greater emphasis on practical deployment conditions and economically viable technology-delivery models alongside technical performance.

A third priority is inclusive digital transformation. The evidence highlights digital divides involving connectivity, affordability, technical skills, gender, access to finance, and participation in technology development (Mollel *et al.,* 2025; Kihoro *et al.,* 2026; Izuogu *et al.,* 2025). Future research therefore needs to examine how digital interventions perform across different farm sizes, socioeconomic groups, genders, and institutional contexts rather than assuming uniform adoption.

A fourth gap concerns system integration and interoperability. Several studies identify challenges associated with integrating heterogeneous data sources and technologies, including IoT, AI, blockchain, remote sensing, and decision-support systems (Ramu *et al.,* 2025; Ahmed *et al.,* 2022). Future research should therefore move toward interoperable architectures capable of linking field, climate, environmental, and management information within unified decision environments.

A further emerging issue is the development of more farmer-centred and transparent digital systems. Recent evidence emphasizes the need for affordable technologies, localized advisory systems, stronger training, and greater participation of farmers in technology development

(Mollel *et al.,* 2025; Izuogu *et al.,* 2025). As smart farming moves toward increasingly complex AI-based systems, future research should also examine how these systems can remain understandable, usable, and appropriately validated in real farming environments.

Table 4: Priority Areas for Future Research in Smart Farming

Research Priority	Evidence-Based Gap	Recommended Research Direction	Expected Contribution
Field-scale and multi-location validation	Technologies frequently require broader validation across crops, regions and seasons	Multi-season and multi-location field trials; agroecological validation	More robust and transferable technologies
Economic feasibility and scalability	High costs, financing constraints and uncertain benefits limit wider adoption	Cost-effectiveness, profitability and scalable technology-delivery models	Greater commercial viability and adoption
Digital inclusion	Smallholders face connectivity, affordability, skills and participation barriers	Gender-, income-, region- and farm-size-sensitive adoption studies	More inclusive digital transformation
Interoperability and data integration	Heterogeneous systems and data sources remain difficult to integrate	Interoperable platforms, common standards and integrated architectures	Scalable digital ecosystems
Farmer-centred technology design	Limited participation and localized adaptation constrain usability	Participatory design, localized advisory systems and user-centred interfaces	Greater relevance, acceptance and continued use
Institutional and extension integration	Weak extension and policy support can restrict scaling	Integrate digital tools with extension, climate services and institutional programmes	Stronger implementation pathways
Advanced AI and autonomous systems	Emerging systems require field-scale validation and clearer deployment conditions	Evaluate agentic AI, autonomous decision systems and human–machine collaboration in real farming settings	Responsible and practically useful Agriculture 5.0

Future research should therefore move from proof-of-concept demonstrations toward validated, economically viable, interoperable, and inclusive digital agricultural systems. The evidence also points toward greater integration of AI, IoT, remote sensing, crop modelling, digital advisory systems, and climate information rather than continued development of isolated technologies (Ramu *et al.,* 2025; Devkota *et al.,* 2025; Huang *et al.,* 2026).

Emerging Agriculture 5.0 and agentic AI deserve particular attention, but the evidence indicates that field-scale validation and deployment challenges remain unresolved. Murad *et al.* (2026), for example, identifies integration complexity, real-time coordination, and the need for broader field validation as future priorities for agentic AI systems. The future research agenda should therefore focus on determining where advanced automation adds measurable agricultural value, where farmer intervention remains necessary, and how these systems can be implemented at practical scale.

7. Proposed Framework for Digital Agricultural Transformation

The evidence synthesized in this chapter suggests that digital transformation in agriculture is best understood as a sequential but interconnected process rather than as the adoption of individual technologies. The proposed framework links five stages: (1) Connect, (2) Understand, (3) Decide, (4) Create Value, and (5) Sustain. The stages represent the movement from data generation and digital connectivity toward intelligent decision-making, agribusiness value creation, and longer-term sustainability and resilience.

7.1 From Connectivity to Intelligence

The first two stages establish the technological foundation of smart farming. Connect represents the generation and acquisition of agricultural data through sensors, satellites, UAVs, weather systems and mobile technologies. Understand converts these observations into useful information through AI/ML, remote sensing analytics, crop models and other analytical approaches. Evidence from the reviewed studies demonstrates that combining these technologies can improve monitoring, prediction and climate-related decision support (Ramu *et al.,* 2025; Mgana *et al.,* 2025; Devkota *et al.,* 2025).

7.2 From Intelligence to Decisions

The third stage, Decide, represents the conversion of analytical outputs into practical agricultural actions. Digital advisory systems, crop models, AI predictions and automated technologies can support decisions on irrigation, nutrient application, crop protection and climate adaptation. For example, digital platforms integrating satellite information, crop modelling and AI have been used to provide field-specific recommendations for rice production (Raksapatcharawong & Veerakachen, 2025).

7.3 From Decisions to Agribusiness Value

The fourth stage, Create Value, extends smart farming beyond farm management. Digital technologies can support precision-agriculture services, advisory businesses, digital finance, traceability and new forms of agricultural entrepreneurship. Evidence from agribusiness research shows that Agriculture 5.0 technologies, precision agriculture, IoT and AI can contribute to resilience and reduction of income-disruption risks in agribusiness systems (Saxena *et al.,* 2025).

This stage is important because technological success does not necessarily represent economic success. Digital information must ultimately translate into measurable improvements in efficiency, profitability, market access, or risk management to create sustained agribusiness value.

Table 5: Proposed Digital Agricultural Transformation Framework

Stage	Core Digital Components	Primary Agricultural Function	Value Generated	Critical Enabling Condition
Connect	Sensors, satellites, UAVs, weather stations, mobile and field data	Data collection and real-time monitoring	Timely and reliable agricultural information	Connectivity, data quality and accessibility
Understand	AI/ML, GIS, remote sensing analytics, crop models	Diagnosis, prediction and risk assessment	Better understanding of crop, climate and resource conditions	Technical capability, data integration and validation
Decide	Decision-support systems, digital advisory, predictive analytics and automation	Farm and agribusiness decision-making	Improved timing, precision and resource allocation	Usability, trust and contextual relevance
Create Value	Digital platforms, precision services, finance, traceability and entrepreneurship	Conversion of digital intelligence into economic activity	Productivity, efficiency, income and market differentiation	Affordability, viable business models and user adoption
Sustain	Climate monitoring, carbon assessment, resource-efficiency tools and resilience systems	Long-term adaptation and sustainability management	Resilience, environmental sustainability and resource security	Institutional coordination, policy support and scalable implementation

7.4 From Value Creation to Sustainability

The final stage, Sustain, links digital transformation with longer-term environmental and climate outcomes. Digital monitoring can support resource-use efficiency, carbon assessment, climate adaptation and resilience planning. Recent evidence shows that digitalization combined with climate-smart technologies and financial support can strengthen agricultural resilience (Huang *et al.,* 2026), while integrated digital monitoring can support soil, carbon and ecosystem assessment.

7.5 Framework Implication

The framework emphasizes that technology is an enabling layer, not the final outcome. A smart-farming system creates sustainable value only when data are converted into useful information, information into decisions, decisions into measurable agricultural or business outcomes, and those outcomes into economically and institutionally viable systems. This means that the success of digital transformation depends on the interaction of technology, infrastructure, skills, finance, business models, institutions and farmer participation rather than on technological performance alone.

Conclusion

Digital transformation is reshaping agriculture through the growing integration of artificial intelligence, machine learning, Internet of Things, remote sensing, crop modelling, digital platforms, and advanced decision-support systems. These technologies are expanding the capacity of farming systems to monitor conditions, predict risks, optimize resources, and support timely and informed management decisions. The chapter demonstrates that the greatest potential of smart farming lies not in individual technologies but in their integration into connected digital ecosystems. When sensing, analytics, modelling, decision support, and digital services work together, they can contribute to improved resource efficiency, climate resilience, crop management, environmental monitoring, and agribusiness performance.

At the same time, technological capability alone does not guarantee successful transformation. Adoption depends on affordability, connectivity, digital skills, access to finance, interoperability, institutional support, and the ability of technologies to address real farmer and agribusiness needs. These factors are particularly important for ensuring that digital transformation remains inclusive and does not widen existing inequalities.

The future of agriculture will therefore depend on developing farmer-centred, affordable, interoperable, and scalable digital systems. The transition toward Agriculture 5.0 should focus not on automation for its own sake, but on using digital intelligence to generate measurable agricultural, economic, environmental, and social value. Integrating technology with agricultural knowledge, viable agribusiness models, institutional support, and farmer participation can provide a stronger pathway toward productive, resilient, inclusive, and sustainable next-generation agriculture.

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SOLAR-POWERED AGRICULTURAL EQUIPMENT AND MACHINES

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Abstract

The agricultural sector is experiencing a technological transformation driven by the increasing demand for sustainable farming practices and energy-efficient systems. Solar-powered agricultural equipment and machines have emerged as an effective solution to reduce dependency on fossil fuels, minimize greenhouse gas emissions, and enhance agricultural productivity. Solar energy offers an abundant, renewable, and environmentally friendly source of power for various agricultural operations including irrigation, harvesting, drying, spraying, and greenhouse management [1,2]. This chapter discusses the principles, components, applications, advantages, challenges, and future prospects of solar-powered agricultural machinery. The chapter also highlights recent technological advancements and the role of solar energy in achieving sustainable agricultural development.

Keywords: Solar Energy, Agricultural Machinery, Renewable Energy, Smart Farming, Solar Irrigation, Sustainable Agriculture, Mechanization.

1. Introduction

Agriculture is one of the oldest and most essential economic activities supporting human civilization. Modern agriculture increasingly relies on mechanization and energy-intensive processes to improve productivity and meet the growing food demand of the expanding global population [3]. Traditionally, agricultural operations have depended heavily on fossil fuels and grid electricity, which contribute significantly to environmental pollution and rising operational costs.

The rapid depletion of conventional energy resources and concerns regarding climate change have accelerated the search for renewable energy alternatives [1]. Among the available renewable energy sources, solar energy is one of the most promising due to its widespread availability, sustainability, and low environmental impact [2]. Solar-powered agricultural equipment and machines provide a viable solution for energy-efficient farming while reducing dependency on diesel-powered machinery.

Solar energy technologies are now being integrated into agricultural applications such as water pumping, crop drying, greenhouse heating, automated irrigation, electric fencing, pesticide spraying, and autonomous farming vehicles [4,5]. These systems not only reduce fuel costs but also improve operational efficiency and sustainability. The integration of solar energy with smart technologies such as the Internet of Things (IoT), sensors, and automation has further enhanced the capabilities of modern agricultural systems [13].

This chapter presents a detailed discussion on solar-powered agricultural equipment, their working principles, applications, benefits, challenges, and future developments.

2. Fundamentals of Solar Energy in Agriculture

Solar energy is the radiant energy emitted by the sun, which can be converted into thermal or electrical energy using solar technologies [1]. The two major methods of harnessing solar energy are:

i. Photovoltaic (PV) Systems
ii. Solar Thermal Systems

2.1 Photovoltaic Systems

Photovoltaic systems convert sunlight directly into electricity using semiconductor materials such as silicon [3]. Solar panels consist of multiple photovoltaic cells that generate direct current (DC) electricity when exposed to sunlight.

Main Components of a PV System

- Solar panels
- Charge controller
- Battery storage
- Inverter
- Electrical loads

The generated electricity can power agricultural machines either directly or through battery storage systems [11].

2.2 Solar Thermal Systems

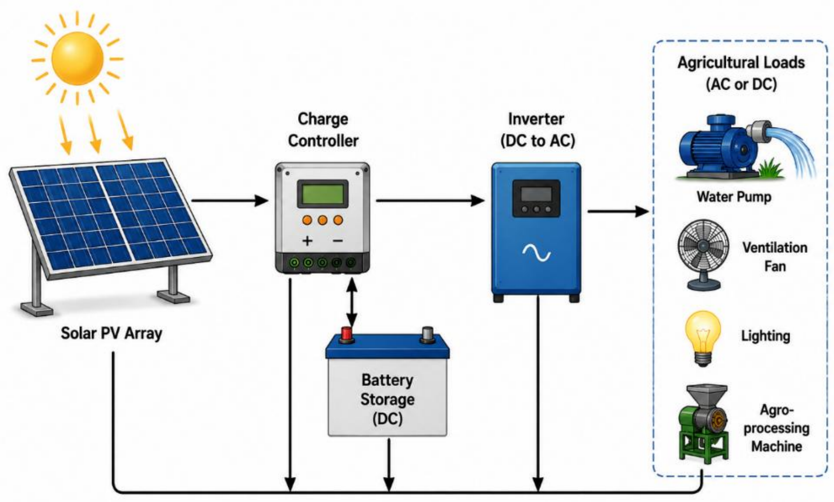

Figure 1: Schematic Diagram of a Solar Photovoltaic (PV) System for Agricultural Applications

Solar thermal systems capture solar heat energy for applications such as crop drying, greenhouse heating, and water heating [7]. Solar collectors absorb solar radiation and convert it into thermal energy.

3. Need for Solar-Powered Agricultural Equipment

Agriculture consumes substantial energy for irrigation, transportation, processing, and storage [5]. Conventional energy sources create several problems including:

- Rising fuel costs
- Greenhouse gas emissions
- Air pollution
- Limited electricity access in rural areas
- Dependence on non-renewable resources

Solar-powered agricultural equipment addresses these issues by providing:

- Clean energy generation
- Reduced operational costs
- Energy independence
- Sustainable farming solutions
- Improved rural electrification [6]

Solar technologies are especially beneficial in remote agricultural regions where grid electricity is unavailable or unreliable [9].

4. Types of Solar-Powered Agricultural Equipment

4.1 Solar Water Pumping Systems

Solar-powered irrigation pumps are among the most widely adopted solar technologies in agriculture [4]. These systems use photovoltaic panels to operate electric water pumps for irrigation.

Components

- Solar PV panels
- DC or AC motor
- Pump controller
- Water pump
- Storage tank

Advantages

- Elimination of diesel fuel costs
- Low maintenance
- Reliable operation
- Reduced carbon emissions

Applications

- Drip irrigation
- Sprinkler irrigation
- Livestock watering
- Pond aeration

Solar irrigation systems have significantly improved water management efficiency and agricultural productivity in rural areas [9].

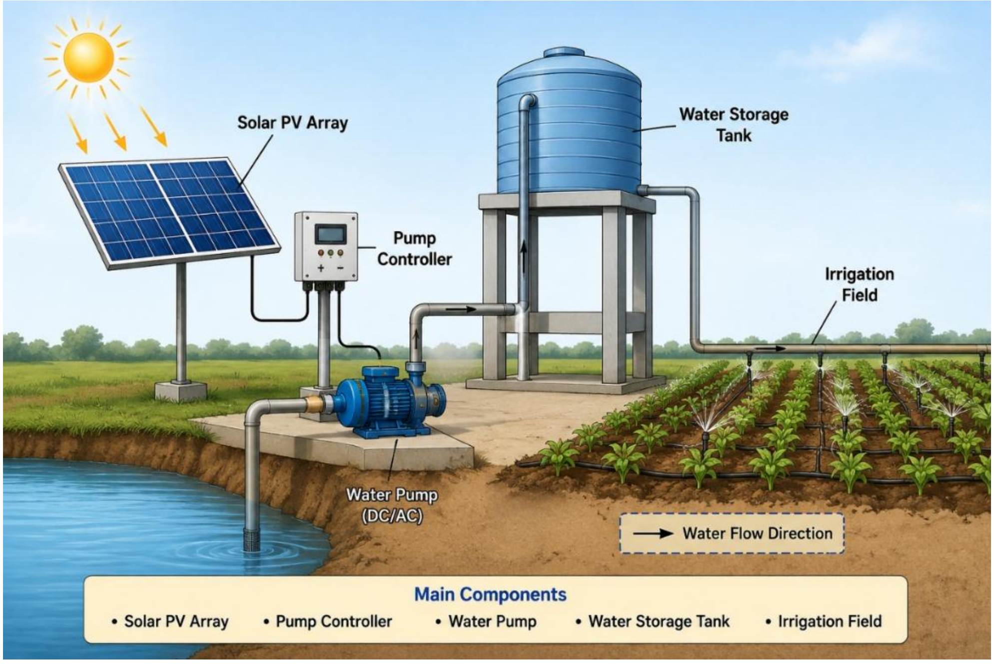

Figure 2: Components of a Solar-Powered Water Pumping System

4.2 Solar-Powered Tractors

Solar-powered tractors use electric motors driven by batteries charged through solar panels [5]. These tractors reduce fuel dependency and emissions.

Features

- Electric drivetrain
- Rechargeable batteries
- Smart energy management systems
- Autonomous operation capability

Benefits

- Low noise pollution
- Reduced operating cost
- Environmentally friendly operation

Despite their advantages, solar tractors currently face challenges related to battery storage capacity and high initial costs [11].

Figure 3: Conceptual Layout of a Solar-Powered Electric Tractor

4.3 Solar Crop Dryers

Crop drying is essential for reducing moisture content and preventing post-harvest losses [7]. Traditional drying methods often depend on fossil fuels or open sun drying.

Solar crop dryers utilize solar thermal energy to dry grains, fruits, vegetables, and spices efficiently.

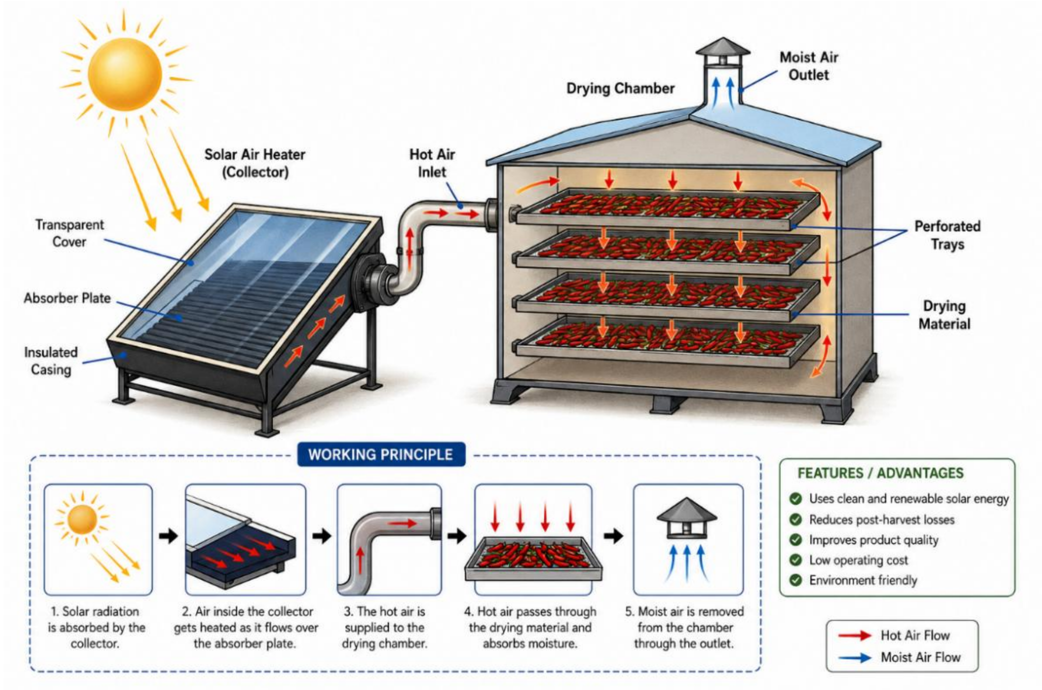

Figure 4: Working Principle of an Indirect Solar Crop Dryer

Types

- Direct solar dryers

- Indirect solar dryers
- Mixed-mode dryers

Advantages

- Improved product quality
- Faster drying
- Reduced contamination
- Lower energy consumption

Solar drying technologies improve food preservation and reduce agricultural wastage [7].

4.4 Solar-Powered Sprayers

Solar-powered pesticide sprayers use photovoltaic energy to power spraying pumps [8].

Components

- Solar panel
- Battery
- Electric pump
- Spray nozzle

Advantages

- Reduced manual effort
- Uniform spraying
- Low operational cost
- Reduced environmental pollution

These sprayers are widely used in small and medium-scale farms [8].

4.5 Solar Greenhouse Systems

Greenhouses require energy for heating, cooling, ventilation, and irrigation [12]. Solar-powered greenhouse systems improve energy efficiency by utilizing solar energy.

Applications

- Temperature regulation
- Ventilation control
- Irrigation automation
- Lighting systems

Integration with IoT sensors enables real-time monitoring and climate control [13].

4.6 Solar Electric Fencing

Solar-powered electric fencing systems protect crops from animals and intruders.

Benefits

- Low power consumption
- Continuous operation

- Easy installation
- Cost-effective protection

These systems are particularly useful in remote agricultural areas [6].

5. Working Principle of Solar Agricultural Machines

Solar agricultural machines generally follow the following operational sequence [3]:

- Solar panels absorb sunlight.
- Photovoltaic cells convert solar radiation into electricity.
- The charge controller regulates voltage and current.
- Electrical energy is stored in batteries.
- Electric motors drive agricultural equipment.
- Sensors and control units optimize performance.

In advanced systems, IoT-based monitoring and automation improve operational efficiency and precision farming capabilities [13].

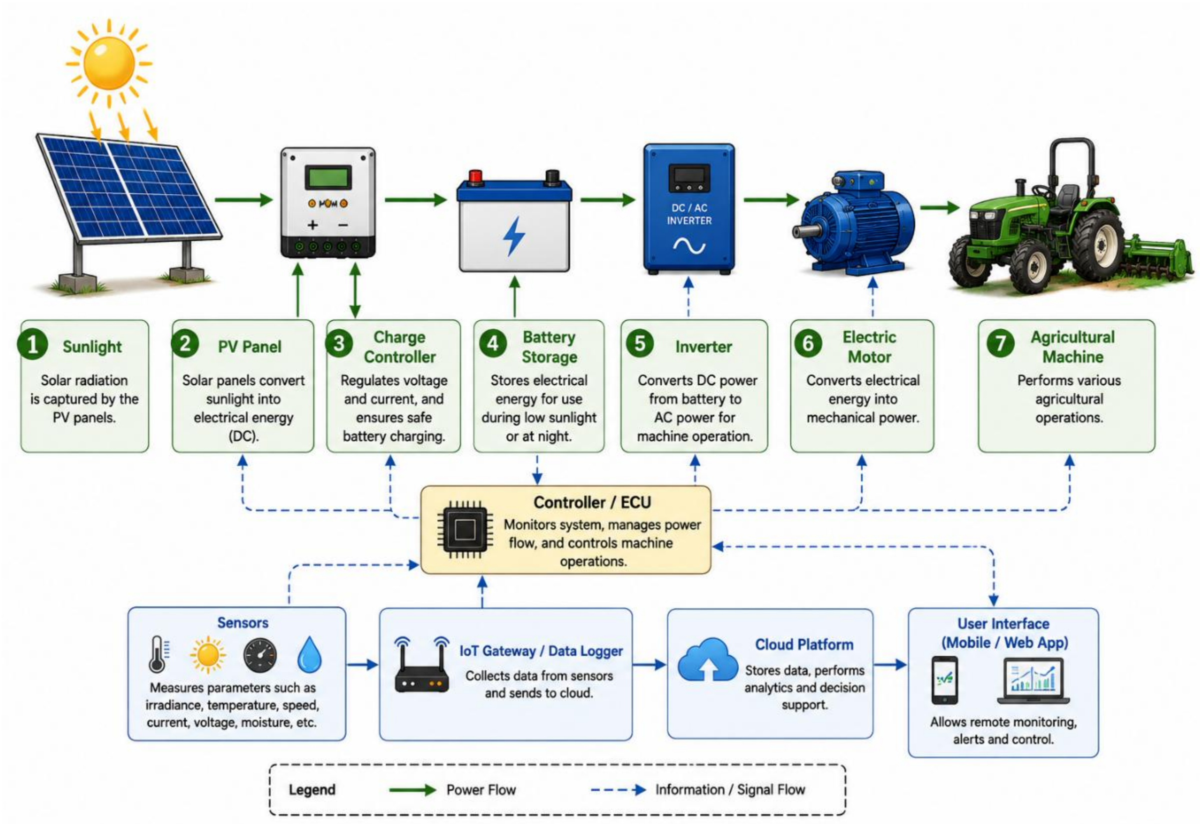

Figure 5: Flowchart Showing the Working Principle of Solar Agricultural Machines

6. Advantages of Solar-Powered Agricultural Equipment

6.1 Environmental Benefits

- Reduction in greenhouse gas emissions
- Lower air pollution
- Sustainable energy utilization [1]

6.2 Economic Benefits

- Reduced fuel expenses
- Lower maintenance costs
- Long operational life [9]

6.3 Social Benefits

- Improved rural electrification
- Enhanced farmer income
- Reduced labor dependency [6]

6.4 Technical Benefits

- High energy efficiency
- Automation capability
- Reliable operation in remote areas [10]

7. Challenges and Limitations

Despite significant advantages, several challenges hinder large-scale adoption.

7.1 High Initial Investment: Solar systems require substantial upfront capital for installation [14].

7.2 Weather Dependency: Solar energy availability depends on sunlight intensity and weather conditions [1].

7.3 Battery Limitations: Battery storage systems increase system cost and require periodic replacement [11].

7.4 Technical Skill Requirements: Operation and maintenance require trained personnel [5].

7.5 Limited Power Output: Large agricultural machines may require higher power capacity than currently available solar systems.

8. Recent Technological Advancements

Technological developments are improving the performance and affordability of solar-powered agricultural systems.

8.1 Integration with IoT

IoT sensors enable:

- Real-time monitoring
- Automated irrigation
- Remote control
- Predictive maintenance [13]

8.2 Artificial Intelligence Applications

AI algorithms optimize:

- Energy consumption

- Crop monitoring
- Machine operation
- Irrigation scheduling [13]

8.3 Advanced Battery Technologies

Lithium-ion batteries provide:

- Higher energy density
- Longer lifespan
- Faster charging

8.4 Autonomous Solar Farming Machines

Self-driving solar-powered agricultural robots are being developed for:

- Seeding
- Weeding
- Harvesting
- Crop monitoring [10]

9. Economic Analysis of Solar Agricultural Systems

Economic feasibility is a critical factor in adopting solar technologies.

9.1 Cost Components

- Solar panels
- Batteries
- Controllers
- Installation
- Maintenance

9.2 Return on Investment (ROI)

Although initial costs are high, long-term savings from reduced fuel consumption provide favorable ROI [9].

9.3 Government Incentives

Many governments provide:

- Subsidies
- Tax incentives
- Low-interest loans
- Renewable energy grants [14]

These policies encourage adoption among farmers.

10. Applications in Smart Farming

Solar-powered systems play a significant role in smart agriculture.

10.1 Precision Irrigation: Solar-powered sensors optimize water usage [13].

10.2 Automated Monitoring: Remote monitoring systems improve farm management.

10.3 Precision Spraying: Solar drones and sprayers reduce pesticide wastage.

10.4 Smart Livestock Management: Solar-powered sensors monitor animal health and environmental conditions.

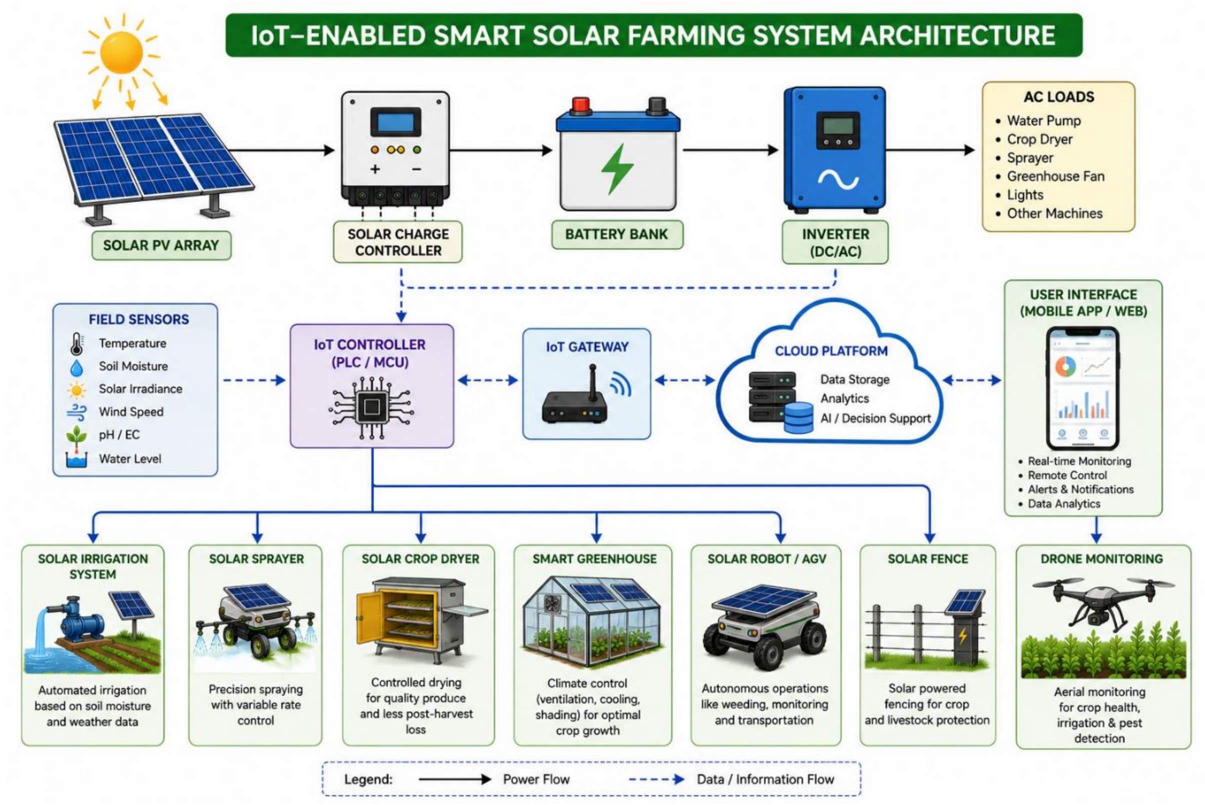

Figure 6: IoT-Enabled Smart Solar Farming System Architecture

11. Future Prospects

The future of solar-powered agricultural machinery appears highly promising due to continuous technological advancements and increasing environmental awareness [2].

Future developments may include:

- Fully autonomous solar tractors
- AI-driven energy management
- Wireless charging systems
- Flexible solar panels
- Hybrid renewable agricultural systems

The integration of renewable energy with digital agriculture will play a major role in achieving sustainable food production [13].

Conclusion

Solar-powered agricultural equipment and machines represent a transformative advancement toward sustainable and environmentally responsible farming. These systems reduce dependency on fossil fuels, lower operational costs, and improve energy accessibility in rural regions [6]. Applications such as solar irrigation pumps, crop dryers, sprayers, greenhouses, and autonomous machines demonstrate the versatility and effectiveness of solar technologies in agriculture [4,7]. Although challenges such as high initial investment and weather dependency remain, ongoing technological advancements and supportive government policies are expected to accelerate adoption worldwide [14]. The combination of solar energy, automation, IoT, and artificial intelligence will significantly shape the future of modern agriculture and contribute to global food security and sustainable development.

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VEGETABLE SEED INDUSTRY: GLOBAL TRENDS AND FUTURE PROSPECTS

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Abstract

The vegetable seed industry has emerged as one of the most dynamic and technology-intensive sectors of global agriculture. Quality seed is the foundation of successful vegetable production because it determines crop establishment, genetic uniformity, productivity, nutritional quality, resistance to biotic and abiotic stresses, and profitability of growers. Vegetable seed systems have transformed from traditional farmer-managed seed conservation into globally integrated industries driven by scientific breeding, biotechnology, digital agriculture and international trade. Increasing population, urbanization, changing dietary preferences and growing awareness of nutritional security have accelerated demand for high-quality vegetables and hybrid seed, particularly in tomato, cucumber, chilli, pepper, watermelon, melon, cabbage, cauliflower and onion. Modern seed development increasingly uses marker-assisted selection, genome-wide association studies, genomic selection, doubled haploid technology, speed breeding, CRISPR-based genome editing, artificial intelligence, machine learning and high-throughput phenotyping. These approaches can shorten breeding cycles, improve selection accuracy and support development of climate-resilient cultivars. At the same time, the sector faces challenges related to climate change, emerging pests and diseases, increasing research costs, intellectual property, regulatory complexity, counterfeit seeds and unequal access to improved technologies. Future vegetable seed systems will therefore require closer integration of genetics, biotechnology, artificial intelligence, sustainability, quality assurance and farmer-oriented innovation.

Keywords: Vegetable Seed Industry, Hybrid Seed, Seed Quality, Vegetable Breeding, Genomic Selection, CRISPR, Artificial Intelligence, Climate-Smart Seeds, Digital Agriculture.

1. Introduction

Vegetables are essential components of healthy diets and contribute vitamins, minerals, dietary fibre, antioxidants and other bioactive compounds. Rising awareness of nutrition and lifestyle-related diseases has increased demand for diverse, safe and attractive vegetables. Global production trends and crop statistics also demonstrate the continuing importance of vegetables in food and nutrition systems (FAO, 2024). Seed is the primary biological input through which genetic potential is delivered to the production field. In vegetable crops, this importance is particularly high because production is generally intensive and market value is strongly influenced by uniformity, fruit or curd quality, maturity, appearance and resistance to pests and diseases.

Vegetable seed systems differ from cereal systems because vegetable crops exhibit diverse reproductive mechanisms, including self-pollination, cross-pollination, self-incompatibility, male sterility, monoecious flowering, dioecious behaviour and parthenocarpy. These features make vegetable seed production a specialized discipline requiring knowledge of genetics, breeding, pollination biology, seed technology and quality management (George, 2011).

Historically, farmers maintained locally adapted landraces by selecting seed from healthy and desirable plants. Such systems conserved genetic diversity and supported adaptation to local environments, but they could also result in variable genetic purity and inconsistent productivity. Genetic erosion can reduce the diversity available for future improvement, making conservation and characterization of vegetable genetic resources an essential component of a sustainable seed sector (Van de Wouw *et al.,* 2010; World Vegetable Center, 2023).

Scientific breeding introduced systematic selection, hybridization, backcrossing and mutation breeding. Pure-line selection became important in self-pollinated crops, pedigree breeding enabled generation-wise selection in segregating populations, and backcrossing facilitated transfer of specific traits into elite backgrounds. Hybrid breeding subsequently became a major commercial strategy because heterosis can combine complementary parental attributes in a high-performing F1 (Acquaah, 2020).

The twenty-first century has introduced precision breeding. Molecular markers, genomic selection, genome editing, speed breeding, artificial intelligence and digital phenotyping increasingly complement conventional breeding. Genomics-assisted breeding can improve the efficiency of selection, while genome editing can provide targeted modification when the underlying gene is sufficiently understood (Varshney *et al.,* 2014; Varshney *et al.,* 2021). Climate change has made this transition more urgent because temperature rise, drought, salinity, irregular rainfall and emerging pathogens can reduce the reliability of existing cultivars (IPCC, 2023; Raza *et al.,* 2020).

2. Historical Evolution of the Vegetable Seed Industry

2.1 Traditional Seed Systems

Traditional seed systems were based largely on farmer selection and storage. Seeds were selected from healthy plants expressing desirable fruit size, colour, flavor, maturity and adaptation, and were retained for subsequent seasons. These systems made an important contribution to conservation of indigenous diversity and local adaptation. However, the absence of systematic genetic purification could lead to variability in plant type, maturity, yield and market quality. Increasing commercialization created demand for uniform and predictable planting material.

- Conservation of local genetic resources and landraces.
- Adaptation to specific agro-climatic conditions.
- Farmer participation in selection and maintenance.
- Potential limitations in genetic uniformity, yield stability and disease resistance.

2.2 Development of Scientific Breeding

The rediscovery and application of Mendelian genetics established the scientific basis for vegetable improvement. Breeders began controlled crossing and systematic selection, allowing useful traits to be assembled into improved varieties. Pure-line selection, pedigree breeding, backcrossing and mutation breeding remain important components of breeding programmes, while hybrid breeding has become especially important where heterosis and uniformity provide strong commercial advantages (Acquaah, 2020).

Breeding Approach	Major Purpose
Pure-line selection	Development of genetically uniform varieties from self-pollinated populations
Pedigree breeding	Selection of superior plants through successive generations
Backcross breeding	Transfer of specific desirable traits into elite backgrounds
Mutation breeding	Generation of useful novel variation
Hybrid breeding	Exploitation of heterosis for commercial F1 hybrids

2.3 Hybrid Seed Revolution

Hybrid seed technology was a major turning point in vegetable breeding. Commercial F1 hybrids can provide high yield potential, uniform growth, early maturity, disease resistance and consumer-oriented quality. Hybrid technology has been particularly successful in tomato, cucumber, chilli, watermelon, melon, cabbage, cauliflower and pepper. The shift toward hybrids also changed the economics of the seed sector: seed became a high-value, research-intensive product requiring parental line development, controlled pollination, specialized seed production, processing, quality testing, marketing and technical support (George, 2011).

3. Global Vegetable Seed Market: Current Status and Emerging Trends

The modern vegetable seed industry is highly specialized and research driven. Compared with many cereal seed systems, vegetable seed has high economic value because of intensive breeding, complex multiplication procedures, strict quality requirements and strong influence on consumer-facing traits. Growth of commercial horticulture, protected cultivation, export-oriented production and hybrid adoption has strengthened demand for improved seed. FAOSTAT provides a major international database for tracking crop production trends and their broader food-system context (FAO, 2024).

3.1 Major Drivers of Industry Growth

- Increasing global vegetable consumption and urbanization.
- Expansion of greenhouse, polyhouse, net-house and other protected cultivation systems.
- Rising demand for disease- and stress-resistant cultivars.
- Growth of export-oriented vegetable production.
- Increasing private and public investment in breeding and seed research.
- Demand for improved nutritional value, shelf life, appearance and processing suitability.

3.2 Changing Consumer Preferences

Consumer expectations increasingly influence breeding objectives. Modern consumers seek vegetables that are nutritious, safe, attractive, uniform and convenient. Consequently, breeders consider nutritional value, antioxidant content, flavour, size and colour uniformity, shelf life and processing suitability alongside yield. Nutritional breeding is therefore becoming an important component of future vegetable cultivar development.

3.3 Expansion of Hybrid Vegetable Seeds

Commercial growers favour hybrids where the production system can capture their advantages. Efficient parental line improvement, flowering synchronization, controlled pollination and genetic purity maintenance are essential for economic hybrid seed production. Hybrid seed production remains closely linked to the reproductive biology of each crop (George, 2011).

3.4 Protected Cultivation and Specialized Seed Demand

Protected cultivation has created a distinct demand for cultivars adapted to controlled environments. Compact plant architecture, continuous fruit production, high productivity, efficient nutrient utilization and resistance to greenhouse diseases are important characteristics. Parthenocarpic cucumber hybrids, indeterminate tomato hybrids, coloured pepper hybrids and specialty lettuce are examples of crops and market segments benefiting from specialized seed development.

3.5 Climate-Smart Seed Demand

Climate variability is changing breeding priorities. Heat, drought, salinity, irregular rainfall and emerging pathogens can affect vegetable production. Breeding programmes are therefore emphasizing heat-tolerant tomato, drought-adapted chilli, salt-tolerant vegetables, disease-resistant cucumber and stress-adaptive rootstocks. Climate resilience is increasingly considered a core component of seed value rather than an optional trait (IPCC, 2023; Raza *et al.,* 2020).

4. Regional Trends in the Vegetable Seed Industry

4.1 Asia-Pacific

Asia-Pacific is a major vegetable production and consumption centre. Large populations, diverse climates and increasing commercialization create strong demand for improved seed. China, India, Japan, South Korea, Thailand and Vietnam are important markets. India is described as a rapidly growing vegetable seed market, supported by commercial cultivation, increasing hybrid adoption, diverse agro-climatic zones, protected cultivation, farmer awareness and government support. Important crops include tomato, chilli, cucumber, okra, watermelon, melon, gourds and brassicas.

4.2 Europe

The Netherlands, France, Germany, Italy and Spain are major centres of vegetable seed innovation. European breeding programmes emphasize disease resistance, sustainability, resource-use efficiency and consumer quality, with increasing integration of genomics, molecular breeding and digital phenotyping.

4.3 North America

The United States and Canada have developed seed industries supported by biotechnology and agricultural research. Strengths include genomics, biotechnology, artificial intelligence, precision agriculture and high-throughput phenotyping. Breeding priorities include processing quality, disease resistance, mechanization suitability and climate adaptation.

4.4 Latin America and Africa

Latin America is an important seed multiplication and export region, while Africa represents an emerging market with opportunities created by increasing vegetable consumption, urban agriculture, nutritional security programmes and improved seed access. Constraints include limited certified seed availability, weak distribution networks, climate vulnerability and limited breeding infrastructure.

Region	Major Strengths	Major Challenges
Asia-Pacific	Large production base; hybrid adoption	Climate stress; fragmented markets
Europe	Advanced breeding; seed export	High research investment
North America	Biotechnology; digital breeding	Regulatory and market complexity
Latin America	Seed multiplication; export	Infrastructure limitations
Africa	Emerging market potential	Limited seed access and infrastructure

5. Major Global Vegetable Seed Companies and Industry Structure

The global industry includes multinational companies with extensive breeding programmes, research stations, seed production facilities and international marketing networks, alongside domestic private companies, public research organizations, farmer seed systems, seed producers, processors, quality-testing laboratories, distributors and retailers. The precise crop focus and regional strength of individual companies vary over time. The broader industry structure is important because cultivar development alone does not guarantee adoption; seed must be produced reliably, tested, packaged, distributed and supported with crop-specific agronomic information.

Company	Country	Major Strengths Highlighted in the Source
Bayer Crop Science	Germany	Hybrid vegetables; biotechnology; disease resistance; protected cultivation
BASF Vegetable Seeds (Nunhems)	Germany	Vegetable genetics; hybrid development; disease resistance; quality
Syngenta Vegetable Seeds	Switzerland	Global breeding network; trait development; digital agriculture
Enza Zaden	Netherlands	Greenhouse breeding; disease resistance
Rijk Zwaan	Netherlands	Greenhouse vegetables; sustainable and consumer-oriented breeding
Sakata Seed Corporation	Japan	Specialty vegetable breeding
East-West Seed	Thailand	Tropical vegetable markets

6. Vegetable Seed Value Chain

A vegetable seed value chain begins with germplasm conservation and continues through breeding, multiplication, processing, testing, marketing and farmer adoption. Each stage contributes to the final value of seed.

- Germplasm conservation.
- Breeding and hybrid development.
- Seed multiplication.
- Seed processing and enhancement.
- Quality testing and certification.
- Marketing and distribution.
- Farmer adoption, performance monitoring and feedback.

6.1 Germplasm Conservation

Germplasm is the genetic foundation of future vegetable improvement. Landraces, wild relatives, indigenous varieties, advanced breeding lines and exotic collections provide variation for productivity, fruit quality, disease resistance, heat tolerance, drought tolerance and salinity tolerance. Conservation of genetic diversity is essential because genetic erosion can reduce opportunities for future breeding (Van de Wouw *et al.,* 2010). National gene banks and international institutions such as the World Vegetable Center contribute to maintenance and use of vegetable genetic resources (World Vegetable Center, 2023).

6.2 Breeding and Hybrid Development

Modern breeding combines conventional and molecular approaches. Parent selection considers yield, quality, disease resistance and adaptation. Controlled crossing combines desirable traits, followed by selection in segregating generations. Advanced lines are evaluated across environments, and experimental hybrids are assessed for yield, quality, resistance and stability before commercial multiplication. Molecular breeding can support earlier and more precise selection for traits controlled by known genes or genomic regions (Collard and Mackill, 2008; Varshney *et al.,* 2014).

6.3 Seed Multiplication

Seed multiplication increases seed quantity while maintaining genetic identity. The progression from breeder seed through foundation seed and commercial seed requires careful field standards and quality control. Genetic purity is particularly critical for hybrid seed production because admixtures can directly reduce hybrid performance and market value (George, 2011).

7. Seed Processing, Enhancement and Production Technologies

7.1 Seed Processing

Modern processing is designed to deliver clean, uniform and physiologically sound seed. Major operations include cleaning, grading, drying, treatment, packaging and storage. Optical sorting, automated grading, precision packaging and digital inventory management can improve consistency and traceability.

7.2 Seed Enhancement

Seed enhancement technologies can improve establishment and handling. Seed priming can improve germination speed, uniform emergence and stress tolerance. Seed coating can provide protection against pathogens, improve handling and facilitate precision sowing. These technologies are particularly relevant where uniform stand establishment is essential for high-value vegetable production.

7.3 Vegetable Seed Production

Vegetable seed production is specialized because crops differ in reproductive biology and pollination behaviour. Production may require controlled pollination, specific isolation distances, skilled labour, strict field inspection, pest management and scientific harvesting. Environmental conditions must be appropriate for flowering, pollen viability, fertilization, fruit development and seed maturation (George, 2011).

7.4 Hybrid Seed Production Technology

Hybrid seed production is a core activity of commercial vegetable seed companies. Superior parental lines, synchronized flowering, controlled pollination, adequate isolation, effective seed extraction and rigorous genetic purity management are essential. The specific system varies with crop biology. Gynoecious lines facilitate cucumber hybrid production, male sterility systems are valuable in chilli and brassicas, self-incompatibility is used in some brassicas, and triploid systems are used to produce seedless watermelon.

Crop	Major Hybrid Production System
Tomato	Male sterility and/or controlled crossing
Cucumber	Gynoecious lines and controlled pollination
Watermelon	Triploid hybrid system
Chilli	Cytoplasmic male sterility
Cabbage	Self-incompatibility/CMS
Onion	CMS system

8. Hybrid Seed Production in Major Vegetable Crops

8.1 Tomato

Tomato is a major hybrid vegetable crop. Hybrid production involves selection of parents, controlled crossing, fruit development, seed extraction and processing. Breeding objectives include resistance to tomato leaf curl virus and bacterial wilt, heat tolerance, fruit firmness and processing quality. Molecular markers and genome-based approaches are increasingly used for trait improvement (Li *et al.,* 2018).

8.2 Cucumber

Cucumber is an economically important hybrid crop. Key breeding traits include gynoecious flowering, parthenocarpy, earliness, fruit uniformity and disease resistance. The source identifies powdery mildew, downy mildew, cucumber mosaic virus and tomato leaf curl New Delhi virus as important resistance targets. Gynoecious female lines and suitable pollinizers can be combined through controlled pollination for commercial hybrid seed production (George, 2011).

8.3 Watermelon

Watermelon breeding increasingly targets seedlessness, sugar content, fruit size, disease resistance and transport quality. Seedless triploid hybrids are produced using a tetraploid parent crossed with a diploid parent, providing a commercially important example of chromosome-based hybrid technology.

8.4 Chilli, Pepper and Brassicas

Chilli and pepper breeding focuses on yield, fruit colour, pungency, disease resistance and uniform maturity. Male sterility systems can reduce the need for manual emasculation. In cabbage, cauliflower and broccoli, self-incompatibility and cytoplasmic male sterility systems facilitate economical hybrid seed production.

9. Seed Quality Assurance and Certification

Seed quality directly affects crop establishment, productivity and farmer profitability. Vegetable seeds often have high economic value and low sowing rates, making quality assurance especially important. Quality is multidimensional and includes genetic, physical, physiological and health attributes (George, 2011; ISTA, 2024).

9.1 Genetic Quality

Genetic purity ensures that seed retains the intended varietal or hybrid identity. Grow-out tests, DNA fingerprinting, molecular markers and biochemical approaches can be used for purity assessment. Molecular methods provide opportunities for rapid and accurate identification of seed identity and purity (Collard and Mackill, 2008).

9.2 Physical Quality

Physical quality includes seed size, colour, weight, cleanliness and freedom from foreign material. Efficient cleaning and grading are important because physical contaminants can interfere with sowing, storage and processing.

9.3 Physiological Quality

Germination, vigour and storage ability are central indicators of physiological quality. High-quality seed should establish rapidly and uniformly under suitable conditions. Storage conditions must be managed to minimize deterioration and preserve viability. International testing procedures provide standardized approaches for evaluating seed quality (ISTA, 2024).

9.4 Seed Health

Seed-borne pathogens can introduce diseases into production fields. ELISA, PCR diagnostics and molecular pathogen identification can support seed health testing. Health testing is particularly important for crops where seed transmission can facilitate rapid disease spread.

9.5 Certification

Seed certification systems support variety authenticity, germination standards, seed health and farmer confidence. International bodies such as the International Seed Testing Association (ISTA) and OECD provide rules and standards for seed testing and certification, while national regulatory systems complement these frameworks (ISTA, 2024; OECD, 2023).

10. Molecular and Genomics-Assisted Breeding

10.1 Marker-Assisted Selection

Marker-assisted selection (MAS) uses DNA markers linked to desirable genes or quantitative trait loci to identify superior plants. In vegetables, MAS can support disease resistance, abiotic stress tolerance, quality improvement and nutritional enhancement. Its principal advantages are early selection, improved accuracy and reduced breeding-cycle time because selection need not wait for complete phenotypic expression (Collard and Mackill, 2008).

10.2 Genome-Wide Association Studies

Genome-wide association studies (GWAS) use diverse germplasm and genome-wide variation to identify associations between markers and important traits. Applications include discovery of genomic regions associated with disease resistance, yield components, fruit quality, stress tolerance and nutritional traits. A unified mixed-model framework can account for multiple levels of relatedness and reduce spurious associations (Yu *et al.,* 2006). The increasing availability of genome sequences and high-density markers has expanded the utility of GWAS in tomato, cucumber, pepper, melon and brassicas.

10.3 Genomic Selection

Genomic selection uses genome-wide marker information to predict breeding values before extensive phenotypic evaluation. It is particularly promising for complex traits such as yield, stress tolerance and quality, where many genes contribute small effects. Early prediction can reduce field-testing costs and increase the rate of genetic gain (Crossa *et al.,* 2017).

Approach	**Primary use**	**Key advantage**
MAS	Selection for known genes/QTLs	Early and targeted selection
GWAS	Discovery of marker–trait associations	Uses diverse germplasm and historical recombination
Genomic selection	Prediction of genomic breeding values	Useful for complex polygenic traits
Genome editing	Targeted gene modification	Potentially precise trait modification

11. Double Haploid Technology and Speed Breeding

11.1 Double Haploid Technology

Double haploid (DH) technology allows rapid development of completely homozygous breeding lines. Conventional inbreeding requires several generations of selfing and selection, whereas DH systems can produce homozygous material in a much shorter time. The source identifies applications in pepper, tomato, cabbage and onion. Rapid parental line development is valuable for hybrid breeding pipelines because stable lines can enter combining-ability and hybrid testing earlier.

11.2 Speed Breeding

Speed breeding accelerates generation advancement by optimizing photoperiod, temperature, light intensity and other growth conditions. Controlled-environment systems can enable multiple generations per year and shorten the interval between crossing and selection. Speed breeding has been demonstrated as a powerful approach for rapid generation advancement and breeding research (Ghosh *et al.,* 2018; Watson *et al.,* 2018).

For vegetable breeding programmes, the greatest benefit is obtained when rapid generation advancement is integrated with a clear selection strategy. Faster generations alone do not guarantee genetic gain; selection accuracy, appropriate population size, trait heritability and reliable phenotyping remain essential.

12. Genome Editing and CRISPR Technology

CRISPR/Cas technology has emerged as a powerful approach for targeted modification of plant genomes. It offers opportunities to modify genes associated with disease resistance, quality, shelf life, nutritional traits and abiotic stress responses. Reviews of CRISPR applications emphasize its potential for crop improvement while also highlighting the importance of transformation efficiency, target validation and regulatory considerations (Jaganathan *et al.,* 2020; Zhu *et al.,* 2020).

In vegetables, potential applications include virus resistance in tomato, powdery mildew and downy mildew resistance, improved nutritional content, enhanced shelf life, modified fruit composition, processing quality, heat tolerance, drought adaptation and salinity tolerance. Genome editing can complement conventional breeding, particularly when a specific gene is known and a precise modification is desired.

Practical deployment requires appropriate transformation systems, validation of edited events, regulatory compliance, evaluation of unintended effects and consideration of consumer acceptance. Thus, CRISPR should be viewed as one component of a broader precision-breeding toolkit rather than a replacement for conventional breeding.

13. Artificial Intelligence and Digital Transformation

Artificial intelligence is increasingly relevant across the seed development pipeline. AI can integrate genomic information, phenotypic observations, environmental data and market requirements to support breeding decisions. Machine-learning models may assist prediction of hybrid performance, disease resistance, environmental adaptation, yield potential and consumer preference (Crossa *et al.,* 2021; Ren and McElroy, 2021).

13.1 High-Throughput Phenotyping

High-throughput phenotyping addresses the labour and time limitations of conventional field measurements. Drone imaging, sensors, computer vision and automated measurement systems can capture plant growth, leaf characteristics, disease symptoms, fruit size and plant architecture. Unmanned aerial vehicle platforms and image-based approaches are increasingly used for field phenotyping and can generate repeated quantitative observations (Yang *et al.,* 2020).

13.2 Digital Seed Production and Traceability

Digital agriculture can improve field monitoring, production forecasting, supply-chain management, inventory control and seed traceability. Internet of Things (IoT) systems, digital inventory platforms and distributed ledgers are emerging tools. Traceability can improve transparency and help address counterfeit seed problems by connecting seed lots with production, testing, processing and distribution records.

14. Climate Change and Future Vegetable Seed Systems

Climate change is one of the most important long-term challenges for vegetable production. Higher temperature, water scarcity, salinity, new disease emergence and pollination problems can reduce productivity and stability. Because vegetables are often high-value crops with narrow quality specifications, even moderate environmental stress can have substantial economic consequences (IPCC, 2023; Raza *et al.,* 2020).

14.1 Future Breeding Priorities

- Heat-resistant vegetables, including heat-tolerant tomato and summer-adapted cucumber.
- Drought-resistant and water-efficient cultivars.
- Salt-tolerant vegetables for stress-prone environments.
- Disease-resistant hybrids that can respond to emerging pathogens.
- Resource-efficient cultivars requiring less water and nutrients.
- Rootstocks and production systems adapted to changing environments.

Climate-smart seeds should combine yield potential with stability under variable environments. Multi-location evaluation will become increasingly important because a cultivar selected under one climate may not perform similarly under another. Breeding programmes therefore need strong environmental characterization and data integration (Dwivedi *et al.,* 2016; IPCC, 2023).

15. Challenges Facing the Vegetable Seed Industry

15.1 Increasing R&D Costs

Modern breeding increasingly requires advanced laboratories, controlled environments, genomic platforms, phenotyping systems and skilled researchers. These investments can be difficult for small seed companies and public programmes with limited resources. Shared platforms, public-private partnerships and open scientific resources can help distribute costs.

15.2 Climate Uncertainty

Rapid environmental changes can reduce the effectiveness of conventional breeding strategies based on historical performance. Breeders must continuously update target environments and evaluate materials under representative stress conditions (IPCC, 2023).

15.3 Seed Quality and Counterfeit Seeds

Poor-quality seed, counterfeit products, inadequate storage and insufficient certification can undermine farmer confidence and cause economic losses. Strong quality-control systems, secure packaging, reliable testing and digital traceability are important safeguards (ISTA, 2024; OECD, 2023).

15.4 Intellectual Property and Access

Balancing breeder rights, innovation incentives and farmer access is a continuing policy challenge. Plant variety protection frameworks can encourage investment in breeding while requiring appropriate consideration of access, seed systems and responsible use of genetic resources (UPOV, 2023).

16. Future Prospects of the Vegetable Seed Industry

16.1 AI-Driven and Predictive Breeding

Future breeding systems are likely to move increasingly toward prediction rather than purely retrospective selection. Integration of genomics, phenomics, environmental modelling and machine learning can help estimate cultivar performance before extensive field testing. AI may support hybrid prediction, automated image-based selection and data-driven breeding decisions (Crossa *et al.,* 2021; Ren and McElroy, 2021).

16.2 Precision Seed Production

Automation and robotics can improve pollination operations, field monitoring, seed harvesting, processing and quality control. Precision production is particularly valuable where seed has high unit value and small deviations in genetic purity or handling can affect commercial performance.

16.3 Sustainable Seed Systems

Future seed systems must simultaneously address productivity, environmental sustainability and accessibility. Priorities include conservation of genetic diversity, climate resilience, resource-use efficiency and reliable farmer access. Sustainable seed systems should also strengthen local capacity for seed production and quality management where appropriate (Van de Wouw *et al.,* 2010; World Vegetable Center, 2023).

16.4 Nutritional Breeding

Vegetable breeding is increasingly expected to contribute directly to nutritional security. Future programmes may place greater emphasis on vitamins, minerals, antioxidants and other functional compounds while retaining agronomic performance, consumer acceptance and marketability.

16.5 Farmer-Oriented Innovation and Market Feedback

The value of a seed product ultimately depends on its performance in farmers' fields and its acceptance in the market. Future breeding programmes should integrate farmer feedback, market segmentation, post-harvest requirements and consumer preferences into product profiles. Participatory evaluation can help identify traits that may not be captured adequately by conventional breeding targets.

17. Integrated Future Model for a Competitive Vegetable Seed Industry

A competitive vegetable seed industry will depend on integration rather than isolated technologies. Germplasm conservation provides diversity; breeding converts diversity into useful parental lines; genomics accelerates selection; DH and speed breeding shorten generation time; controlled-environment and field phenotyping provide reliable measurements; hybrid testing establishes performance; seed production converts breeding products into commercial seed; quality assurance protects genetic and physiological quality; and digital traceability supports distribution and farmer confidence.

Stage	Priority Technologies/Activities	Expected Contribution
Germplasm	Conservation; characterization; diversity analysis	Broad genetic base
Breeding	MAS; GWAS; genomic selection; DH	Accurate and rapid selection
Generation advancement	Speed breeding; controlled environments	Shorter breeding cycles
Phenotyping	Sensors; imaging; computer vision	Higher-throughput, objective data
Product development	Hybrid testing; multi-location evaluation	Stable, market-fit products
Seed production	Controlled pollination; purity management	Reliable commercial seed
Quality assurance	Germination; health; genetic purity tests	Farmer confidence
Supply chain	Digital inventory; traceability	Transparency and reduced counterfeiting
Farmer interface	Demonstrations; feedback; market intelligence	Higher adoption and product relevance

Conclusion

The vegetable seed industry has transformed from traditional farmer-managed seed systems into a sophisticated global enterprise driven by genetics, biotechnology, digital technologies and international trade. Hybrid seed technology has played a central role in increasing yield, uniformity, quality and disease resistance in commercially important vegetable crops. The expansion of protected cultivation, changing consumer preferences and climate uncertainty are further reshaping breeding objectives.

Modern innovations such as marker-assisted selection, genome-wide association studies, genomic selection, doubled haploid technology, speed breeding, CRISPR genome editing, artificial intelligence and high-throughput phenotyping are accelerating the development of improved cultivars. Their greatest value will arise when they are integrated with sound breeding principles, reliable phenotyping, efficient seed production and strong quality assurance (Collard and Mackill, 2008; Crossa *et al.,* 2017; Ghosh *et al.,* 2018; Varshney *et al.,* 2021).

The future of the vegetable seed industry will depend not only on technological progress but also on sustainability, genetic-resource conservation, farmer accessibility, responsible regulation and market relevance. Public research institutions, private seed companies, policymakers and farmers have complementary roles. Collaborative approaches can strengthen the entire seed value chain and support development of climate-resilient, nutritionally improved and market-oriented vegetable cultivars. The next generation of vegetable seed systems will therefore be defined by precision breeding, climate adaptation, nutritional enhancement, digital traceability and farmer-centred innovation, contributing substantially to global food and nutritional security.

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FUNCTIONAL AND NUTRACEUTICAL POTENTIAL OF ONION PEEL-A COMPREHENSIVE REVIEW

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Abstract
Due to the increased preference for natural antioxidants and preservatives over synthetic ones, onion peel, a plentiful agro-industrial by-product, has recently attracted interest in the food business. Its potent antioxidant and anti-inflammatory qualities are attributed to its abundance of bioactive substances, which include flavonoids like quercetin and vitamins A, C, and E. New research demonstrates the potential health advantages of onion peel, such as its ability to lower cholesterol, control blood pressure, lessen inflammatory reactions, and aid in weight control and the prevention of obesity. Recent research has shown that onion peel extracts can effectively prevent lipid oxidation and prolong the shelf life of a variety of food products, suggesting its use a s a functional food ingredient in addition to their potential as a nutraceutical. Additionally, because of its high quercetin and vitamin C content, there has been increased scientific attention in its potential usefulness in immune support, especially during the COVID-19 pandemic. Considering how much onion peel is thrown away as trash worldwide, its valorization offers a cost-effective and environmentally friendly way to create useful components with additional value. With an emphasis on onion peel's potential as a natural antioxidant and preservative in food systems, this review attempts to thoroughly investigate the phytochemical composition, health advantages, and industrial uses of onion peel.

Keywords: Antioxidants, Anti-Inflammatory, COVID-19, Onion Peel, Quercetin, Value-Added.

Introduction

For the food processing sector, food waste is an important concern, in particular if there is a loss of precious minerals and phytochemicals. The development in non-communicable diseases (NCDs) conditions as the world's top cause of death such as cardiovascular illnesses, cancer and diabetes has led to healthier eating habits worldwide (Marmot *et al.,*2018). The use of phenolic-rich foods and phenol- enriched food supplements on a daily basis has been linked to the prevention of NCD disease. The global production of onion has expanded over the previous 20 years by at least 25% (Faostat 2020), with yearly production of about 47 million tones and the second largest vegetable crop. This is also due to a rise in the demand for ready-to-eat vegetables, such as onion, as a result of changing lifestyles.

The increasing demand for foods with a higher nutrition and greater sustainability because of the value of their by-products has increased the interest in choosing enhanced agricultural and/or local species which produce food and food ingredients that have a higher bioactive Phyto molecule content and improved health advantages. The majority of studies concentrated on the chemical and biological functions of onion bulbs and paid little attention to the unkitted onion skin (Rice-Evans *et al.,* 1996).

The most common by product of onion, soft and deformed bulbs is dry skin, two outer flesh scales and roots (grown during industrial peeling). Dry skin is the most common by-products. These waste products are a significant environmental issue since their potential usage is limited by their susceptible to microbial deterioration. Onion waste, like fleshy scales, is not good for food in high quantities because of the unique fragrance of the onion (Majewska. *etal.*,2017). Previous research has shown that dried onion peel powder can be integrated into a variety of food items to boost antioxidant activity without compromising sensory qualities. Onion (*Allium cepa L.*) is a common vegetable used both in food and in medicines in the human diet. Due to its distinct scent and high nutritional value, it is grown and traded for culinary purposes all over the world. In each of these days, the production and demand of Onion are rising, with a significant amount of industrial waste occurring. The bulk of waste biomass is composed of external scales, skin, roots, ampoules and degraded bulbs. A technique of boosting the value of onion waste is to make it a functional food source that reflects trends in the food industry that are boosting the reuse of trash while satisfying the need for functional foods. Flavonols such as quercetine and quercetine glucosides, known as antioxidants; fructooligosaccharides, well-known prebiotics; polysaccharide cell-wall, which is a food fibre part or, especially, pectin, which is a recognized food additive, or a possible source of prerebiotic oligomers; organosulfuric, well known prebiotic. and organosulphuric compounds. Powdered onion waste concentrate and extracts are still being added to various food formulations for the purpose of achieving innovative products of improved antioxidant and prebiotic quality, but it is showing promising results by adding concentrate and extracts into various food matrices in order to obtain innovative products with improved antioxidants and prebiotics (Aleksandra Vojvodi Cebin and colleagues, 2020). By processing and stabilizing onion trash can address the environmental problem created by huge amounts of onion leftovers disposal (residues and surpluses). Stabilized onion by-products as the ingredient natural antioxidant food can also help the food business to gain new natural and functional components, not just in terms of increasing their use (Eduvigis Rolda´n .*et al*.,2007. Onions are one of the most widely grown vegetables. As the amount of waste produced from various sectors of onion develops, more efficient environmental disposal and usage for these waste products is required. Onion waste, on the other hand, is a rich source of bio-active antioxidants used in the food and pharmaceutical industries. ((Fredotovi.*et al.,* 2021).

Polyphenols-Flavonoids

Flavonoids are a class of potent antioxidant polyphenolic chemicals. Fruit and vegetables are one of the most important food sources of flavonoids, with one of the richest onions. In addition, the most common polyphenolic components of onions are flavonoids with two primary groups: flavonols, which are found in yellow varieties, and (ii) anthocyanins, which are found in red/purple varieties (Griffiths *et al.,* 2002). Onion variety, bulb section, and onion growing conditions all influence the representation of flavonol groups, as well as individual compounds within each group (Bentez *et al.,* 2011). The highest number of quercetin-4'-glucoside and quercetin- 3,4'-diglucoside flavonols are Quercetin and its derivatives, representing up to 80 per cent of the total flavis.). (Bentez *et al.,* 2012) The monoglyceride: diglycosidic ratio varies by bulb section, with the outer scales having more monoglyceride content (Bentez *et al.,* 2011). Quercetin diglucoside is thought to form during storage, and its higher content is required in inner scales (Slimestad *et al.,* 2007). Quercetin has a number of biological functions, which include antioxidant, anti- inflammatory, anti-cancer, prevention of cardiovascular diseases (Griffiths. *et al.,* 2002; Wang *et al.,* 2016).

Antioxidants

Antioxidant such as quercetin is abundantly found in onion peel is a potent antioxidant flavonoid also found in grapes, berries, broccoli, berries, citrus fruits. It is known to have protective functions against tissue injuries, anttiobesity, antidiabetics and antihypertensive effect. Onion peel is also an excellent source of vitamin A, C and E. The skin of the onion is highly concentrated in free and glycosidically bound quercetin (2-10% w/h) and oxidised quercetin products such as small flavanols and phenolic substances (Griffiths. *et al.,* 2002 and Suh *et al.,* 1999). Antioxidants are chemicals that suppress oxidation and can cause free radicals and modify processes that can harm living cells. Natural and plant-based antioxidants have recently gained appeal because of their low cost, safe status and physiological system efficacy. Interest in aging-related diseases such as ageing and degenerative diseases is growing as society ages, and interest in metabolic syndrome and adult diseases is increasing as a result of economic growth and dietary changes. It's getting worse. As the public becomes more aware of these illnesses, free radicals as a cause of disease (also referred to as reactive oxygen species) and antioxidant-properties will be the cause of the ailments. It has been used to eliminate free radicals and reactive oxygen species in body by means of an antioxidant mechanism that involves macromolecular antioxidant enzymes and vitamins like Superoxide Dismutase (SOD) and Peroxidase (POD). However, antioxidant system of the human body eventually becomes unable to function normally as a result of pollution, ultraviolet rays, or multiple factors such as biological stress and ageing, and in this situation, the active oxygen species may be removed to protect by ingesting antioxidants. There is a need for an *in vivo* supply of an antioxidant-capable drug.

Onion peel, which is a potent antioxidant is been produced from the processing of onion is usually discarded and thus causing environmental pollution. The demand for porous agro-waste-derived carbon from the onion peel is enormous for the application of supercapacitors. The most abundant biomass onion peel has been synthesised using a double sink method and has been explored as a renewable carbon source for low-cost energy storage devices (Manohar D. Mehare. *et al*.,2020). Onion skins may be used to produce organic potassium rich fertiliser for all indoor and outdoor plants. It enhances resistance, growth, strong stems, and productivity to their diseases. Calcium, iron, magnesium, and copper are rich in this skin fertilizer.

Red onions are one of Egypt's most widely consumed and rich in antioxidants that decrease diabetes risk and lose weight. The effect of red onion peel (*Allium cepa L.*) is to reduce cancer risk and protect it against cardiovascular diseases, such as antioxidant, antimicrobial, antitumor.

Some studies demonstrate the increase in the nutrient properties in addition to non- auditioned pasta of onion peel powder in wheat pasta. The overall fibre, phenolic content, flavonoids and antioxidant capacity are significantly increased. The dry skin onion can be a technological addition that enhances the pasta (Majewska *et al*.,2020). Another study has focused on the efficacy of onion peel dust in the elimination of nitrate ion from the aqueous solution. OPD, a waste product, has a good effectiveness in eliminating nitrate ions from aqueous solutions, according to the results; (Mondal *et al.,* 2019).

Onion Peel as Functional Ingredient in Food Formulations

A study evaluated the effect of purple onion peel extract on the oxidative study of soyabean oil under oven accelerated storage where the soyabean oil was added with onion peel extract ,tocopherol ,ascorbyl palmitate and TBHQ(200mg/kg)antioxidants, isolated or combiner(100mg/kg of each antioxidant and the treatments were subjected to accelerated storage conditions(60°C/21days)and samples were taken after 0,7,14 and 21 days which showed that although TBHQ has shown high efficiency in controlling oxidation, its composition with purple onion peel has shown synergistic effect which retarded the occurrence of degradation product and retention of total tocopherol. This finding emphasizes on the use of natural antioxidants which can reduce the concentration of synthetic antioxidants (Umeda *et al*.,2021). Another experiment conducted in fish sausages to examine the antioxidant impact of onion peel. The sausages were separated into four groups with varied onion powder concentration (OPP): 0% (check), 1%, 2%, 3%. These samples were then evaluated for 28 days of organoleptic characteristics after storage at a rate of 5°C in the case of thiobarbuteric acid compounds, antioxidant activity, total polyphenol levels The addition of OPP has been reported to enhance antioxidant activity, total phenolic content, and lipid oxidation. An addition of 1–2% of OPP improved sensory qualities which, due to strong fishy smells, could not be observed in the control samples without OPP. Thus, this concludes that addition of 1-2% of onion peel powder can enhance shelf life with a preservative effect without destroying the sensory characters in fish meat sausages (Jan Badrnicek *et al*.,2020).

Another study evaluated the influence of onion peel and kimchi powder extract on the qualitative features of radiated pork emulsion sausages. The emulsion sausage formulated 2% kimchi and/or 0.05% onion skin extract. The results revealed that the addition of onion peel extract lowered the thiobarbuteric acid reactive material saucing value, and that microbial populations were lower than the other treatments when treated with onion peel or kimchi powder. In combination with kimchi powder and onion peel extract, the self- stability and qualitative features of sausage emulsion from irradiated pork may be improved under cold storage (Soo-Yoen Lee. *et al*.,2015).

In one recent study, onion peel powder was used to replace semolina in pasta at 2.5,5 and 7, 5gram/100gma concentrations. In comparison to the control sample, of onion peel powder on the chemical composition of the antioxidant characteristics of the pasta supplemented. Increased in content, dietary fiber, total phenol compound, antioxidant activity, and flavonoid content, considerably enhancing the overall nutritional quality. In the addition to the control sample, the use of onion peel powder decreased the cooking time, water solubility index and elevated redness (a*). This study suggests that onion peel powder is a very effective component that may replace nutritionally enhanced pasta (Majewska *et al*.,2020)

The importance of onion pelts in boosting shelter lives and antioxidant qualities of multi-grain bread has been shown in another experiment. Onion skin powder was used to give four distinct functional grains to a concentration of 1,2,3 or 4%. Total phenols, flavonoids, antioxidant activity, sensory characteristics, texture analyses products have been analyzed and compared to product control (Without onion skin powder). The results revealed that, in terms of colour, flavor and overall sensory acceptability, the texture, i.e. hardness and chewiness, reduced when added to the onion skin powder and 3% of the onion skin powder. Additionally, the maximum antioxidant activity was 4% of onion skin powder and there were substantial increases in phenols, total flavonoids in the product then control products andenhanced with onion skin powder. During 28 ambient days at 2°C and 5-day cooling storage in 2°C, shelf life extended to 11-13 days, while cooling stocks were more efficient. This study therefore found that onion skin powder is a naturally very efficient antioxidant and preservative to improve shelf life and other quality metrics (Sagar *et al*.,2021).

Onion skin powder is also a highly powerful meat products antioxidant. Jan Bedrnicek examined pigs with various onion skin water extract concentrations. It has been separated into five treatments with sample control 10% and 20% of the skin water extract of the yellow onion, 10% and 20% of the skin water extract of the red onion. For antioxidant activities, total polyphenols, reactive thiobarbituric acid components, sensory analysis, it was then accessible. Added antioxidants Patties demonstrated increased antioxidant activity, total polyphenol content and no antioxidant patties (control). Thus, onion skin has a much important significance as a natural antioxidant in highly saturated food products. (Bedrnicek *et al*.,2019).

Onion Peel as a Farmer's Choice

Every year, hundreds of thousands of tons of onion waste are produced by the onion processing industry. Onion peel trash is typically disposed of in landfills, adding to the sources of greenhouse gasses. Onion peel can be converted into beneficial agricultural goods like soil amendments and even bio stimulants as research has confirmed that it is a concentrated source of bioactive chemicals. (Zhang *et al.,* 2024).

In comparison to the well-irrigated control group, the use of red, yellow onion, and garlic peels for rice cultivation in soil irrigated with 50% field capacity was accomplished through physicochemical analysis. Red onion peels had the highest sulfur content (0.147 g/g), whereas garlic peels had the lowest (0.007 g/g). Different species had different amounts of crude fiber, ash, proteins, carbs, phenolic compounds, and flavonoids.

Future Projections

Vegetable skins and fruit peels can be used in a variety of ways, from composting to cooking to making them a part of our beauty and wellness routine, if we put your mind to it. Experts agree that eating vegetables and fruits with the skin on is more nutritious and safer. These are high in important micronutrients including fibre and antioxidants, which help with digestion and overall health. Onion peel being a potent antioxidant and its numerous benefits has to be incorporated in food formulations (Esmer& Hepsag 2025) There is a need to encourage the more use of natural antioxidants rather than artificial antioxidants which causes adverse health effects in population.

Onions are a tremendous source of phytochemicals and bioactive compounds despite the fact that the enormous volumes of trash and byproducts generated during their processing are usually thrown away. However, given the increased interest in the economy and sustainable use of resources to reduce adverse environmental consequences, food processing wastes like onion peel and skin can be collected and used as inputs in the production or reformulation of pharmaceutical medications and nutrient supplements (Kumar *et al* 2022).

Conclusion

Basically, we come across various articles, magazines, internet, YouTube stating the beneficial use of vegetables, fruits, various uses of their pulps and the peels are thrown away. Well, the lesser-known fact is that, even the peels of certain fruit and vegetables contain a whole lot of nutrition and come with medicinal properties. The onion has been around since ancient times and was most likely a staple of our prehistoric ancestors' diet. It's mostly avoided because of its strong odour and flavour, as well as the unpleasant after taste of "onion" breath. The sulphur-containing compounds in onions, which are also responsible for onions' incredible health benefits, give them a good smell and taste. Onions aren't generally associated with being a trendy "superfood," but the humble onion is, in reality, a superfood in its own right. We discharge tons of onion peels every day, but this peel has got to do all beneficialities not only to food industries, agricultural land but also to human health against various diseases. During this pandemic what is needed in our body to hold a strong immunity like vitamin Which is present in onion peel and the most potent compoundquercetin present in onion peel has the ability to to reduce free radicals and allergic reactions. Also, quercetin being a natural ingredient is inexpensive.

Food industry had always been working towards human safety in providing safe, healthy and nutritious food. The industry is turning more towards the use of natural supplements in food as today people are more concern about their health's and eating organic foods. As mentioned above, quercetin was an efficient antioxidant and was employed in many food formulations, tested and tested to increase food shelf-life and nutritional quality without compromising the sensory features of food. Onion peel has gained importance in markets being used for weight loss specially in obese conditions. Apart from weight loss it has proved to be an essential ingredient in curing many health-related diseases like cardiovascular diseases, respiratory, gastro-intestinal, urinary bladder, skin disorders etc. Apart from this, it has a beneficial role in agricultural land as well. As discussed above onion peel could be farmer's best friend.

Onion peel can serve as a fertilizer as it has richness of all minerals, nutrients, vitamins and biologically active compounds. Hence regardless of its immense benefits, its uses are still limited. There is a need to turn this waste into a useful ingredient which was hidden since years. But recent experiments have proved its potency and capability as an antioxidant, preservative, fertilizer, disease resistant component. With advancement of technologies coming future can incorporate this into various fields like few studies have also shown its use as an excellent packaging material. As the demand for packaged food, ready to eat food is increasing, industry is focusing into use of natural packaging antioxidants. To conclude we as a citizen should take this initiative to let others know the hidden benefits of Onion peel and help in preserving more and most onion peels for its better utility.

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CLIMATE CHANGE, WATER SCARCITY AND THE FUTURE OF AGRICULTURE

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Abstract

The multifunctional role of urban green spaces (UGS) is crucial for modern cities, as it contributes to enhancing the quality of life of urban residents and to the sustainability of urban development. Water availability, quality and timeliness are critical for agriculture. Climate change is affecting the hydrological cycle in many ways, thru increasing temperatures, changing precipitation patterns, longer droughts, floods and higher evapotranspiration. Population growth, urbanization, intensifying agriculture and conflicting demands from residential, industrial and ecological sectors are already placing strain on freshwater resources. Hence, the shortage of water is one of the biggest obstacles to agriculture and food security in the future. The concept of the "water footprint" is an effective way of understanding the direct and indirect use of freshwater associated with agricultural production and food systems. Blue, green and gray water footprints can be used to identify opportunities to increase water production, reduce pollution and develop more sustainable agricultural systems. Important in research have also been water shortage assessment, virtual water trading, effective irrigation, groundwater management, rainfall collection, waste water reuse, regenerative agriculture and reduction of food loss. The future of agriculture demands a shift from water-intensive agricultural methods to resource-conscious, water-efficient, and climate-resilient farming. This transition can be assisted by intelligent irrigation, precision farming, improved crop varieties, soil-water conservation, agricultural managed aquifer recharge, water recycling, and integrated land-water management. Conservation and regenerative agriculture can further improve water retention, carbon storage and soil health. We also explore the relationship between climate change, water scarcity and agricultural sustainability in this chapter, along with technological, ecological and policy approaches for resilient food systems.

Keywords: Regenerative Agriculture, Groundwater, Food Security, Climatic Resilience, Smart Irrigation, Water Productivity, Agriculture, Water Footprint, Climate Change.

Introduction

Agriculture is a key sector of the global water system. Freshwater is critical for crop production, livestock, agroforestry and aquaculture. Increasing food demand has historically been associated with expansion of irrigated agriculture and with increased extraction of surface and groundwater. Agriculture is one of the main industries impacting freshwater consumption and water scarcity. We are increasingly challenged to produce more food, but more food that also preserves the ecological integrity of land and water resources.

Climate change adds a new dimension to this problem. Changes in temperature, rainfall patterns, evaporation and the occurrence of extreme weather events affect water availability and agricultural water demand. Systems in agriculture that depend on dependable rainfall or irrigation are particularly susceptible to long-lasting drought, more erratic rainfall, or diminished access to groundwater. Therefore, water scarcity research has emphasized the necessity of considering not only the quantity of water available but also its spatial and temporal distribution and the competing demands for it *Gleick et. al.,* (2021).

Water scarcity can be caused by inadequate infrastructure, unequal access, poor water quality or when demand for fresh water exceeds the available supply. Thus, water scarcity is a problem that simultaneously affects the environment, technology, economy and society. These aspects can be exacerbated by climate change which alters precipitation and runoff, increases evaporation, and increases the frequency of drought and flood events.

Therefore, the agricultural sector should adopt approaches that incorporate energy efficiency, biodiversity, soil conservation, water management, climate change adaptation, and food system sustainability. Water footprint assessment, life-cycle assessment and water-scarcity indicators are tools to understand the environmental impact of agricultural production *Bayart et. al.,* (2010) and *Pfister et. al.,* (2009) These strategies can complement practical measures such as efficient irrigation, rainwater harvesting, wastewater reuse, groundwater recharge and conservation agriculture.

Climate Change and the Water Cycle of Agriculture

One of the ways climate change influences agricultures is thru the hydrological cycle. Higher temperatures increase the demand for evaporation, and changes in precipitation patterns influence how much water enters rivers, reservoirs, soils, and aquifers and when it does. The impacts are location specific but there is often more uncertainty about the availability of water for agricultural production.

Higher temperatures can increase crop evapotranspiration and thus demand for irrigation. *Anderson et al.* (2017) stressed the importance of adequately accounting for field-level wind conditions in heterogeneous agricultural settings when predicting crop ET. Such advances in crop water requirement estimation are more important in situations where irrigation water is scarce.

Differences in rainfall can lead to two seemingly contradictory problems of water scarcity and abundance. Long periods of rainfall deficits can cause soil moisture deficit and reduced agricultural productivity, while heavy rainfall can cause flooding, soil erosion, loss of nutrients and water logging. Hence, in agricultural water management, there is a need to manage drought as well as excess water.

Climate variability also affects groundwater recharging. Excessive abstraction for irrigation may lower groundwater levels. Recharging may be reduced by decreased or erratic rainfall. *Levintal et al.* (2023), investigated agricultural managed aquifer recharge as a potential method of sustainable groundwater management while the relationship between recharge, abstraction and groundwater levels was emphasized by *Nyakundi et al. (2022).*

These changes have ripple effects beyond individual farms. Agriculture is an integral part of watersheds and river basins where domestic, industrial, ecological and agricultural needs compete for scarce water resources. Sustainable agricultural water management needs to be planned at the catchment scale, not thru isolated actions at the farm scale.

Water Scarcity Risk to Food Security

Water scarcity is one of the greatest barriers to agricultural productivity. Water scarcity is very variable in time and space as shown by Hoekstra *et al.* [8] and the same amount of water use can have very different environmental impacts depending on the location and time. *Wang et al. (2021)* also emphasized the necessity of the inclusion of water-stress and water-footprint accounting in the water use assessment.

Water scarcity in agriculture is especially relevant because irrigation increases yields and reduces dependence on erratic rainfall, but overirrigation can accelerate the depletion of groundwater and promote competition among users. In their assessment of global agricultural economic water scarcity *Rosa et al. (2020)* demonstrated the significance of considering both the economic dimension of agricultural water use and physical water constraints.

Water scarcity also has social implications. Water scarcity can cause lower crop production and this can impact the income of rural areas relying on agriculture. This may, therefore, reinforce poverty and inequality thru water precarity. Water availability effects are not limited to agricultural production. *Motoshita et al., (2011)* associated domestic water scarcity with health effects.

The problem is made worse by a growing population and evolving diets. Agriculture has to feed not only a growing population, but also a growing diversity of consumption patterns. The importance of food choices in the water footprint of food consumption was shown by *Harris et al. (2020).* Similarly, *Jalava et al.* (2017) demonstrated how reducing food loss and changing diets can affect water scarcity and the global water budget.

Therefore, increasing water supplies alone will not be enough to address agricultural water scarcity. Demand management, increased production, appropriate crop selection, reduced losses and changes throughout the food chain are all equally important."

Water Footprint of Agriculture – What Does It Mean?

The concept of water footprint is a comprehensive methodology to assess the freshwater use associated with goods, operations, customers and production systems. The analytical background of water footprint assessment including the distinction of green, blue and gray water has been developed by *Hoekstra et al. (2011).*

Water Footprint (Green)

The "green water footprint" is rainwater held in the soil and used by crops thru evapotranspiration. It is very important in rainfed agriculture. Maintaining crop residue, reducing unnecessary soil disturbance, improving soil structure and adding soil organic matter can improve the ability of agricultural soils to hold rainfall.

Blue Water Footprint

The blue water footprint is the consumption of groundwater and surface water. Blue water is mainly used for irrigated agriculture; Precision water application, better irrigation scheduling, and efficient irrigation technologies are all ways to reduce unwanted withdrawals.

Altobelli et al., (2018) proposed the evaluation of the water footprint as an assessment of the environmental, social and economic sustainability of irrigated agricultural systems, while *Lovarelli et al. (2016)* stressed the importance of the assessment of the water footprint of crop production.

Gray Water Footprint

The "grey water footprint" relates to the freshwater necessary to dilute pollutants produced by production activities to certain standards of water quality. Water pollution can be caused by pesticides, fertilizers and other agricultural inputs. So, reducing pollution is just as important to water sustainability as cutting down on water consumption.

Life-cycle assessment is another framework for the assessment of water-related environmental impacts throughout agricultural supply chains. *Bayart et al.* (2010), *Pfister et al.* (2009) have contributed to the development of methods to evaluate freshwater consumption and water footprints within the framework of environmental assessments.

Climate Change, Water Footprint and Sustainability in Agriculture

A water footprint is more than simply quantifying the amount of water used. Water use can have a very high environmental importance depending on water availability, seasonality, scarcity and biological circumstances. The environmental impact of a liter of water drunk in an area with plenty of water may be vastly different from the same amount eaten in an area with severe water scarcity *Hoekstra et. al., (2012)*. This difference is very critical in view of climate change. As temperatures rise or precipitation patterns become more erratic, places that now have plenty of water may find themselves with less. The significance of water shortage assessment in past, present and future situations was emphasized by *Liu et al.* (2017).

Thus, for agricultural sustainability, there is a need to move from volume-based water management to a productivity- and scarcity-based water management. And the goal should be to maximize the nutritional and economic value of each unit of water, without losing ecological services.

Water-footprint assessment can also inform decisions in the supply chain. Growing relevance of water footprint in supply-chain management. According to *Aivazidou et al. (2016)*, water considerations should extend beyond individual farms to processing, distribution and consumption.

Food products may also contain large quantities of virtual water. The international trade of agricultural commodities is associated with a flux of water, referred to as virtual water trade. This allows water-intensive activities to be geographically redistributed, but can also transfer environmental stresses from one region to another. Thus, the sustainable planning of agriculture must take into account not only local water use but also global food trade.

Smart Irrigation and Precision Water Management

Smart irrigation is among the most promising avenues for water-efficient agriculture. Smart systems can take data on soil moisture, crop condition, weather and evapotranspiration to decide when and how much water is needed, while conventional irrigation may simply apply water on a set schedule.

Examples include drip irrigation, micro-irrigation, irrigation based on sensors, automated control systems, remote sensing and decision-support tools. These solutions can help keep crop production going while cutting down on runoff, evaporation, and losses from overwatering.

*Chazarra-Zapata et al., (*2020) showed the adaptation of traditional irrigation systems to smart agricultural growth. *Anderson et al.,* (2017) also emphasized the need for accurate evapotranspiration estimation to improve irrigation management.

Smart farms of the future might have soil-moisture sensors, satellite observations, weather forecasts, artificial intelligence and automated watering systems. Rather than providing farmers with one-size-fits-all irrigation schedules, these technologies might be able to provide field-specific advice.

However, technical efficiency alone is not sufficient to guaranty sustainability. If improvements in irrigation efficiency led to expansion of irrigated areas or introduction of water intensive crops, total water use may not decline. smart irrigation should be integrated with groundwater regulation, water accounting, suitable cropping pattern and basin level water governance.

Alternative Water Source and Groundwater Management

Today, groundwater is an essential component of agricultural water security in many regions. It is a fairly reliable source in periods of low rainfall, but over-abstraction can lead to falling water tables, land subsidence, salinization and ecological damage.

Agricultural managed aquifer recharge (Ag-MAR) is a method of enhancing groundwater storage by the intentional infiltration of suitable water into aquifers under controlled conditions. *Levintal et. al., (2023).* These methods can be used to capture surplus seasonal water for future agricultural use, their effectiveness depends on hydrogeological conditions, water quality and sound management.

Another important strategy is rainwater harvesting. Rainwater harvesting as an element of sustainable water management has been highlighted by *Yildirim and Alim* (2022) in their review of literature. In periods of intense rainfall rainwater harvesting can reduce flow and provide additional water during dry periods.

And reusing wastewater can help ensure there's enough water for agriculture, too. *Ingrao et al. (2020)* studied manmade wetlands as environmentally relevant treatment methods. *Meneses et al.,* (2017) discussed reconditioning and reuse of water in the food processing business. Properly treated wastewater can be an alternative source of irrigation water but the risks posed by contaminants, salinity, nutrients and health must be carefully managed.

Desalination is another potential source of fresh water, particularly in coastal areas under water stress. However, energy needs, costs and brine disposal still are a significant part of the sustainability *Molinari et. al., (20203); Badruzzaman et. al., (2019); Rios0Arriola et. al., (2022) and Gude et. al., (2018).* Thus, alternative sources of water should be looked at, considering integrated environmental, economic and social factors.

Regenerative & Conservation Farming

Ecological solutions have to go hand-in-hand with technological ones. Soil physical structure plays an important role in the water cycle of agriculture because it controls water infiltration, storage and availability to plants.

Regenerative agriculture focuses on soil health, biodiversity, carbon capture, minimal soil disturbance, crop diversification and enhanced ecosystem functioning. *Rhodes, (2017)* mentioned the demand for regenerative agriculture, and *Bradford et al., (2019)* emphasized the role of soil-carbon science in agricultural practice and policy.

The concepts underpinning conservation agriculture include crop diversity, permanent soil cover and minimal soil disturbance, all of which can lead to improved soil structure and reduced erosion. These concepts are important for sustainable agricultural production in relation to FAO's framework for conservation agriculture FAO (2023).

Healthy soils may also reduce irrigation requirements by enhancing rainfall infiltration and water retention. Organic matter can improve the soil's ability to hold onto water and nutrients. Crop residues can moderate soil temperature and reduce water evaporation from the soil surface;

Agroforestry can provide additional benefits by integrating trees with crops and cattle. Trees support biodiversity, soil protection, carbon storage and microclimate adjustment. For the analysis of environmentally friendly farming systems, including agroforestry, *Platis et al.* (2019) demonstrated the need to consider the energy, carbon and water footprints together.

Saving Water, Diet and Food Loss

Water conservation doesn't stop at the farm gate. Food that is lost or wasted is food that was produced with an unnecessary amount of freshwater resources. As *Marston et al.* (2021) showed, the reduction of food loss and waste can help to reduce water shortages.

"Food loss can happen at any stage, from when it is harvested, stored, processed, transported and sold all the way thru to when it is consumed. Improvements in cold chains, market access, processing efficiency and storage infrastructure can reduce losses and increase agricultural water output.

Dietary habits impact the water demand in agriculture as well. *Harris et al.,* (2020) also studied the water footprint of diets and stressed the importance of taking into account both the production and consumption. *Jalava et al.,* (2016) showed that food loss reduction and change of diet can have a cumulative effect on water use at the global level.

This implies that future agricultural policy should be food-system oriented. While increasing agricultural yields is critical, so too are reducing post-harvest losses, improving nutritional effectiveness and encouraging sustainable consumption habits.

Climate-Resilient Cropping Systems

Future agriculture will need crops and ways of producing them that can work despite greater climate unpredictability. When selecting crops, keep in mind the length of the growing season, local soil conditions, drought and temperature tolerance, and water needs.

Climate resilient farming practices include drought tolerant cultivars, crop diversification, altered planting dates, intercropping, agroforestry and soil water conservation. These methods decrease reliance on a single crop or climate.

Climate change can also influence the geographic suitability of crops. *Jabal et al.,* (2022) proved the capability of remote sensing and MODIS-NDVI time-series analyzes for assessing the effect of climate change on crop productivity. These technologies can contribute to better agricultural planning and early stress detection.

Real-time monitoring can further increase resilience in digital agriculture. Drought stress can be identified, crop water requirements can be estimated and resource application can be optimized with the use of satellite imagery, sensors, geographic information systems, meteorological stations and artificial intelligence.

Thus, the agricultural system of the future will probably be increasingly data-driven. But small and marginal farmers have to continue to have access to technology. Expensive, complex digital solutions or those that rely on advanced infrastructure could increase inequality rather than reduce it.

Integrated Water, Energy and Food Management

The larger water-energy-food nexus is closely tied to agriculture. The energy demand for irrigation is related to pumping and delivery. The energy demand for generation per se may require large amounts of water. Agriculture produces food, but also stresses the environment thru water withdrawals, fertilizer use, greenhouse gas emissions, and land use change.

D'Odorico et al., (2000) emphasized the interdependence of food, energy and water systems. One intervention that fixes one problem may create another. For example, groundwater pumping protects crops from drought but consumes more energy and accelerates aquifer depletion.

Desalination can make more fresh water available, but it can be very energy-intensive and create challenges with brine management. Wastewater treatment can produce irrigation water, but requires energy and tight contamination control.

Future agricultural planning should consider impacts of land, energy, water and carbon, rather than optimizing each resource separately. Integrated evaluation can be used to find strategies which offers a number of advantages and avoid unexpected trade-offs.

Farmer Participation, Policy and Governance

Appropriate governance of ecological and technological solutions. Water allocation is a complex social and institutional problem because water is often shared by farmers, households, businesses and ecosystems.

Good water governance requires rules on groundwater, clear ways to allocate water, incentives to use water efficiently, protection of the environment, and involvement of communities. Water-footprint assessments can be useful to policy makers, but indicators need to be assessed according to local hydrological and socioeconomic conditions. *Savenije (2000)*

Farmers could be convinced to use efficient irrigation and conservation methods thru financial incentives. Subsidies, might make scarcity worse if they encourage too much pumping or the growing of water-intensive crops. Water rules must therefore address supply and demand.

And it is equally important to involve farmers. The most successful agricultural technologies are those that address the practical needs, financial constraints, and local knowledge of farmers. Training, extension services and easy-to-access digital advisory systems can help adoption of climate-smart activities.

The participation of women and marginalized rural communities in decisions on water management is also important, as unequal access to water can further entrench existing social vulnerabilities. So sustainable water administration has to be socially and environmentally just.

Future Prospects: To Water-Smart Agriculture

The future of agriculture will be based on the ability to get the maximum value from each unit of water while doing the least damage to the environment. This shift will probably be influenced by a number of parallel

The timing and amount of water applied will be better with precision irrigation.

Artificial intelligence and remote sensing will enhance field conditions and crop water stress monitoring.

Crops that can withstand heat and drought will lessen their susceptibility to extreme weather conditions.

Reducing erosion and increasing water retention are two benefits of managing soil health.

Local water storage will be enhanced via regulated aquifer recharging and rainwater collection.

There will be more sources of irrigation water thanks to safe wastewater reuse.

Ecological resilience will be enhanced by conservation and regenerative agriculture.

Reducing food loss will stop agricultural water from being used needlessly.

Water-footprint accounting will help make better supply-chain and manufacturing decisions.

Resource trade-offs will be minimized by integrated water, energy, and food planning.

A single technology shouldn't be the foundation of the shift. Digital tools, ecological management, infrastructure development, institutional reform, and farmer expertise will all be integrated into a resilient agricultural landscape.

Conclusion

Water shortage and climate change are inter-related issues which will have increased impact on agriculture in future. Food security may be compromised by increased temperatures, changes in precipitation patterns, droughts, floods, depletion of groundwater and increased competition for freshwater. Even agriculture itself puts pressure on fresh water supplies thru irrigation, pollution and intensive, resource-heavy production methods.

The concept of a 'water footprint' provides a useful framework to understand these challenges, distinguishing between green, blue and gray water use, and linking agricultural production with regional water scarcity. However, in an effort to enable effective decision making, water-footprint assessment should be combined with life-cycle assessment, water-scarcity indicators and local hydrological data.

That is why it is the agriculture of the future: resource-efficient, climate-resilient, water-smart agriculture. Resilience can be enhanced by precision irrigation, remote sensing, drought resistant crops, groundwater recharge, rainfall collection, wastewater reuse, conservation agriculture and regenerative soil management. The hidden water demand of food systems can also be further reduced by reducing food loss and looking into eating habits.

In the end, sustainable agriculture under climate change will need a paradigm shift from merely increasing agricultural output to increasing water productivity, ecological resilience and nutritional value while protecting freshwater ecosystems. Future agricultural systems will need to be able to produce enough food with less water, have fewer negative impacts on the environment and be more resilient to unpredictable weather. That change will take farmers, scientists, governments, businesses and communities working together. But there's a path to a more secure and sustainable agricultural future thru the convergence of water science, digital technologies, climate-smart agriculture and regenerative practices, despite the major obstacle.

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PM-MKSSY: VALUE CHAIN ANALYSIS, GOOD PRACTICE NOTES, AND UNIVERSITY CONSORTIUM

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Abstract

The fisheries sector has emerged as an important contributor to India's economy by supporting employment, nutritional security, and rural livelihoods. To address the growing need for sustainable and efficient fisheries development, the Pradhan Mantri Matsya Kisan Samridhi Sah-Yojana (PM-MKSSY) was introduced with a focus on improving productivity, promoting innovation, and creating stronger market linkages. This review examines the scheme from the perspective of fisheries value chain development and highlights the importance of Value Chain Analysis (VCA) in identifying constraints, improving operational efficiency, and enhancing the competitiveness of fisheries enterprises. The review also discusses the role of Good Practice Notes (GPNs) as effective tools for documenting successful field experiences and facilitating the wider adoption of proven technologies and management practices. In addition, it explores the contribution of the consortium of universities and Nodal Officers in providing technical support, capacity building, project monitoring, and knowledge exchange, which are essential for effective implementation of the scheme. By bringing together scientific expertise, field-level experience, and institutional collaboration, PM-MKSSY provides a framework for strengthening fisheries development while encouraging sustainable resource use and continuous learning. The review emphasizes that a combination of value chain-based planning, systematic documentation of good practices, and strong institutional partnerships can significantly improve the long-term effectiveness of the scheme and contribute to the overall advancement of India's fisheries sector.

Keywords: PM-MKSSY, Fisheries Development, Value Chain Analysis, Good Practice Notes, University Consortium, Nodal Officers, Sustainable Aquaculture.

Introduction

The Pradhan Mantri Matsya Kisan Samridhi Sah-Yojana (PM-MKSSY) is a flagship initiative of the Government of India under the Department of Fisheries, Ministry of Fisheries, Animal Husbandry and Dairying(Government of India, 2023). The scheme aims to modernize the fisheries sector by improving productivity, promoting technological advancement, strengthening infrastructure, enhancing traceability, and creating a resilient and sustainable fisheries ecosystem. It complements earlier initiatives by focusing on quality, value addition, market competitiveness, and the economic prosperity of fish farmers and fishery entrepreneurs (Government of India, 2020; FAO, 2024).

Importance of PM-MKSSY in Strengthening the Fisheries Sector

PM-MKSSY is an important initiative aimed at improving the overall growth and sustainability of India's fisheries sector. The scheme focuses on enhancing fish production, increasing farmers' income, strengthening fisheries infrastructure, promoting scientific aquaculture, and encouraging the adoption of modern technologies (Government of India, 2023). By combining financial support with technical guidance and capacity building, PM-MKSSY seeks to create a more efficient, resilient, and market-oriented fisheries sector while improving the livelihoods of people who depend on fisheries.

For beneficiaries, the scheme offers more than financial assistance. It enables fish farmers, fishers, entrepreneurs, processors, and vendors to adopt better production and management practices. Through improved culture techniques, efficient feed management, disease prevention, water quality monitoring, and better post-harvest handling, beneficiaries can increase productivity, reduce losses, and improve the quality of their products (FAO,2024) These improvements ultimately contribute to higher income, better market opportunities, and more sustainable livelihood options.

PM-MKSSY also plays a significant role in strengthening the fisheries value chain. The scheme supports interventions at different stages, including input supply, fish production, harvesting, processing, storage, transportation, and marketing. Investments in infrastructure such as hatcheries, cold-chain facilities, transportation systems, and value-addition units help minimize post-harvest losses and improve product quality (World Organisation for Animal Health. (2023). Aquatic Animal Health Code.) As each stage of the value chain becomes more efficient, the overall competitiveness of the fisheries sector also improves, benefiting both producers and consumers.

Value Chain Analysis (VCA) is an important component in achieving these objectives. By examining every stage of the fisheries value chain, VCA helps identify existing challenges, opportunities for improvement, and areas where targeted interventions can have the greatest impact (Food and Agriculture Organization of the United Nations. (2014). Developing Sustainable Food Value Chains). The findings of VCA support better planning, efficient use of resources, and informed decision-making, ensuring that investments made under PM-MKSSY generate meaningful and long-lasting benefits (Porter,1985).

Another important outcome of the scheme is the development of Good Practice Notes (GPNs). Experiences gained during project implementation, field verification, and monitoring can be documented to highlight successful practices and innovative solutions (Food and Agriculture Organization of the United Nations. (2018). These Good Practice Notes serve as practical learning resources that allow successful approaches to be shared and replicated in other locations, reducing implementation challenges and encouraging the adoption of proven technologies.

The consortium of universities and Nodal Officers further strengthens the implementation of PM-MKSSY by providing technical guidance, conducting field verification, monitoring project progress, and organizing training and capacity-building programmes. Their continuous interaction with beneficiaries helps ensure that projects are implemented according to technical standards while also promoting knowledge exchange between researchers and farming communities (Government of India, 2023)

Overall, PM-MKSSY adopts a comprehensive approach to fisheries development by integrating financial support with scientific knowledge, infrastructure development, value chain strengthening, and knowledge sharing. Its emphasis on sustainable production, efficient resource use, and continuous learning not only benefits individual stakeholders but also contributes to the long-term growth, resilience, and competitiveness of India's fisheries sector.

Relationship Between PM-MKSSY and Value Chain Analysis

A fisheries value chain encompasses all activities involved from production to final consumption stages. The scheme strengthens each stage of this chain, making the entire system more efficient and profitable (Porter, 1985).

1. Input Supply: The scheme promotes access to quality seed, feed, broodstock, and improved farming technologies, ensuring higher productivity and better resource utilization (Government of India, 2023)
2. Production: Scientific aquaculture practices, disease surveillance, biosecurity measures, and climate-resilient farming methods improve production efficiency while minimizing environmental impacts (Food and Agriculture Organization of the United Nations, 2024)
3. Harvesting: Modern harvesting techniques reduce physical damage to fish, preserve quality, and minimize losses.
4. Processing and Value Addition: PM-MKSSY encourages the establishment of hygienic processing units, packaging facilities, cold storage, and innovative value-added fish products. These interventions increase shelf life, improve consumer acceptance, and enhance profitability (Food and Agriculture Organization of the United Nations (2022)
5. Marketing and Distribution: Digital platforms, traceability systems, improved logistics, and cold-chain infrastructure facilitate better market access, higher price realization, and greater consumer confidence (Government of India, 2023; Food and Agriculture Organization of the United Nations, 2014).

6. Consumer Satisfaction: High-quality, safe, and traceable fish products strengthen consumer trust and improve domestic as well as international market competitiveness (Food and Agriculture Organization of the United Nations, 2024; Codex Alimentarius Commission, 2023).

PM-MKSSY Support for Good Practice Notes (GPNs)

Although PM-MKSSY is primarily designed to provide financial support to the fisheries sector, its role extends well beyond funding. The scheme creates opportunities to identify, document, and share successful interventions implemented by beneficiaries across different regions (Government of India, 2023) This makes PM-MKSSY a valuable source for developing Good Practice Notes (GPNs), which compile practical experiences, innovative approaches, lessons learned, and successful models that can be replicated in similar situations.

Good Practice Notes are evidence-based documents that describe techniques, technologies, or management practices that have produced positive results under actual field conditions (Food and Agriculture Organization of the United Nations, 2018; Organisation for Economic Co-operation and Development, 2020). Within PM-MKSSY, these notes can be developed using information collected during project implementation, field verification, stakeholder consultations, routine monitoring, and performance assessment. As a result, GPNs become useful references for policymakers, extension workers, researchers, and fish farmers seeking practical solutions to improve fisheries production and management. A key feature of the scheme is its focus on promoting scientific aquaculture and responsible fisheries practices (Food and Agriculture Organization of the United Nations, 2022; World Organisation for Animal Health, 2023). The scheme encourages beneficiaries to adopt improved culture techniques, maintain better biosecurity, optimize feed management, regularly monitor water quality, and follow environmentally sustainable farming practices. Experiences gained from successfully implementing these interventions provide valuable material for Good Practice Notes, allowing effective methods to be shared with a wider farming community.

The scheme also supports the creation and modernization of fisheries infrastructure, including pond renovation, hatcheries, feed storage facilities, cold-chain systems, transportation networks, and value-addition units. Documenting these investments along with their technical, economic, and social outcomes helps demonstrate how appropriate infrastructure contributes to improved productivity and profitability. Such examples can guide future beneficiaries in making informed investment and management decisions (Government of India, 2023)

Another important contribution of PM-MKSSY is the generation of reliable field-level information. Project implementation involves the collection of baseline data, regular monitoring, physical verification, financial records, and performance evaluations. These data provide a strong foundation for preparing Good Practice Notes based on actual project experiences rather than theoretical assumptions. Consequently, the recommendations presented in these documents are more credible, practical, and relevant to field conditions.

PM-MKSSY also promotes environmentally sustainable and climate-resilient fisheries development. The adoption of renewable energy technologies, efficient water-use practices, reduction of post-harvest losses, proper waste management, and conservation of natural resources are encouraged under the scheme. Documenting these successful interventions through Good Practice Notes helps demonstrate how sustainable practices can improve productivity while minimizing environmental impacts (Food and Agriculture Organization of the United Nations, 2024; Intergovernmental Panel on Climate Change, 2023).

An additional strength of the scheme is its emphasis on collaboration among government departments, fisheries universities, research institutions, financial agencies, and producer organizations. This collaborative approach facilitates the exchange of knowledge, technical expertise, and field experiences. Information gathered from different stakeholders and geographical regions can be integrated into comprehensive Good Practice Notes that address diverse production systems and local challenges (Government of India, 2023).

The monitoring and evaluation mechanism established under PM-MKSSY also contributes significantly to the preparation of Good Practice Notes. Continuous assessment of project performance helps identify both successful strategies and implementation challenges. Recording these experiences allows future programmes to build upon proven approaches while avoiding common constraints, thereby improving the effectiveness of fisheries development initiatives (Government of India, 2023).

From a policy perspective, Good Practice Notes prepared under PM-MKSSY provide valuable evidence for informed decision-making. They demonstrate how specific interventions have improved fish production, farmer income, employment generation, and environmental sustainability under different field conditions. Such documentation can support the design of future development programmes and encourage the wider adoption of successful fisheries practices across the country (Food and Agriculture Organization of the United Nations, 2024).

Role of the Consortium of Universities and Nodal Officers under PM-MKSSY

The success of PM-MKSSY depends not only on financial assistance but also on effective technical support, coordination, and continuous monitoring. In this context, the consortium of fisheries universities and the designated Nodal Officers play an important role in ensuring that the scheme is implemented efficiently and that beneficiaries receive the technical guidance needed throughout the project cycle (Government of India, 2023).

The consortium of universities serves as a centre of technical expertise by bringing together specialists in fisheries science, aquaculture, fish processing, extension, and other related fields. Through research, education, and outreach activities, universities help transform scientific knowledge into practical solutions that can be adopted by fish farmers and entrepreneurs. They also contribute to the development of technical guidelines, training resources, and best management practices that improve the quality and sustainability of fisheries projects (Government of India, 2023; Government of India (2023).

Indian Council of Agricultural Research. (2023)

Nodal Officers act as the primary link between the consortium of universities and the beneficiaries. They assist applicants throughout the implementation process, coordinate field activities, and ensure that projects are carried out in accordance with the scheme guidelines. Their involvement helps maintain transparency, consistency, and accountability during project execution (Government of India, 2023; Indian Council of Agricultural Research, 2023)

One of the key responsibilities of Nodal Officers is conducting field verification. During site visits, they assess the feasibility of proposed projects, verify the infrastructure and resources available with the applicants, and confirm that the information provided in the applications accurately reflects the actual field conditions. These assessments support fair evaluation and help ensure that assistance is directed toward genuine and technically feasible projects (Government of India, 2023).

In addition to verification, Nodal Officers monitor the progress of approved projects by documenting field observations, identifying implementation challenges, and providing technical guidance whenever necessary. Regular monitoring allows timely corrective measures to be taken and encourages beneficiaries to adopt better management practices, ultimately improving project outcomes.

The consortium of universities also plays a significant role in capacity building. Through training programmes, workshops, demonstrations, and farmer interactions, beneficiaries gain practical knowledge on improved aquaculture practices, disease management, water quality monitoring, biosecurity, post-harvest handling, and value addition. These activities strengthen technical skills and enhance the long-term sustainability of fisheries enterprises (Government of India, 2023; Indian Council of Agricultural Research, 2023)

Another important contribution of the consortium is the documentation of successful field experiences. Information collected during project implementation, monitoring, and field verification can be compiled into case studies, technical reports, and Good Practice Notes. These documents capture effective practices, innovative solutions, and lessons learned, providing valuable guidance for future projects and promoting knowledge sharing across different regions.

Universities also support continuous improvement through research and innovation. By evaluating emerging technologies and assessing their suitability under diverse farming conditions, they generate scientific evidence that can be used to refine future interventions. This close interaction between research and field implementation helps ensure that the scheme remains relevant, practical, and responsive to the changing needs of the fisheries sector.

Role of the National Fisheries Digital Platform (NFDP) in PM-MKSSY

The National Fisheries Digital Platform (NFDP) is a key digital initiative developed under the Pradhan Mantri Matsya Kisan Samridhi Sah-Yojana (PM-MKSSY) to formalize India's fisheries and aquaculture sector. It provides work-based digital identities to fishers, fish farmers, vendors, processors, cooperatives, and fisheries enterprises, thereby creating a comprehensive national database. Through this platform, registered beneficiaries can access institutional credit, aquaculture insurance, performance-based incentives, traceability systems, capacity-building programmes, and other government services. By improving transparency, digital governance, and service delivery, NFDP plays a pivotal role in achieving the objectives of PM-MKSSY, including enhancing financial inclusion, strengthening the fisheries value chain, and promoting sustainable growth of the fisheries sector.

Table 1: State-wise Datas of NFDP Registrations in India (Present Status)

Sl. No.	State/UT	NFDP Registrations
1	Andaman & Nicobar Islands	4,535
2	Andhra Pradesh	2,79,578
3	Arunachal Pradesh	4,227
4	Assam	2,44,469
5	Bihar	1,72,724
6	Chandigarh	219
7	Chhattisgarh	58,951
8	Dadra & Nagar Haveli and Daman & Diu	4,789
9	Delhi	940
10	Goa	2,834
11	Gujarat	1,15,682
12	Haryana	8,291
13	Himachal Pradesh	12,040
14	Jammu & Kashmir	30,853
15	Jharkhand	41,591
16	Karnataka	2,00,203
17	Kerala	2,51,378
18	Ladakh	101
19	Lakshadweep	3,292
20	Madhya Pradesh	89,445

21	Maharashtra	2,76,431
22	Manipur	25,412
23	Meghalaya	23,951
24	Mizoram	4,601
25	Nagaland	9,436
26	Odisha	2,39,363
27	Puducherry	14,544
28	Punjab	4,704
29	Rajasthan	6,032
30	Sikkim	2,031
31	Tamil Nadu	3,56,673
32	Telangana	2,63,054
33	Tripura	1,01,424
34	Uttar Pradesh	1,22,312
35	Uttarakhand	10,730
36	West Bengal	74,005
37	Total	30,60,845

(Source data as reported by the Government of India)

Conclusion

PM-MKSSY represents a comprehensive approach to fisheries development by integrating productivity enhancement, value chain strengthening, quality assurance, sustainability, and market competitiveness. Through its support for Good Practice Notes and scientific management, the scheme promotes safe, traceable, and high-quality fish production while protecting the environment. By reducing waste, encouraging value addition, improving livelihoods, and fostering sustainable resource management. It serves as a vital pillar in achieving a resilient fisheries sector and advancing India's Blue Economy vision

An important strength of PM-MKSSY lies in its emphasis on knowledge generation and dissemination. The active involvement of the consortium of universities and Nodal Officers facilitates technical guidance, field verification, project monitoring, and documentation of successful interventions. This creates opportunities to develop Good Practice Notes that capture field-based experiences, innovative approaches, and practical lessons. Such documentation supports evidence-based decision-making and enables the replication of successful models across different regions.

Overall, PM-MKSSY has the potential to transform the fisheries sector by fostering collaboration among academic institutions, technical experts, and beneficiaries while promoting sustainable and inclusive growth. Continued implementation, regular monitoring, and systematic documentation of best practices will further strengthen the impact of the scheme and contribute to the development of a more productive, resilient, and environmentally responsible fisheries sector in India.

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SOLAR-POWERED ENERGY-EFFICIENT SHRIMP FARMING

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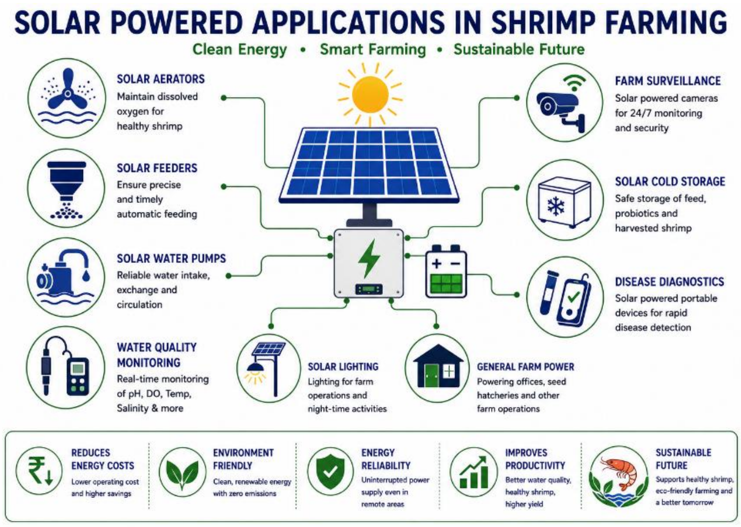
Abstract

Shrimp farming is an aquaculture practice that requires a substantial amount of energy, primarily for tasks like aeration, pumping, feeding, water exchange, lighting, security, and monitoring water quality. The rising energy costs, dependence on grid electricity and diesel systems, and the need to reduce aquaculture's environmental footprint have driven interest in renewable energy-based production systems. Solar photovoltaic (PV) technology stands out among renewable options for shrimp farming due to its scalability, modularity, low operational demands, and suitability for tropical regions with abundant sunlight. Solar PV systems can supply clean electricity for essential farm operations, including aerators, pumps, automatic feeders, lighting, security devices, and sensor-based monitoring systems. Innovative uses of solar energy, such as integrating solar power with energy-efficient equipment, battery storage, automated controls, and IoT-enabled technologies, can improve energy efficiency, reduce operating costs, and enhance operational reliability. Additionally, solar-powered systems can lessen dependence on diesel generators and conventional electricity sources, contributing to lower greenhouse gas emissions and promoting more climate-resilient shrimp production. Therefore, combining solar PV with energy-efficient equipment and advanced technologies offers a promising approach to developing sustainable, economically viable, and climate-resilient shrimp farming systems.

Keywords: Solar Energy, Solar Photovoltaic, Energy Efficiency, Shrimp Aquaculture, Solar Aeration, Solar Feeders.

Graphical Abstract:



Introduction

Aquaculture has emerged as one of the fastest-growing food production sectors globally, with shrimp farming being one of its most commercially important and rapidly expanding components. Global shrimp production is overwhelmingly dominated by Pacific white shrimp (*Penaeus vannamei*) owing to its high growth rate, adaptability to intensive culture conditions, and suitability for commercial production. Global farmed shrimp production was estimated at approximately 5.8 million metric tons (MMT) in 2023, with Ecuador, China, India, Vietnam, and Indonesia being the leading shrimp-producing countries, together accounting for approximately 74% of the global production (Campbell *et al*.,2026). India has emerged as a major contributor to global shrimp production and trade, with coastal states such as Andhra Pradesh, Gujarat, Odisha and Tamil Nadu playing important roles in the expansion of shrimp aquaculture. India's shrimp exports increased by approximately 123%, from ₹19,368 crore in 2013–14 to ₹43,135 crore in 2022–23 (Mandal and Singh,2025). This expansion has been greatly aided by the intensification of P. vannamei farming, which has enabled higher stocking density and elevated production levels. However, it has also led to a heightened reliance on energy-consuming operations. Intensive shrimp farming relies heavily on electricity and fuel for aeration, pumping, feeding, and environmental monitoring, making energy costs approximately 15–30% of operational expenditure, with aeration alone contributing approximately 20–25% of total shrimp production costs. Aeration is a key energy cost in shrimp farming, primarily because aerators must operate continuously to maintain adequate dissolved oxygen levels. Total energy demand in shrimp production ranges from 11.4 to 41.6 GJ per tonne of shrimp, with energy expenditure accounting for approximately 10% of total variable production costs. Aeration is a major component of this energy demand, and its cost is influenced by aerator type, oxygen-transfer efficiency, installed capacity, operating duration, and electricity or fuel prices. Reported aeration costs vary from approximately US$0.031 to US$0.079–0.11 per kg of oxygen transferred, depending on aerator type and efficiency. Electricity consumption can also vary considerably; inefficient aeration systems have been reported to require about 4,847 kWh per tonne of shrimp, corresponding to approximately US$436/t shrimp, whereas more efficient systems could reduce electricity costs to about US$297/t or US$242/t under comparable oxygen-transfer requirements. In addition to recurring energy expenses, the initial investment in aeration equipment varies according to system type and capacity. Improving aerator efficiency, optimizing operating schedules, and integrating renewable energy sources such as solar power offer important opportunities to reduce aeration-related energy costs while maintaining adequate dissolved oxygen for shrimp growth and survival (Boyd and McNevin, 2021; Nguyen *et al.,* 2024). Rising electricity and diesel prices further increase production costs, and farms in remote coastal areas may depend on diesel generators where grid electricity is unreliable. This dependence on conventional energy sources increases operating expenditures, exposure to power interruptions and fuel price fluctuations, and greenhouse gas emissions. As uninterrupted aeration is essential for shrimp survival, prolonged power failures can rapidly deteriorate water quality and increase the risk of stress and mortality. To ensure that shrimp production remains economically viable, sustainable, and resilient to climate change, it is crucial to enhance energy efficiency and expand the variety of farm energy sources by adopting renewable energy technologies (Ahmed, 2025).

Renewable Solar Energy

Renewable energy offers a practical pathway to reduce the dependence of shrimp farming on conventional grid electricity and fossil fuels. Among the available renewable sources, solar energy is particularly promising for aquaculture because it is abundant, renewable, and well-suited to shrimp farms that are generally located in open coastal and rural areas with high solar exposure and adequate space for photovoltaic installations. Solar power is particularly significant for farms because of its decentralized nature, especially in areas where grid electricity is inconsistent or diesel generators serve as a backup, contributing to reduced greenhouse gas emissions (Huang *et al.,* 2024)

Solar Energy Development and Policy Initiatives in India

India possesses significant potential for solar energy, as it typically receives solar radiation ranging from about 4 to 7 kWh m^{-2} per day and experiences close to 300 days of sunshine each year in most regions. Solar development has progressed from early research and decentralized applications to large-scale grid-connected and distributed PV systems, supported by declining costs, technological advances, and expanding domestic manufacturing. growth has been reinforced by key policy initiatives, including the Electricity Act (2003), National Electricity Policy (2005), Tariff Policy (2006), National Action Plan on Climate Change (2008), and the Jawaharlal Nehru National Solar Mission (JNNSM) (2010). These measures have accelerated solar deployment across utility, rooftop, agricultural, and rural applications. With the national target of 500 GW of non-fossil fuel capacity by 2030 and net-zero emissions by 2070, solar energy has become central to India's energy and climate strategy (Umar & Yadaw, 2024; Chaturved *et al.,* 2024). This growing solar infrastructure can provide reliable, decentralized electricity to shrimp farms, especially in rural and coastal areas with limited or no grid electricity. In the context of shrimp farming, solar energy provides more than merely an alternative electricity source; it facilitates the transition towards energy-efficient, automated, and resilient production systems. The integration of solar photovoltaic (PV) technology with energy-efficient equipment, battery storage, automated controls, and digital monitoring systems can optimize energy consumption and enhance operational reliability. This integration presents opportunities for the broader application of solar power in shrimp farming, encompassing solar-powered aerators, feeders, water pumps, sensors, and Internet of Things (IoT)-based monitoring and management systems.

Solar Photovoltaic (PV) Technology

Solar photovoltaic (PV) systems have emerged as a leading renewable energy technology for sustainable aquaculture, providing a clean, reliable, and cost-effective alternative to traditional electricity sources. This technology has transitioned from being merely an alternative renewable energy option to becoming a significant component of the global energy system. Its scalability, modularity, decreasing costs, and broad geographic applicability have facilitated its rapid deployment across utility-scale, rooftop, decentralized, and off-grid applications. By 2024, global installed solar capacity surpassed 1.5 TW, indicating substantial growth over the preceding decade. Technological advancements, economies of scale, supportive policies, and increased investment have further enhanced the economic competitiveness of PV systems. The integration of battery storage, smart-grid technologies, digital monitoring, and intelligent energy management is progressively enhancing the reliability and flexibility of solar power. However, challenges such as intermittency, grid integration, storage requirements, land availability, supply-chain risks, financing constraints, and policy uncertainty persist. Therefore, continued technological innovation, grid modernization, energy-storage deployment, and supportive policy frameworks will be crucial for fully realizing the potential of solar PV in a resilient, low-carbon, and sustainable energy future (Rezaee & Silva, 2026). Solar PV systems can effectively meet a substantial share of shrimp farm energy requirements while reducing electricity costs and emissions. Solar PV, particularly when integrated with battery storage, improves energy independence and reliability. The preferred grid-connected PV–BESS system achieves an 85.4% renewable energy contribution, an 85% reduction in electricity costs, and emissions, while providing 18.3 hours of backup power. Although fully off-grid PV–BESS systems can provide a complete renewable energy supply, their higher investment costs make grid-connected PV with battery storage a more economically balanced option for shrimp farming (Fikriyadi *et al.,* 2025). An important advancement in solar-powered aquaculture is the development of aquavoltaic systems. This technology involves the installation of solar photovoltaic panels on or near shrimp farms to generate electricity and produce food. By optimizing the use of land and water resources, aquavoltaic systems enhance the sustainability of farms. Since 2014, there has been a notable increase in both research and commercial implementation of these systems in regions such as China, Taiwan, Japan, Southeast Asia, Europe, and North America (Imani *et al.,* 2023). In addition to electricity generation, photovoltaic panels provide shading, which helps maintain uniform water temperatures, inhibits algae growth, and reduces water evaporation. Another innovative technology is the floating photovoltaic (FPV) system, where photovoltaic panels are installed directly on ponds and other water storage units. FPV systems significantly increase the potential for agricultural land use while benefiting from the cooling properties of water. Floating photovoltaic (PV) systems have the potential to generate more electricity than traditional ground-mounted systems. This increased efficiency is attributed to the cooling effect of water on the panels and the enhancement of performance through reflected solar radiation. Research conducted in South Korea has indicated that floating PV systems exhibit a conversion efficiency that is approximately 7.6–17.6% higher than that of reference ground-mounted systems (Campana *et al.,* 2019). In addition, FPV installations can reduce pond water evaporation improve water-use efficiency, and generate sufficient renewable electricity to operate essential aquaculture equipment. (Vo *et al.,* 2021). These findings underscore the potential of floating PV systems to enhance energy output while effectively utilizing water surfaces

Solar Energy Based Applications in Shrimp Farming

Solar-Powered Aeration

Mechanical aeration is the most energy-intensive operation in shrimp farming because it is indispensable for maintaining adequate dissolved oxygen levels under high stocking density. In intensive P*enaeus vannamei* culture, aerators often operate continuously during the night and for extended periods during the day as the stocking density and biomass increase. Consequently, the need for electricity significantly increases during the culture cycle, positioning aeration as a key factor in the economics of production. Conventional electric aerators typically consume between 0.75 and 2.2 kW per unit, whereas large commercial farms may deploy multiple aerators operating for 12–24 h per day. Paddle wheel aerators use as much as 19.8 GJ per ton of shrimp produced. The energy consumption for shrimp production can range from 11.4 GJ to 41.6 GJ per ton, contingent upon specific circumstances (Boyd & McNevin, 2021). The aeration of shrimp ponds depends on several factors. Factors such as stocking density, pond and aerator management, and the efficiency and survival rate of shrimp can be included. The prevalence of diseases and comprehensive farm management can significantly influence outcomes. Therefore, electricity for aeration can be a large operating expense. It accounts for approximately 20–30% of the overall cost of producing shrimp, and nearly 23% of operating expenses are used to pay for electricity. As intensive shrimp production continues to increase, so does the reliance on constant aeration, which rapidly increases the cost of production and negatively impacts the environment through greenhouse gas emissions. This is especially the case when shrimp farms use electricity from coal-based power plants. Therefore, there is a need for improved aeration systems that use renewable energy sources. Therefore, improving aeration efficiency through renewable energy integration has become a major research priority in sustainable aquaculture. Given the high energy demand for aeration in intensive shrimp farming, the integration of solar photovoltaic (PV) systems with aeration equipment offers an effective approach to reduce reliance on conventional electricity and lower operational expenses (Sulthan *et al.,* 2026).

Solar-Powered Feeding

Feed management is a crucial determinant of productivity and profitability in shrimp farming, with feed expenses constituting over 50% of production costs. Traditional manual feeding is labour-intensive and frequently results in uneven feed distribution, irregular feeding schedules, and excessive feed wastage. These issues contribute to suboptimal feed conversion, degradation of water quality, and heightened disease risk. Solar-powered automatic feeders offer a sustainable alternative by integrating photovoltaic (PV) technology with automatic feed dispensers. These solar-powered systems operate programmable feeders, reducing reliance on grid electricity and enabling precise and frequent feed deliveries. Such feeders are particularly advantageous for remote aquaculture farms with inconsistent electricity supply, as they enhance operational efficiency and support sustainable aquaculture practices (Ani *et al.,* 2015; Boonraksa, & Boonraksa, 2025).

Integration of Solar Energy and Smart Technologies

Renewable energy adoption in shrimp farming should be complemented by energy-efficient equipment, intelligent control, and digital monitoring systems to minimize unnecessary energy consumption and optimize farm operations. Aeration is a major area for energy optimization, where high-efficiency motors, appropriately sized aerators, variable frequency drives (VFDs), and dissolved oxygen (DO)-based automatic controls can regulate aeration according to the actual oxygen demand. Incorporating energy-efficient feeders, pumps, water circulation systems, sensors, and IoT-driven automation can reduce energy consumption and enhance efficiency. The integration of solar PV, battery storage, IoT, smart sensors, and automation can establish a sophisticated energy management system for shrimp farming. This system utilizes IoT platforms to remotely monitor the dissolved oxygen, temperature, and water quality via cloud connectivity (Prapti *et al.,* 2022; Novianarenti *et al.,* 2026). Smart and automated circulation systems are employed to periodically remove sludge as needed, whereas automated aerators adjust their operations based on requirements, reducing energy waste by approximately 30-40% under optimal conditions. Solar-powered automatic feeders dispense precise amounts of feed to minimize waste. Additionally, solar energy powers smart pumps for efficient resource use and supports IoT sensors, CCTV cameras, motion sensors, alarms, and Internet-based communication devices with built-in battery backup. This setup ensures continuous monitoring and alerts throughout the day and night, even during power outages. This approach reduces costs, achieves a high degree of energy efficiency, improves energy autonomy, optimizes resource utilization, enhances farm security, and increases resilience to climate risks (Yadava *et al.,* 2023).

Solar-Powered Auxiliary Operations

In addition to high-energy-consuming components such as pumping, aeration, and circulation, shrimp farms can benefit from the integration of photovoltaic (PV) solar technologies in various auxiliary operations. The application of solar energy extends beyond major energy-consuming activities to include several supplementary farm functions. Photovoltaic systems can support lighting, communication and telemetry equipment, surveillance cameras, and other low-energy electrical applications. Solar-powered LED lighting enhances visibility around farm entrances, embankments, pathways, storage areas, and equipment sheds, thereby reducing reliance on conventional electricity. In remote and off-grid farming locations, these decentralized applications enhance operational reliability and reduce energy costs (Chen *et al.,* 2024). To improve energy efficiency and minimize potential disturbance to aquatic organisms, lighting should be restricted to essential areas and employ low-intensity, shielded, or motion-activated LEDs rather than continuous illumination over culture ponds. Overall, integrating solar energy across both critical and auxiliary farm operations contributes to more energy-efficient, resilient, and environmentally responsible aquaculture systems (Vo *et al.,* 2021). Furthermore, inadequate electrical infrastructure, including poor grounding, current leakage, improper wiring, and insufficient protection against electrical surges and lightning, can compromise the safety and reliability of aquaculture operations. These challenges underscore the need for integrated energy solutions that combine renewable energy generation with energy storage, efficient electrical equipment, automated load management, and appropriate safety measures. Solar-powered systems incorporating photovoltaic generation, battery storage, efficient motors, automated controls, and electrical protection can reduce dependence on conventional grid electricity and diesel generators while improving energy reliability, operational efficiency, and farm safety (Arsalan *et al.,* 2026).. Such integrated approaches are particularly valuable in remote aquaculture areas where access to reliable grid electricity may be limited. Although specific studies on solar-powered security systems in shrimp farming remain limited, their integration with solar energy offers considerable potential for enhancing farm security, worker safety, energy independence, remote monitoring, and overall operational efficiency in sustainable shrimp farming.

Advantages of Solar Energy Integration in Shrimp Farming

Solar energy offers several advantages for shrimp farming, particularly by reducing the dependence on grid electricity and diesel-based power sources. The major advantages of solar energy in shrimp farming are summarized in following Table1.

Table 1: Key Benefits of Solar Energy for Shrimp Farming (Vo *et al.,* 2021; Isaac, 2025).

Economic Advantages	Operational Advantages	Environmental Advantages
Reduces dependence on grid electricity and diesel.	Provides an alternative electricity source for critical farm equipment.	Reduces greenhouse gas (GHG) and carbon dioxide (CO_2) emissions.
Lowers recurring electricity and fuel expenditure.	Improves energy security during grid interruptions.	Minimizes dependence on fossil fuels.
Reduces exposure to fluctuating electricity and fuel prices.	Supplies power for aerators, pumps, feeders and monitoring systems.	Produces no direct air pollution during electricity generation. Supports climate-change mitigation.

Provides long-term savings after recovery of the initial investment.	Can be integrated with battery storage for operation during low-solar periods.	Improves the environmental sustainability of shrimp production.
Supports decentralized electricity generation, particularly in remote areas.	Enables integration with automated and IoT-based farm-management systems.	Contributes to national renewable-energy and decarbonization objectives

Challenges in Adopting Solar Energy for Shrimp Farming

The integration of solar energy into shrimp farming, despite its significant potential, encounters numerous technical, economic, environmental, and operational challenges. The substantial initial investment required for photovoltaic (PV) panels, inverters, batteries, mounting structures, and installation poses a significant barrier, particularly for small-scale farmers. Battery storage, essential for ensuring power availability during nighttime, periods of low solar irradiance, and extended cloudy or rainy conditions, further increases capital, maintenance, and eventual replacement costs. Solar power generation's inherent dependence on weather and solar irradiance necessitates appropriate system sizing, energy storage, and backup arrangements to maintain reliable power for critical operations. Additional constraints include limited space for PV installation, integration with existing farm infrastructure, installation logistics, limited technical expertise, and ongoing maintenance requirements. In marine and floating applications, exposure to saltwater can accelerate corrosion, while biofouling and material degradation may diminish system performance and service life. Floating systems also demand appropriate structural strength, anchoring, electrical protection, and designs capable of withstanding environmental forces. The positioning, inclination, and spacing of PV arrays require careful optimization to balance energy generation, structural stability, maintenance access, and potential shading effects on the culture environment. Excessive shading may alter light availability and associated ecological processes within the pond or water body. Moreover, the limited availability of standardized design and engineering procedures, uncertainties regarding environmental regulations and water-use policies, and insufficient long-term information on the ecological effects of floating solar installations can hinder wider adoption. Therefore, the successful deployment of solar energy in shrimp farming necessitates site-specific techno-economic assessment, appropriate system sizing and energy storage, robust and corrosion-resistant materials, environmentally compatible designs, adequate electrical and structural safety measures, technical capacity building, clear regulatory frameworks, and long-term monitoring of both system performance and environmental impacts (Pringle *et al.,* 2017; Isaac, 2025).

Future Research Directions

Research should be conducted to develop an integrated smart and techno-economic solar energy system for shrimp culture. Areas to be targeted by research include integrated Solar PV with

Internet of Things (IoT) and artificial intelligence (AI) and automation for the management of the pond environment as well as for real-time energy profile, DO-based smart aeration that optimizes power utilization, and hybrid renewable energy sources integrated with state-of-the-art battery storage for electricity provision. Work should be carried out on the optimization and feasibility study of aquavoltaic and floating PV, their impact on pond conditions such as shade, productivity, and evaporation, and on pond biology and aquaculture ecosystem services provided. Life-cycle and techno-economic studies should focus on life-cycle carbon emission reduction, energy payback, investment costs, and long-term sustainability. Research should be applied toward the design of corrosion-resistant systems, establishment of standard designs and systems, improvement of reuse and recycling protocols for PV and battery components, and long-term environmental monitoring of solar-energy farming systems for safe management and promotion of renewable energy adoption. New technologies, such as green hydrogen may present future prospects for development of sustainable low-carbon aquaculture systems (Yadava *et al.,* 2023; Guo *et al.,* 2025)

Conclusion

Integrated Solar Solutions have the potential to significantly reduce dependence on grid electricity and diesel-powered pumps, thereby fostering a future in shrimp aquaculture characterized by low carbon emissions, climate resilience, and energy efficiency. Photovoltaic (PV) technology can directly support numerous high-demand activities, with its advantages further enhanced when combined with efficient equipment, energy storage solutions, and smart technologies such as smart IoT, autonomous control, and automated feeders. Additionally, recent advancements in solar solutions, including aquavoltaic and floating PV systems, offer supplementary renewable energy sources. However, it is crucial to consider factors such as (a) cost feasibility, (b) system durability, longevity, and resistance to corrosion in highly saline environments, (c) effects on light penetration, gas exchange, food production, habitat structure, and biodiversity, and (d) installation and maintenance operations. Ultimately, the implementation of truly integrated and intelligent solar-powered systems is poised to transform shrimp cultivation into a more sustainable practice, enhancing energy efficiency, economic benefits, environmental impact, and ensuring a resilient agricultural future.

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MANGROVE - AGRICULTURE NEXUS IN THE SUNDARBANS: ECOSYSTEM SERVICES, CLIMATE CHANGE AND PATHWAYS TO SUSTAINABLE FARMING

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Abstract

The Sundarbans represents a highly interconnected mangrove–agriculture socio-ecological system where ecosystem health and agricultural sustainability are closely dependent on one another. This chapter examines the ecological and functional role of mangrove vegetation in supporting agriculture under a changing climate in Sundarbans. Mangroves contribute to coastal protection, sediment stabilization, nutrient cycling, carbon sequestration, biodiversity conservation and fisheries productivity, thereby indirectly strengthening agricultural and livelihood security. However, increasing salinity, sea-level rise, cyclones, storm surges, changing rainfall, water logging and freshwater scarcity are creating growing challenges for both mangrove ecosystems and agricultural production. The chapter highlights climate-smart strategies including salt-tolerant crops, rainwater harvesting, land shaping, improved drainage, crop diversification, integrated farming, soil organic matter management and GIS-based site-specific agricultural planning. Community participation, mangrove restoration and ecosystem-based disaster-risk reduction are also emphasized as essential components of long-term adaptation. Integrating mangrove conservation with agricultural planning can enhance resource security, ecological resilience and livelihood stability. Healthy mangroves function as natural guardians of sustainable agriculture and climate resilience in the Sundarbans.

Keywords: Climate-Smart Agriculture, Ecosystem-Based Adaptation, Mangrove Ecosystem, Salinity, Sundarbans.

Introduction

The Sundarbans, situated within the Ganges–Brahmaputra–Meghna delta along the Bay of Bengal, is world's largest mangrove forest, covering approximately 10,000 sq. km across India and Bangladesh (Bandyopadhyay *et al*, 2026). It is characterized by tidal rivers, creeks, mudflats, islands and salt-tolerant vegetation. The ecological condition of this landscape is closely connected with the livelihoods of surrounding communities, particularly through agriculture, fisheries and forest-based resources. In the Indian Sundarbans, agriculture remains an important livelihood activity, but agricultural production is increasingly hampered by salinity, freshwater scarcity, flooding, drainage problems and extreme climatic events (Ghosh and Roy, 2021).

The relationship between mangroves and agriculture may initially appear contradictory because mangroves occupy saline wetlands whereas agriculture requires relatively freshwater conditions. In reality, the two systems are interconnected. Mangrove forests function as protective ecological buffers between estuarine waters and human settlements. Their roots trap sediments, reduce erosion and influence hydrological processes, while their above-ground vegetation can reduce wave and storm energy. These functions can help protect agricultural landscapes from some of the impacts of cyclones and tidal flooding (Alongi, 2008).

The concept of a mangrove–agriculture ecosystem is therefore increasingly important. Degraded mangrove, rice-based agriculture and aquaculture occur in close proximity in entire Sundarbans. Freshwater scarcity, salinity, extreme events and inadequate agricultural infrastructure are major constraints requiring site-specific adaptation strategies (Padhy *et al.,* 2022).

Mangroves as Ecological Guardians

Mangroves are specially adapted halophytic plants capable of surviving high salinity, tidal inundation, anaerobic soils and strong coastal winds. Species belonging to genera such as *Avicennia*, *Sonneratia*, *Ceriops*, *Excoecaria* and *Heritiera* contribute to the structural and functional diversity of the Sundarbans (Gopal and Chauhan, 2006; Sreelekshmi *et al.,* 2020).

The ecological importance of mangrove vegetation in the Sundarbans can be understood through a range of interconnected ecosystem functions. Coastal protection is one of the most important services, as dense mangrove roots and above-ground vegetation help attenuate waves, reduce tidal energy and protect adjoining islands from erosion and storm surges. Mangrove root systems also promote sediment stabilization by trapping suspended particles and facilitating sediment deposition, thereby contributing to the maintenance of coastal landforms. Through the decomposition of leaf litter, roots and other organic matter, mangroves actively participate in nutrient cycling, enriching surrounding sediments and estuarine waters and supporting aquatic productivity. Mangrove forests are also highly efficient carbon sinks, storing carbon in their biomass and waterlogged sediments and thereby contributing to climate-change mitigation. Their structurally complex habitats provide shelter, feeding and breeding grounds for numerous plants, microorganisms, fish, crustaceans, birds and other organisms, making them essential for biodiversity conservation and fishery and nursery support. These ecological services directly and indirectly sustain local communities by supporting fisheries, agriculture, forestry and other natural-resource-based activities, thereby strengthening livelihood security. Collectively, these functions make mangroves an important nature-based solution for climate-change mitigation and adaptation, helping coastal communities copes with increasing salinity, sea-level rise, cyclones, flooding and coastal erosion (Alongi, 2002; Alongi, 2008; Lee *et al.,* 2014). Healthy mangrove belts can act as living coastal buffers by modifying tidal and wave dynamics and limiting shoreline erosion. Their presence may consequently reduce the vulnerability of nearby agricultural settlements and infrastructure to coastal hazards. Mangroves are therefore not simply forests; they function as natural infrastructure along vulnerable coastal margins (Alongi, 2008; Lee *et al.,* 2014).

Mangrove Vegetation and Soil Stabilization

The architecture of mangroves forms a complex below and above the ground which influences sediment transport within intertidal areas. Pneumatophores, prop roots and other root structures increase hydraulic resistance and favour the retention and deposition of suspended sediments. This process contributes to vertical accretion, shoreline stabilization and the development and maintenance of mangrove platforms (Krauss *et al.,* 2003; Alongi, 2008; Lee *et al.,* 2014). In the Sundarbans, the dense network of aerial roots further modifies tidal flow and facilitates the settling of fine sediment, making mangrove forests important natural sediment sinks (Chaudhuri *et al.,* 2020).

This function is particularly important for the Sundarbans because its agricultural islands are predominantly low-lying and highly vulnerable to coastal erosion, tidal flooding and storm surges. Mangrove-mediated sediment accumulation can help maintain coastal elevation and reduce shoreline instability, although the ability of mangroves to keep pace with sea-level rise depends on sediment supply, tidal dynamics and rates of vertical accretion (Lovelock *et al.,* 2011). Research in the Sundarbans has documented substantial shoreline erosion and highlighted the vulnerability of fringe mangroves to future sea-level rise and changing hydrological conditions (Muralidhar *et al.,* 2022).

The stabilization of coastal margins is consequently important for agriculture because erosion and embankment failure can reduce cultivable land and expose agricultural fields to saline tidal water. Mangrove belts established or conserved in front of vulnerable embankments can also reduce physical damage during extreme events. Following Cyclone Aila, areas of the Indian Sundarbans where embankments were protected by mangrove vegetation experienced comparatively less structural damage, demonstrating the potential of mangroves as a nature-based coastal protection measure. Therefore, mangrove conservation and restoration can indirectly support agricultural sustainability by maintaining coastal stability, protecting embankments and reducing the exposure of agricultural land to erosion and saline submersion (Alongi, 2008; Lee *et al.,* 2014).

Mangroves as Natural Barriers against Cyclones

The Sundarbans is highly vulnerable to tropical cyclones, storm surges, tidal flooding and coastal erosion because of its low-lying deltaic landscape. These hazards can damage crops, breach embankments, inundate agricultural fields and introduce saline water into freshwater ponds and soils, thereby reducing soil fertility and agricultural productivity (Singh *et al.,* 2019; Padhy *et al.,* 2022). Mangrove forests provide an important natural buffer against cyclones and storm surges. During cyclonic events, the physical structure of mangrove stands can modify water movement and dissipate part of the energy associated with waves and storm surges, although the magnitude of this effect depends on forest characteristics and local geomorphology. Fallen mangrove litter is colonized and decomposed by bacteria, fungi and other microorganisms, resulting in the transformation and recycling of organic matter and nutrients. The effectiveness of this protection depends on forest width, vegetation density, root structure, topography and tidal conditions (Dasgupta *et al.,* 2019). Healthy mangrove belts along vulnerable coastal margins can therefore reduce erosion and lessen the hydraulic pressure on embankments, complementing conventional engineering structures. This protective function represents an important form of ecosystem-based disaster-risk reduction, in which natural ecosystems are conserved to reduce human vulnerability to environmental hazards. Besides coastal protection, mangroves provide sediment stabilization, carbon storage, biodiversity conservation and fisheries support (Alongi, 2008; Lee *et al.,* 2014). Thus, mangroves should be considered natural green infrastructure for the Sundarbans. Their conservation and restoration, together with strengthened embankments, early-warning systems and climate-resilient agricultural practices, can enhance agricultural and livelihood security. However, mangroves cannot completely prevent cyclone damage; their effectiveness varies with local ecological and geomorphological conditions (Dasgupta *et al.,* 2019).

Mangroves, Detrital Food Webs and Nutrient Cycling

Mangrove forests are highly productive ecosystems in which leaves, roots, branches and other organic materials contribute substantially to the detrital food web. Mangrove litter provides an important source of organic material for microbial decomposers. Microbial processing subsequently transforms this material and facilitates the transfer of carbon and nutrients into adjacent estuarine food webs (Alongi, 2002; Kristensen *et al.,* 2008).

The decomposed organic matter supports a complex food web involving microorganisms, zooplankton, benthic invertebrates, fish and crustaceans. Mangrove-derived detritus can therefore contribute to secondary production in adjacent estuarine waters and enhance the ecological productivity of coastal ecosystems (Lee, 1990; Bouillon *et al.,* 2008). In addition, mangrove sediments act as important sites for nutrient transformation and recycling, linking terrestrial vegetation with estuarine primary and secondary production (Kristensen *et al.,* 2008).

The ecological significance of this nutrient and energy transfer extends directly to local livelihoods. Productive mangrove-associated estuaries provide feeding, breeding and nursery habitats for numerous commercially and locally important fish and crustacean species. Consequently, healthy mangrove ecosystems can support fisheries and provide food and supplementary income for coastal communities, thereby diversifying livelihoods and reducing exclusive dependence on agriculture (Lee *et al.,* 2014; Nagelkerken *et al.,* 2008). In the Sundarbans, where farming is increasingly affected by salinity, flooding and cyclones, the maintenance of mangrove-supported fisheries can therefore contribute to livelihood resilience and food security.

Mangroves, Fisheries and Livelihood Security

Mangrove creeks and complex root systems provide important feeding, breeding and nursery habitats for fish, crustaceans and other aquatic organisms. Mangrove-derived detritus and habitat complexity enhance estuarine food-web productivity, supporting fisheries that contribute to local food security and income (Nagelkerken *et al.,* 2008; Lee *et al.,* 2014). Thus, the ecological pathway can be summarized as mangrove vegetation → habitat and detritus → aquatic organisms → fisheries → food and income. Mangrove degradation can consequently reduce fisheries productivity and weaken livelihood resilience. In the Indian Sundarbans, agriculture and fishing are closely linked livelihood activities, making communities particularly vulnerable to ecological and climatic changes (Ghosh and Roy, 2021).

Mangroves and Carbon Sequestration

Mangrove ecosystems are among the most efficient coastal carbon sinks, storing substantial quantities of carbon in living biomass, roots and, particularly, waterlogged sediments. Mangroves can accumulate substantial carbon because productive vegetation supplies organic material while waterlogged, oxygen-poor sediments can slow its decomposition and long-term mineralization (Alongi, 2002; Donato *et al.,* 2011). Consequently, mangrove conservation and restoration can contribute significantly to climate-change mitigation by preventing the release of stored carbon while maintaining ongoing carbon sequestration.

The importance of mangroves extends beyond carbon storage. Mangrove forests simultaneously provide several ecosystem services, including coastal protection, sediment stabilization, nutrient cycling, biodiversity conservation, fisheries support and livelihood benefits (Lee *et al.,* 2014). This multifunctionality makes mangrove conservation particularly valuable in climate-vulnerable regions such as the Sundarbans, where communities are exposed to sea-level rise, cyclones, coastal erosion and increasing salinity.

In the Sundarbans, maintaining healthy mangrove forests can therefore contribute to both climate mitigation and adaptation. Protection of existing forests, restoration of degraded mangrove areas and prevention of unnecessary mangrove conversion should be integrated with sustainable agricultural and coastal-management strategies. Such ecosystem-based approaches can help maintain carbon stocks while strengthening the ecological resilience of coastal communities (Alongi, 2008; Lee *et al.,* 2014).

Climate Change and Mangrove Vulnerability

Climate change is creating multiple and interacting pressures on the Sundarbans mangrove ecosystem. Major threats include rising temperature, sea-level rise, increasing salinity, altered rainfall patterns, changes in freshwater discharge, cyclones and storm surges, coastal erosion and prolonged flooding. These environmental changes can influence mangrove growth, regeneration, species composition and ecosystem productivity. Because mangroves depend strongly on tidal and freshwater conditions, alterations in salinity and hydrology are particularly important for their long-term survival (Alongi, 2008; Dasgupta *et al.,* 2017).

Increasing aquatic salinity is a major concern because different mangrove species have different tolerances to salt stress. Dasgupta *et al.* (2017) demonstrated that climate-induced salinization could substantially alter the distribution of important mangrove species in the Sundarbans, potentially affecting ecosystem services and forest-dependent livelihoods. Similarly, research from Patibania Island in the Indian Sundarbans reported increasing soil salinity, declining rainfall and changes in mangrove density, indicating that climatic and edaphic changes can influence mangrove structure and distribution (Mukherjee and Paul, 2021).

Therefore, effective conservation should extend beyond maintaining existing forest cover. Mangrove restoration, freshwater management, salinity monitoring, protection of natural regeneration zones and climate-resilient coastal planning should be integrated to maintain mangrove ecosystem health under future environmental change (Alongi, 2008; Dasgupta *et al.,* 2017; Lee *et al.,* 2014).

How Climate Change Affects Agriculture in the Sundarbans?

The agricultural system of the Sundarbans is particularly vulnerable to climate change because cultivated lands are generally low-lying and closely connected with tidal rivers, creeks and coastal waters. Soil salinity, waterlogging, freshwater scarcity, cyclonic flooding and changing rainfall patterns are among the major constraints affecting agricultural productivity. Saline-water intrusion increases soil electrical conductivity and creates physiological stress in crops by restricting water uptake and causing ion toxicity. Cyclonic storm surges and embankment breaches can rapidly introduce saline water into agricultural fields, while prolonged flooding can further deteriorate soil conditions. Recent research has demonstrated that storm-surge-induced salinization has a significant impact on agricultural land in the Indian Sundarbans (Mandal *et al.,* 2025). Long-term satellite-based analysis has also reported an expansion of saline agricultural areas, highlighting increasing pressure on coastal farming systems (Mandal *et al.,* 2025).

Water logging and freshwater scarcity represent equally important challenges. Heavy monsoon rainfall, flat topography, low infiltration and inadequate drainage can produce prolonged water logging, delay crop establishment and reducing cropping intensity. Conversely, during the dry season, limited freshwater availability and increasing salinity of surface and groundwater restrict irrigation. Climate-related water threats have already affected agricultural output, freshwater availability and food security in the Indian Sundarbans (Datta *et al.,* 2024). Groundwater studies further indicate increasing susceptibility to salinization under changing hydroclimatic conditions (Mondal *et al.,* 2024). Cyclones add another dimension by damaging crops and agricultural infrastructure; Mandal *et al.* (2024) demonstrated the significant relationship between cyclonic hazards, environmental change and agricultural conditions in the Indian Sundarbans. More recent agricultural research emphasizes salt-tolerant varieties, crop diversification, improved irrigation, land shaping, water harvesting and site-specific management as important adaptation pathways (Paul and Mathimaran, 2026).

Mangrove Conservation as an Agricultural Adaptation Strategy

The relationship between mangrove conservation and agricultural sustainability should be incorporated into regional planning because healthy mangrove buffers provide multiple ecosystem services, including coastal protection, sediment stabilization, carbon sequestration, biodiversity conservation and fisheries support. Mangroves should therefore be regarded as natural protective infrastructure rather than unused land. In the Sundarbans, integrated mangrove–agriculture planning can combine rainwater harvesting, salt-tolerant cultivars, improved water management, land shaping and crop diversification to strengthen agricultural resilience under increasing salinity and climatic extremes (Padhy *et al.,* 2022). Recent research further emphasizes integrated farming, rainwater harvesting and organic practices as important pathways for climate-smart agriculture in the Sundarbans (Das, 2025).

Strategies For Sustainable Agriculture in the Sundarbans

- **Salt-tolerant crops:** The adoption of salt-tolerant rice and other suitable crops is an important adaptation strategy for agricultural areas affected by increasing soil salinity. Salt-tolerant varieties can maintain comparatively better growth and yield under saline conditions than conventional varieties. However, crop selection should be based on local soil electrical conductivity, irrigation-water quality, seasonal salinity and farmers' preferences. Combining improved salt-tolerant cultivars with appropriate water and nutrient management can substantially improve agricultural resilience in coastal environments (Padhy *et al.,* 2022; Das, 2025).
- **Rainwater harvesting:** Rainwater harvesting can help address the seasonal freshwater shortage experienced in the Sundarbans. Farm ponds, community ponds and small reservoirs can capture and store monsoon rainfall for irrigation during the dry season, thereby reducing dependence on saline surface water and groundwater. Properly designed water-storage structures can also contribute to integrated crop - fish production and improve the availability of freshwater for agricultural activities (Mandal *et al.,* 2019; Padhy *et al.,* 2022).

- **Land shaping:** Land shaping is a particularly promising technique for simultaneously addressing waterlogging, salinity and freshwater management. Farm ponds, raised beds, deep furrows and suitable paddy - fish configurations can improve drainage while creating opportunities for freshwater storage and diversified production. Mandal *et al.* (2019) demonstrated that land-shaping interventions in the Indian Sundarbans could reduce the effects of waterlogging and salinity while increasing cropping intensity and farm profitability. Thus, land shaping can transform climate-related constraints into opportunities for more diversified farming.
- **Crop diversification:** Agricultural dependence on a single rice crop increases vulnerability to cyclones, salinity, drought and irregular rainfall. Crop diversification through vegetables, pulses, oilseeds, fruits and other locally suitable crops can distribute climatic and economic risks while improving household nutrition and income. The selection of crops should be guided by local soil and water conditions, market opportunities and seasonal climatic variability (Dutta *et al.,* 2021; Das, 2025).
- **Integrated farming:** Integrated farming systems, including crop-fish and crop – livestock-fish combinations, can provide multiple sources of food, nutrition and income. Such systems can improve resource use efficiency and reduce dependence on a single agricultural activity. However, aquaculture and livestock activities must be carefully planned to prevent excessive water consumption, salinization, pollution or conversion of natural wetlands and mangrove habitats. Integrated approaches are particularly relevant to the Sundarbans because they can strengthen livelihood resilience under environmental uncertainty (Padhy *et al.,* 2022).
- **Soil organic matter management:** Maintaining adequate soil organic matter is essential for improving soil structure, water holding capacity and nutrient availability. Application of compost, farmyard manure, crop residues and other locally available organic materials can improve soil quality and potentially enhance crop tolerance to environmental stresses. Integrated nutrient management based on soil testing should be encouraged to avoid excessive fertilizer application and maintain long term soil health (Dutta *et al.,* 2021).
- **Improved drainage:** Effective drainage management is essential in the low lying agricultural landscapes of the Sundarbans, where intense monsoon rainfall and tidal flooding can cause prolonged water logging. Properly designed drainage channels can remove excess water, improve root aeration and reduce crop losses. Combining drainage with raised beds, farm ponds and controlled water storage can provide a more effective water management system. Land shaping research from the Sundarbans has demonstrated the potential of such integrated approaches for improving agricultural productivity under saline and waterlogged conditions (Mandal *et al.,* 2019).

Agricultural Strategy for Future Sundarbans

Future agriculture in the Sundarbans should adopt site specific, climate - smart planning rather than uniform practices. Recent RS-GIS based analysis identified 1,474.5 sq. km as biophysically suitable for salt tolerant agriculture and a further 537 sq. km as potentially cultivable without encroaching on vegetation or water bodies (Paul and Mathimaran, 2026). Integrating remote sensing, GIS, salinity mapping, water availability, crop suitability and mangrove conservation can guide agricultural intensification while protecting ecologically sensitive areas.

Community Participation in Climate Adaptation

Successful climate adaptation in the Sundarbans requires community participation alongside scientific and technological interventions. Local communities possess valuable knowledge of soils, water resources, crops, fisheries and climatic variability. Their involvement should be integrated into mangrove restoration, embankment maintenance, rainwater harvesting, crop selection, disaster preparedness, freshwater management, livelihood diversification and ecological monitoring. Community based approaches can improve the effectiveness and long-term sustainability of adaptation measures (Padhy *et al.,* 2022). Singh *et al.* (2019) reported that existing adaptation practices provide some resilience but remain inadequate for future climate risks, emphasizing coordinated action among communities, institutions and policymakers.

Future Research Priorities in Sundarbans

Future research should focus on the mangrove–agriculture nexus, integrating ecological and agricultural systems rather than studying them independently. Priorities should include quantifying mangrove mediated coastal protection, monitoring long term soil and water salinity, evaluating salt tolerant crops, developing mangrove-compatible agricultural buffers and assessing mangrove carbon storage. GIS, remote sensing and climate modelling should support agricultural suitability mapping, ecosystem-service valuation and climate-informed crop advisories. Community based mangrove restoration and participatory ecological monitoring should also be strengthened. Integrating mangrove conservation into agricultural and coastal policies will be essential for long term resilience. Reliable, long term ecological and agricultural datasets are crucial for developing evidence based adaptation strategies (Lee *et al.,* 2014; Padhy *et al.,* 2022; Das, 2025).

Conclusion

The Sundarbans shows that mangrove conservation and sustainable agriculture are complementary, not competing goals. Mangroves protect coasts, stabilize sediments, recycle nutrients, store carbon and sustain fisheries, thereby supporting agricultural communities (Lee *et al.,* 2014; Padhy *et al.,* 2022). Climate change intensifies salinity, flooding, cyclones and freshwater scarcity, demanding ecosystem-based adaptation through salt tolerant crops, rainwater harvesting, land shaping, drainage and crop diversification (Mandal *et al.,* 2019). Therefore, the pathway can be expressed as: Healthy mangroves → resilient coasts → secure natural resources → climate-smart agriculture → stronger livelihoods. In this interconnected socioecological system, mangroves should be recognized as the natural guardians of sustainable agriculture and climate resilience in the Sundarbans.

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EMERGING TECHNOLOGIES IN SUSTAINABLE AGRICULTURE: FROM PRECISION SYSTEMS TO CONTROLLED ENVIRONMENTS

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Abstract

Agriculture is changing rapidly. Farmers today have to produce food under conditions that are different from those faced by earlier generations. Changes in climate, shortage of water, declining soil quality, increasing production costs and changing food requirements are creating new challenges for agriculture. At the same time, new technologies are providing farmers with better ways to monitor crops and manage farms. Smart farming is one such approach. It uses technologies such as sensors, mobile applications, artificial intelligence, drones, satellite images and automated systems to support farming decisions. Along with smart farming, new methods such as vertical farming, hydroponics, aeroponics and controlled-environment agriculture are also developing. These approaches can help in using land, water and other resources more carefully. However, modern technology is not a solution to every agricultural problem. High cost, poor internet connectivity, lack of technical knowledge and limited access to technology can make adoption difficult, especially for small farmers. This chapter discusses the meaning of smart farming, important technologies used in modern agriculture, new methods of food production, their role in sustainability and food security, and the opportunities and challenges associated with their use. The chapter also discusses the Indian context and the possible role of smart farming in the future of agriculture.

Keywords: Smart Farming, Digital Agriculture, Precision Agriculture, Artificial Intelligence, Internet of Things, Sustainable Agriculture, Food Security, Vertical Farming.

Introduction

Agriculture is an important part of human life. It provides food and raw materials and supports the livelihoods of a large number of people. Agriculture is also connected with rural development, employment, trade, food security and nutrition.

However, farming has become more difficult in many parts of the world. Farmers have to deal with changing weather, irregular rainfall, water shortages, soil problems, pests and diseases. The cost of agricultural inputs and labour can also be a major concern. At the same time, the demand for food continues to increase. These changes have created a need to look at agriculture in a different way. Farmers need methods that can help them use available resources carefully while maintaining production. Technology can be useful in this situation.

The use of technology in agriculture is not completely new. Tractors, harvesters, irrigation pumps and other machines have already changed farming. The newer development is the use of digital technology. Farmers can now use sensors, smartphones, satellite images, drones and computer-based systems to collect information about their farms.

This new approach is commonly referred to as smart farming. It does not simply mean using more machines. It means using information and technology to understand the condition of crops, soil, water and weather and then making better decisions.

The Food and Agriculture Organization has noted that digital automation can improve agricultural productivity, efficiency and resilience. However, it also points out that the benefits may not reach all farmers equally because of high costs, poor infrastructure and limited technical skills (FAO, 2022).

Along with smart farming, new methods of growing food are also being explored. Vertical farming, hydroponics, aeroponics and controlled-environment farming are examples. These methods can be useful where land or water is limited.

The future of agriculture is therefore likely to involve a combination of traditional farming knowledge and modern technology. The aim should be to make farming more productive, sustainable and useful for farmers and consumers.

Why Agriculture Needs New Approaches

Traditional farming practices remain important and will continue to be used. However, farmers are facing several new problems.

Climate Change

Changes in temperature and rainfall can affect crop growth. Extreme weather events such as droughts, floods and heat waves can cause crop losses. Farmers therefore need better information about weather and crop conditions.

Water Shortage

Agriculture uses a large amount of freshwater. In areas where water is limited, unnecessary irrigation can increase pressure on available resources. Better irrigation management is therefore important.

Soil Problems

Continuous cultivation, erosion and excessive use of some agricultural inputs can affect soil quality. Regular monitoring of soil conditions can help farmers understand what their crops actually need.

Labour Shortage

Some agricultural activities require large amounts of physical labour. Finding workers at the right time can be difficult in some areas. Mechanisation and automation may help with certain tasks.

Increasing Food Demand

The world needs to produce sufficient food while land and natural resources remain limited. This creates a need to improve productivity without putting unnecessary pressure on the environment.

These challenges do not mean that traditional agriculture has failed. Rather, they show that farmers need additional tools and information to deal with changing conditions.

What is Smart Farming?

Smart farming is a modern approach to agriculture in which information and technology are used to improve farm management.

A farmer using smart farming may collect information about:

- Soil moisture
- Temperature
- Humidity
- Crop growth
- Weather
- Plant diseases
- Water requirements
- Soil nutrients

This information can then help the farmer decide what action is needed.

For example, a soil sensor can indicate that the soil is becoming dry. Instead of irrigating the whole field at regular intervals, the farmer may use this information to decide when irrigation is actually required.

In the same way, a drone can provide images of a crop field. Areas showing unusual growth may then be examined more closely.

Smart farming therefore follows a simple idea:

Observe → Understand → Decide → Act

The technologies may be advanced, but the purpose is quite practical: to help farmers make better decisions.

Modern reviews show that technologies such as the Internet of Things, artificial intelligence and drones are increasingly being studied together for crop monitoring, resource management and decision-making (El Alaoui *et al.,* 2024).

Precision Agriculture and Smart Farming

The terms precision agriculture and smart farming are sometimes used together, although they are not exactly the same.

Precision agriculture mainly focuses on managing differences within a farm or field. A field may not have the same soil fertility or moisture level everywhere. Precision agriculture tries to identify these differences and manage each area according to its requirements.

For example, one part of a field may need more water while another part may have sufficient moisture. Applying the same amount of water everywhere may not be efficient.

Precision farming can involve:

- GPS
- Soil testing
- Satellite images
- Field sensors
- Variable-rate fertilisation
- Crop mapping
- Yield monitoring

Smart farming has a wider meaning. It may combine precision farming with artificial intelligence, mobile technology, IoT, automation and other digital tools.

The two approaches can work together to make farming more efficient.

Important Technologies in Smart Farming

Sensors

Sensors are small devices that can measure different conditions. In agriculture, sensors can be used to measure soil moisture, temperature, humidity and other factors.

Sensors can provide information regularly and sometimes continuously. This can be more useful than relying only on occasional observation.

For example, if a sensor shows that soil moisture is already adequate, irrigation may be delayed. This can help avoid unnecessary water use.

Internet of Things

The Internet of Things, commonly called IoT, refers to connected devices that can collect and share information.

In agriculture, a group of sensors may collect information from a field and send it to a computer or mobile device.

IoT can be used for:

- Irrigation
- Greenhouse monitoring
- Soil monitoring
- Weather monitoring
- Crop monitoring
- Livestock management

Recent research has identified IoT as an important technology for improving agricultural monitoring and resource management.

The advantage of IoT is that farmers can receive information without having to check every condition manually.

Artificial Intelligence

Artificial intelligence, or AI, allows computers to analyse information and identify patterns. In agriculture, AI may help in:

- Identifying crop diseases
- Predicting crop yields
- Detecting weeds
- Studying weather information
- Monitoring plant growth
- Supporting irrigation decisions

For example, a farmer may take a photograph of a diseased-looking leaf. An AI-based system may compare the image with a large collection of images and suggest a possible disease.

AI should be seen as a support system. The final decision may still require the experience of the farmer or an agricultural expert.

Recent research has explored the combined use of AI and IoT for crop monitoring, disease detection, soil management and other agricultural applications (Hassan *et al.,* 2024).

Drones

Drones are small flying devices that can carry cameras and other equipment.

In agriculture, drones can be used to take photographs of fields from above. These images can help identify areas where crops are growing differently.

Possible uses include:

- Crop monitoring
- Disease detection
- Checking crop damage
- Estimating plant numbers
- Monitoring irrigation
- Spraying in selected situations

Drones can save time when large fields need to be examined. However, their use requires training and proper regulation.

Satellite Images

Satellites can provide information about large agricultural areas. Farmers and agricultural organisations can use satellite-based information to monitor vegetation, crop conditions and changes in land.

This is particularly useful for large areas where it is difficult to physically inspect every field.

Mobile Applications

Mobile phones have become an important part of digital agriculture. Farmers can use agricultural applications to obtain:

- Weather information
- Crop advice
- Market information
- Pest and disease information
- Information about agricultural inputs
- Digital payment and marketing services

Mobile technology is particularly important because it may be more affordable than expensive farm machinery.

Robots and Automated Machines

Agricultural robots are being developed for activities such as planting, harvesting, weed control and crop monitoring.

Automation can reduce physical labour and help farmers perform some repetitive tasks more efficiently.

However, machines cannot simply be introduced without considering local conditions. Their cost, maintenance and usefulness must be evaluated before adoption.

FAO has stressed that automation can improve productivity and working conditions but that unequal access may increase existing inequalities if small producers cannot afford the technology (FAO, 2022).

Smart Irrigation

Water management is one of the most useful areas for smart farming.

In traditional irrigation, farmers may follow a fixed schedule. But crop water requirements can change depending on temperature, rainfall, soil type and stage of crop growth.

Smart irrigation systems can use soil-moisture information and weather data to help decide when water is needed.

The basic idea is simple:

Give the crop the right amount of water at the right time.

This may reduce water wastage and improve crop management.

IoT-based irrigation systems are among the areas being explored for more efficient agricultural resource use (Shahab *et al.,* 2024).

However, smart irrigation should not be considered useful only because it uses technology. Its actual benefit depends on whether the system is affordable, properly maintained and suitable for local farming conditions.

Vertical Farming

Vertical farming is a different approach to food production. Instead of growing plants across a large horizontal area, plants are arranged in layers.

It is often associated with indoor farms and controlled growing conditions. Vertical farms may use:

Artificial lighting

Hydroponics

Sensors

- Temperature control
- Automated irrigation
- Artificial intelligence

One of the main attractions of vertical farming is its ability to produce crops in places where land is expensive or limited.

Recent research has examined the use of IoT and AI in vertical farming for irrigation, disease detection, crop monitoring and yield prediction (Rathor *et al.,* 2024).

However, vertical farming also has limitations. Indoor systems may require considerable investment, electricity and technical knowledge. Therefore, they are not suitable for every crop or every location.

Hydroponics

Hydroponics is a method of growing plants without using ordinary agricultural soil. Instead, plants receive water containing the nutrients required for growth.

Hydroponics can be useful where:

- Good agricultural soil is not available
- Land is limited
- Water needs to be carefully managed
- Food needs to be produced close to urban areas
- The system requires careful control of nutrients, water and other growing conditions.

Hydroponics is therefore an interesting option for the future, but it should not be viewed as a complete replacement for conventional farming.

Aeroponics

Aeroponics is another method of growing plants without conventional soil. In this system, plant roots are exposed to air and receive nutrients through a fine mist.

The method allows close control of plant nutrition and water supply.

Aeroponics can save space and may be useful in controlled environments. However, it requires specialised equipment and regular monitoring.

If electricity or equipment fails, the plants may be affected quickly. This makes proper management particularly important.

Controlled-Environment Agriculture

Controlled-environment agriculture refers to growing plants under conditions where factors such as temperature, humidity, light and water can be managed.

Greenhouses are a common example.

The main advantage is greater control over the growing environment. Farmers can reduce the effect of unsuitable outdoor conditions and provide plants with more suitable conditions for growth.

This approach can be useful for vegetables, herbs and other high-value crops.

At the same time, controlled systems can be expensive. Their success depends on the cost of energy, equipment, labour and the market price of the produce.

Smart Farming and Sustainable Agriculture

Agriculture needs to produce food without exhausting the resources needed by future generations. Smart farming can support this goal by helping farmers use inputs more carefully.

For example:

- Sensors can help monitor soil moisture.
- Precision systems can help target fertiliser application.
- Drones can help identify problem areas.
- Digital weather information can support farm planning.
- Automated systems can reduce unnecessary operations.

The benefit of technology is therefore not simply that it makes farming "modern." Its value lies in whether it helps farmers use resources more wisely.

FAO has reported that digital automation can contribute to productivity, resilience and resource efficiency, while also noting that environmental and social outcomes depend on how technologies are introduced.

Sustainable farming therefore requires more than technology. It also requires responsible use of land, water, soil and energy.

Smart Agriculture and Food Security

Food security means that people should have regular access to sufficient, safe and nutritious food. Agriculture has a direct role in food security because it determines much of the food that is available. Smart agriculture can support food security in several ways.

First, better crop monitoring may help farmers identify problems early. Second, improved irrigation and nutrient management may support better use of resources. Third, digital information may help farmers connect with markets.

Reducing losses is also important. If farmers can identify disease, weather damage or harvesting problems early, some losses may be prevented.

Digital agriculture can also help connect farmers with consumers and markets. In India, digital agriculture has been used in areas such as remote sensing, precision agriculture, e-commerce, AI, drones and satellite imagery (FAO, 2022).

The future of agriculture should therefore consider not only how much food is produced but also the quality, diversity and accessibility of that food.

Smart Farming and Nutrition

Agriculture and nutrition are closely connected.

The foods available in a community depend partly on what farmers produce, how food is distributed and whether people can afford it.

Modern agriculture can contribute to nutrition by supporting the production of fruits, vegetables, pulses, cereals and other nutritious foods.

New farming systems can also provide opportunities for producing fresh vegetables closer to urban populations.

For example, small hydroponic or controlled-environment systems may allow certain vegetables and herbs to be grown where conventional agricultural land is not easily available.

However, technology should not make agriculture focus only on profitable crops. Future agricultural planning should also consider dietary diversity and access to nutritious foods.

A successful agricultural system should therefore answer two questions:

Can we produce enough food?

and

Can we produce food that supports a healthy diet?

Opportunities for Small Farmers

Technology is often associated with large commercial farms, but simple digital tools can also help small farmers.

A farmer may not be able to purchase an expensive drone or automated tractor. However, the farmer may be able to use a mobile phone to obtain weather information or agricultural advice.

Similarly, farmers can share expensive equipment through cooperatives or service providers. Possible approaches include:

- Shared machinery
- Drone services
- Mobile agricultural advice
- Farmer groups
- Digital marketplaces
- Online training

- Shared storage and processing facilities

FAO case studies show that high investment costs, limited digital skills and weak infrastructure are important barriers for small-scale producers. At the same time, hiring services and digital platforms can improve access to technology (McCampbell, 2022).

This means that the future of smart agriculture should not depend on every farmer owning advanced equipment.

Access may be more important than ownership.

Major Challenges

Smart farming has many possibilities, but it also has limitations.

Cost

Modern equipment can be expensive. Small farmers may not have enough money to invest in advanced systems.

Lack of Training

Technology is useful only when people know how to use it. Farmers may need simple and practical training.

Internet Connectivity

Some digital systems require reliable internet connections. Rural areas with poor connectivity may face difficulties.

Electricity

Many automated and indoor farming systems require a reliable power supply.

Maintenance

Sensors, computers and machines require regular maintenance. Local technical support is therefore important.

Data Concerns

Digital farming generates information about farms and farmers. Questions about who owns this information and who can use it need attention.

Unequal Access

If technology is available only to wealthy farmers, the gap between different groups of farmers may increase.

Environmental Cost

Some technologies, especially indoor farming systems, may require substantial energy. Therefore, their environmental benefits should be assessed carefully.

These challenges show that technology should be introduced according to actual agricultural needs rather than simply because it is new.

Indian Perspective

India has a large and diverse agricultural sector. Farmers work under very different conditions depending on region, climate, soil, crop and farm size.

Digital agriculture can provide useful opportunities in this situation. Mobile phones, satellite images, drones, weather services and digital marketplaces can help farmers access information and services.

FAO has documented Indian examples involving digital advisory services, remote sensing, precision agriculture, e-commerce, AI, drones and satellite imagery. These technologies have the potential to support productivity, resilience and rural development.

However, India also faces challenges. A technology that works well on a large commercial farm may not be suitable for a small farmer.

Therefore, agricultural technology in India should be:

- Affordable
- Easy to use
- Available in local languages
- Suitable for small farms
- Supported by training
- Supported by reliable infrastructure

Farmer organisations and cooperatives can play an important role in making expensive technologies more accessible.

Scope in Jammu and Kashmir

Jammu and Kashmir has a strong agricultural and horticultural base. The region is known for fruits, vegetables, saffron, walnuts and other agricultural products.

Smart farming may provide useful opportunities in horticulture. For example, digital tools could support:

- Orchard monitoring
- Weather-based advice
- Irrigation planning
- Disease identification
- Soil monitoring
- Crop forecasting
- Post-harvest management
- Market information

Drones and remote sensing may be particularly useful for monitoring large orchards and identifying areas that require attention.

However, the use of technology in the region should be based on local conditions. Farmers should be provided with practical training and affordable services rather than being expected to purchase expensive equipment individually.

Future of Agriculture

Agriculture is likely to become more connected to digital technology in the coming years.

Artificial intelligence may become better at analysing crop images and predicting agricultural conditions. Sensors may become cheaper and easier to use. Drones may become more common for crop monitoring. Mobile applications may provide more personalised agricultural advice.

Robots may also take over some repetitive activities.

However, the farmer will continue to have an important role. Farming involves practical experience and knowledge of local conditions that cannot always be captured by a computer.

The future should therefore not be viewed as:

Technology replacing farmers.

A better way to understand it is:

Technology helping farmers make better decisions.

This distinction is important because agriculture is not only a technical activity. It is also a social and economic activity involving farmers, families, communities and consumers.

Recommendations

The following measures can help make smart agriculture more useful and inclusive:

- Develop low-cost technologies that small farmers can afford.
- Provide training in simple language and local languages.
- Improve rural internet and electricity facilities.

Encourage shared use of expensive equipment through cooperatives and service providers.

Strengthen agricultural extension services so that farmers can understand new technologies.

Protect agricultural data and clearly explain who can use it.

Test technologies under local conditions before recommending them on a large scale.

Give attention to environmental impacts, especially energy use in controlled farming systems.

Include nutrition in agricultural planning so that food production is linked with healthy diets.

Involve farmers in technology development. Technologies are more likely to succeed when farmers' practical needs are considered from the beginning.

Conclusion

Agriculture is moving towards a new stage. Farmers are beginning to use digital tools, sensors, drones, artificial intelligence and automated systems to understand and manage their farms. At the same time, new production methods such as vertical farming, hydroponics and controlled-environment agriculture are creating additional possibilities.

Smart farming can help farmers use water, fertilisers, labour and other resources more carefully. It can also provide better information for managing crops and responding to changing conditions. However, technology is not a complete answer to the problems of agriculture.

High cost, poor connectivity, lack of training, maintenance difficulties and unequal access can prevent many farmers from benefiting from new technologies. These issues are especially important in countries where small and marginal farmers form a large part of the agricultural community.

The future of agriculture should therefore focus on appropriate technology rather than technology for its own sake. A useful agricultural technology is one that solves a real problem, is affordable, can be maintained locally and is easy for farmers to understand.

For India and regions such as Jammu and Kashmir, smart agriculture has considerable potential. With proper training, infrastructure and institutional support, digital tools can complement farmers' traditional knowledge and improve agricultural decision-making.

The agriculture of the future will probably not be completely traditional or completely automated. It will be a combination of farmer knowledge, scientific research, digital information and responsible use of natural resources. Such an approach can help build an agricultural system that is productive, sustainable and capable of supporting both farmers and consumers.

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ADVANCEMENTS IN FARM MACHINERY: SMART AND SUSTAINABLE TECHNOLOGIES

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1. Introduction

1.1 Need for farm mechanization

At present the agriculture system must produce more food for the growing population along with the protection of environment (Çakmakçi *et al.,* 2025). The traditional farming methods are often labour-intensive and may not provide good productivity, efficiency, and quality. To address these challenges, the farm machinery has developed from simple mechanical tools into advanced automatic systems that use sensors, data analytics, along with renewable energy sources (Kumar *et al.,* 2020). These smart technologies would help in increasing the efficiency of farm operations, use of resources wisely, reduce waste, and increase farm profitability. They can also help in the reduction of soil damage, greenhouse gas emissions, and other environmental impacts (Mhlanga & Dzingirai, 2024). Therefore, the understanding in the development of farm mechanization and modern smart machinery it is important for building an efficient, sustainable, and future-ready farming systems.

1.2 Evolution and Need for Farm Mechanization

Historically, it is found that farming was totally depended on human and animal labour. The farmers used simple hand tools and animal-drawn implements, which had limited the speed and scale of operations. As the demand for food increased and labour became unavailable or less available, machines like tractors, threshers, and mechanical harvesters are required. These machines helped the farmers to cultivate larger areas, with reduce physical effort more quickly than that of conventional methods (Rakhra *et al.,* 2022).

However, the conventional farm machinery is mainly focused on increasing power and work capacity rather than saving resources and environment. The extensive use of heavy machines may cause soil compaction, increase in fossil fuel consumption, and raise the production costs. In many developing countries, small and marginal farmers also found difficult to use modern machinery because of their high purchase costs, limited technical support, and fragmented landholdings (Awachat & Sharma, 2024).

The necessity for a new approach in farm mechanization has increased with rising input costs, shortage of farm labor, and growing environmental concerns. The modern agriculture needs machines that can increase production while using water, fertilizers, fuel, and energy in more efficient way. All of this has led to the development of smart farm machinery equipped with latest technologies like as GPS, sensors, actuators, and communication systems. These machines can perform precise operations, collect real-time information, and help farmers to take better decisions (Maravarman *et al.,* 2024).

The sustainable farm machinery focuses not only on improving the farm operations but also on reducing environmental damages. The machines designed for the conservation of tillage, equipment powered by renewable energy, and systems that apply fertilizers and other inputs. The smart and sustainable machinery represents an important step in the development of modern farm mechanization. These technologies can help to improve the farm productivity along with saving of resources and environment. The sections discuss the major types of advanced farm machinery, their benefits, limitations, and possible role in the future of agriculture (Omowumi, 2025).

2. Modern Farm Machinery

The modern farm machinery has developed from purely mechanical devices to integrated systems that combine with advanced engineering, electronics, and data-driven control. On the bases of field operations tillage, sowing, harvesting, and crop protection modern equipment are designed to improve operational time, precision, and productivity while reducing the environmental impact. Many of the latest machines incorporate with GPS, variable-rate technology, and sensor-based feedback, that enabling farmers to match operations more carefully with soil, crop, and weather conditions (Stombaugh & Shearer, 2000).

2.1 Tillage Machinery

The modern tillage machinery contains a wide range such as rotary tillers, disc harrows, chisel ploughs, subsoilers, power harrows, and cropping systems. These machines are engineered to achieve optimal seedbed preparation, residue incorporation, and soil loosening with minimal passes, thus saving fuel and time. The conservation tillage equipment, including zero-till seed drills and strip-till implements, is increasingly adopted to reduce soil disturbance, maintain surface residues, and to control erosion. Many of the tractors and tillage tools are now compatible with precision guidance systems, which help to maintain a straight passes, reduce overlapping, and limit compaction by controlling the wheel traffic (Blevins *et al.,* 2018). The photographic view of an autonomous tillage robot is shown in Figure 1.

Figure 1: Autonomous Tillage Robot

2.2 Sowing and Planting Machinery

The sowing and planting machinery has evolved for greater precision in seed placement, depth control, and other input application. Modern seed drills, planters, and transplanters are often equipped with metering systems that ensure uniform seed spacing for improving the yield of crop. A pneumatic and vacuum planters can handle a variety of seed with high accuracy even and operating speeds. Advanced machines can be integrated for the fertilizer and seed placement in a single pass. In some of the systems, electronic monitors and sensors track seed flow, detect blockages, and provide real-time feedback to the operator (Akhalaya *et al.,* 2020). The photographic view of an autonomous planting and seeding robot is shown in Figure 2.

Figure 2: Autonomous Planting and Seeding Robot

2.3 Harvesting Machinery

All modern harvesting machinery, such as combine harvesters, forage harvesters, and mechanized pickers, are designed to perform multiple operations like cutting, threshing, cleaning, and collection simultaneously. Combines are also available with adjustable rotor speeds, and cleaning settings for different crops and moisture conditions. Larger grain tanks, faster unloading systems, and improved ergonomics enable longer operating hours with less downtime with low operator fatigue. Progressively, harvesters are fitted with yield monitors, moisture sensors, and GPS receivers, making georeferenced yield maps for precision agriculture. These data would help to the farmers in identify spatial variability for maximum field (Yadav *et al.,* 2025).

2.4 Crop-Protection Machinery

The crop-protection machinery has now become more sophisticated to ensure effective pest, disease, and weed control with minimum chemical uses. All the modern sprayers mounted, trailed, or self-propelled precise metering systems, and boom-leveling mechanisms has maintain consistent nozzle height over uneven land. The nozzle technology has also improved, the droplet size with the reduction in drift. The integration of GPS, section control, and automatic rate controllers allows variable-rate application on the bases of preloaded maps and sensor readings. Camera-based and sensor-guided smart sprayers can differentiate the crop and weeds in real time, enabling a targeted spraying with significant reductions in chemical use (Miller, 2025).

Genially, modern machinery for tillage, sowing, harvesting, and crop protection shift toward a more efficient, and environmentally conscious farming. These technologies enhance the precision and reliability at each stage of production. The photographic view of an autonomous crop-protection robot is shown in Figure 3.

Figure 3: Autonomous crop-protection Robot

3. Smart Machinery

A smart farm machinery builds on conventional equipment by implanting digital technologies that sense, analyze, and respond in real time. By linking machines with data available on soils, crops, and weather enable site-specific management, to reduce waste, and for decision-making. The key enabling components like precision agriculture tools, networks of sensors and Internet of Things (IoT), global positioning systems (GPS), and artificial intelligence (AI) (Laskar, 2024).

3.1 Precision Agriculture

Precision agriculture is a particular farming approach that recognizes and manages the variations in field conditions over space and time. Instead of applying the same number of seeds, fertilizers, and chemicals, farmers use previous data to apply the right amount according to the needs of different areas of the field. A smart machinery can play an important role by applying the inputs at different rates and controlling farm operations according to digital data. The yield monitors, soil maps, satellite, drone images, and sensors can provide useful information about crop health, nutrient levels, and soil conditions. This information will be used to prepare application maps, which can be used with compatible tractors, planters, sprayers, and spreaders. These machines use variable-rate technology for automatically adjustment for the number of seeds, fertilizers, or pesticides as they move across the field. This targeted approach would help the farmers to use inputs more efficiently, increase profits, and to reduce environmental problems (Singh, 2024).

3.2 Sensors, IoT, and GPS

In smart farming, sensors and IoT technologies act as the 'nervous system'. Different types of sensors are being used for the measure of soil moisture, temperature, electrical conductivity, leaf chlorophyll, crop temperature, and machine performance. These sensors continuously collect data from fields and store it in storage facilities. All these devices are usually connected with each other through wireless networks to farm management platforms, where it is stored, processed, and displayed in the required form. The GPS is an important part of all smart farming applications because it provides accurate information about the location during field operations. The GPS-based guidance systems would help to the machines that follow straight and repeated paths, reduce overlaps, missed areas, and support-controlled traffic farming. The combination of automatic steering with GPS reduces the operator fatigue and maintains high precision even under low visibility conditions.

The IoT connectivity allows all farm machines, sensors, and systems to communicate with each other. For example, soil-moisture sensors can detect moisture when needed and send this information to the irrigation system or farmer. Similarly, telematics systems in tractors and harvesters send information about fuel use, engine load, and performance of machine on remote dashboards. This helps farmers for plan maintenance, reduction in machine downtime, and the use of machines more efficiently (Prasath & Navaneethan, 2022).

4. Automation and AI

Both automation and AI technologies allow farm machines to perform many tasks with minimum or less human effort. All modern machines can control steering automatically, turn at the ends of the field, adjustment of implemented depth, and switching between sections on or off as required. These features reduce the need of continuous manual control from machines and improve the accuracy of farm operations. The advanced systems can also coordinate to the multiple machines. For example, a combine harvester and a grain cart can match their speed and position automatically during grain unloading (Jana *et al.,* 2023).

The AI techniques, that include machine learning and computer vision, enhance the ability of machines to observe their environment and to make decisions. A camera-based systems can differentiate crops from weeds and detect pests or diseases on leaves; AI algorithms process all these images to trigger the targeted spraying or mechanical preparing. In harvesting, vision and AI assist in the fruit recognition and ripeness valuation, guiding robotic arms and picking mechanisms. The predictive models analyse past and real-time data to optimize planting dates, irrigation timetables, and input plans, often joined into decision-support tools linked with machinery (Vardhan *et al.,* 2025).

Collectively, the precision agriculture, sensor–IoT–GPS technologies, and automation with AI are transforming farm machinery from conventional mechanical equipment to intelligent systems. These machines perform agricultural operations with greater accuracy by analysing data. All of this enables better farm management, continuous improvement in field operations, and supports the transition towards more resilient, efficient, and sustainable agricultural systems.

4.1 Autonomous and Robotic Systems

Autonomous and robotic systems characterize the next stage in farm mechanization, ever-changing from operator-dependent machines to capable of observing their environment and acting with nominal human intervention. These systems syndicate with advanced sensing, location, control algorithms, and AI to perform tasks such as soil grounding, imbedding, weeding, spraying, and harvesting with high accuracy and repeatability. By dissociating field operations from labour accessibility and working hours, they offer the potential for incessant operation, enhanced timing of interventions, and safer working circumstances, particularly for repetitive or hazardous responsibilities (Pearson, 2025).

4.2 Autonomous Tractors

An autonomous tractors are self-driving machines that can perform field operations based on predefined routes and task preparations. These are equipped with GPS/RTK receivers, LiDAR, radar, cameras, and inertial sensors, they can navigate, avoid obstacles, and can maintain consistent performance without continuous human intervention. An on-board control system integrates sensor data with digital field maps to follow prearranged paths, control speed, and manage implements for actions such as tillage, seeding, or spraying.

Many of the ideas having an automatic tractor utilized a smaller and lighter platforms with reduced soil compaction. The online remote monitoring helps to control multiple machines for controlling the machine from a central operating station. The system must have geofencing, emergency stop button, and redundant sensors to prevent accidents and to ensure obedience with guidelines. A fully automatic tractors could be developed with the help of an automatic driver-assist systems (Titova, 2025). The photographic view of an autonomous robot tractor with AI is shown in Figure 4.

Figure 4: Autonomous robot tractor with AI

4.3 Agricultural Robots

Agricultural robots are the dedicated machines designed to perform specific tasks with precision and selectivity. The farm robots use cameras and machine-learning techniques for the identification of crops and weeds. All these allows the robot to remove weeds automatically or by applying small amounts of herbicide for the weed plants. As a result of this chemical use will be reduced. The robots which perform the tasks of removing weeds between crop rows utilizing the fertilizer at specific locations, by collecting samples of soil. These robots are usually operating independently at low speeds for long duration.

In high-value crops and horticulture, robotic harvesters are increasingly uses to pick fruits and vegetables from field. They use cameras with 3D technology, object detection systems, and robotic arms for the identification of fruits, and harvest them without damaging the plants by assess their maturity. Similar type of technologies is being used for pruning, thinning, and other operations in orchards. Many of the agricultural robots have a small and modular designs specifications, fitted with different tools and sensors according to the requirements. All of these makes them flexible and useful for farming with site-specific, especially in areas where manual labour is costly (Furnitto *et al.,* 2026).

4.4 Drone Applications

An unmanned aerial vehicle (UAVs) is commonly known as drones. Now a days they become important tools for rapid, high-resolution monitoring and, in some cases, for input submission. Multispectral and thermal cameras mounted on drones capture comprehensive information, nutrient status, water stress, and disease. Compared with satellite images, drones offer better spatial resolution and flexible timing, allowing farmers to monitor specific fields shortly after critical events such as storms, irrigation. In drone's images are converted into vegetation indicters that help then to guide variable-rate applications.

In addition to monitoring and sensing applications, drones are being used to for the spread of pesticides in the field especially in areas where ground machinery has limited access. The farm drones use GPS and flow-control systems to maintain precise rates of application. Number of drones can also work together to cover larger areas in an effective way. However, regulatory requirements, battery life, capacity of payload, and operator training remain an important challenge. The continuous improvements in drone technology use in crop protection, field monitoring, and fertilizer application etc. Overall, drone's accompaniment ground-based independent and robotic systems by providing timely, spatially rich data and, in some cases, direct interference from the air (Satish *et al.,* 2025). The photographic view of unmanned aerial vehicle for spray in large field is shown in Figure 5.

Figure 5: Unmanned aerial vehicle for spray in large field

5. Energy-Efficient Machinery

An energy-efficient farm equipment aims to deliver the essential field performance while diminishing fuel consumption, emissions, and overall energy use. This shift is determined by rising fuel costs, harsher environmental guidelines, and the need to reduce agriculture's carbon footprint. A key development includes electric and hybrid powertrains, incorporation of renewable-energy sources into farm operations, and low-emission technologies to improve system efficiency.

5.1 Electric and Hybrid Systems

An electric and hybrid systems adopt ideas from the automotive and industrial sectors to agricultural machinery. In fully electric apparatuses, batteries or fuel cells supply power to electric motors that drive wheels, and tracks.

In hybrid field processing machines, an internal combustion engine works together with an electric motor. This arrangement improves the energy utilization by recovering energy from braking system and manage the engine load more efficiently.

An electrical drive offers several advantages such as high torque at low speeds, precise motion control, and the to operate multiple auxiliary systems independently. For smaller machines such as compact tractors, loaders, and robotic platforms, battery-electric systems are more practical. They are observed very useful in greenhouses and livestock buildings (Scolaro *et al.,* 2021).

The hybrid tractors and harvesters having engine-generator systems doesn't require traditional mechanical and hydraulic transmissions. The hybrid system improves the efficiency under part-load operation, reduces fuel consumption, and simplifies the power distribution. An electric PTOs provides a better control on speed and torque transmission than that of conventional mechanical drives.

5.2 Renewable-Energy Integration

A renewable-energy incorporation connects farm machinery and processes to on-farm energy production from sources such as solar, wind, and bioenergy. Photovoltaic (PV) plants on farm buildings and dedicated solar installations can provide electricity to charge batteries for electric tractors, loaders, and utility vehicles, as well as to power immobile equipment like pumps, grain dryers with heat pumps (Karanjikar *et al.,* 2024).

Wind turbines and small-scale biogas plants can also contribute to the farm's energy mix. In some cases, biogas is upgraded to biomethane and used as a fuel, partially replacing diesel. Renewable-powered charging stations, sometimes combined with stationary battery system, help buffer alternating solar or wind generation and confirm reliable power accessibility for machinery. Smart energy-management systems direct when to charge machines, run high-demand apparatus, or export surplus electricity to the grid, weather forecasts, and operational agendas. This addition of renewables with farm machinery not only cuts the use of fossil-fuel and greenhouse-gas emissions but also improve energy security with reduced operating costs (Shafie *et al.,* 2023).

5.3 Low-Emission Technologies

The low-emission technologies in agricultural machinery aims to the reduction of pollutants such as NOx, particulate matter, and greenhouse gases. The modern diesel engines used in tractors and harvesters has strict emission standards through high-pressure common-rail fuel injection system, turbocharging, exhaust-gas recirculation (EGR), diesel particulate filters (DPF), and selective catalytic reduction (SCR) using urea-based additives (AdBlue). These technologies significantly reduce the harmful exhaust emissions and improving the engine power and fuel efficiency (Troeger *et al.,* 2018).

In addition to exhaust gas treatment systems, low-emission technologies such as improved power management systems, lightweight machine designs, and more efficient drivetrains. The continuous variable transmissions (CVTs), efficient hydraulic systems, and advanced engine control units (ECU) will help to the operate.

The alternative fuels such as biodiesel, hydrotreated vegetable oil (HVO), biomethane, ethanol blends, and hydrogen can provide options for reducing CO_2. At the same time, precision-control technologies like automatic steering, section control, and variable-rate application help in the reduction of emissions by avoiding unnecessary field passes, overlap, and reduced overall energy inputs (Mathur *et al.,* 2022).

Thus, hybrid systems, renewable energy technologies, and low-emission technologies are transforming the operation of agricultural machineries. These technologies would help to the farmers to maintain their production with decreased environmental impacts.

6. Performance and Economic Assessment

The performance and economic evaluation of modern farm machinery emphasis on how effectively the machines use time, energy, and labour. The important indicators such as field efficiency, fuel or energy consumption per unit of output, labour requirements, and overall operating costs etc. The evaluation of these factors would help to the farmers make better investment decisions, and identify opportunities to improve the efficiency.

6.1 Farm Efficiency

The farm efficiency is the ratio of actual farm capacity to theoretical farm capacity. Theoretical capacity of the farm depends on the working width of the machine and its operating speed. However, actual capacity of the farm is lower than that of. The smart and autonomous machinery can improve the farm efficiency with the help of accurate path planning, precise guidance, and automated turning (Al-Amin *et al.,* 2023).

That data collected from machine provide detailed information about the time spent on productive activities and non-productive activities (turning, waiting, transportation, and machine setup). The analyses of this data help to improve the operating methods by optimizing the farm layouts, and logistics planning. The higher farm efficiency reduces the time required for farm operations.

6.2 Energy/Fuel Consumption

The energy or fuel consumption is an important indicator of both the economic performance and environmental impact of farm machinery. It is usually measured as per hectare (L/ha or kWh/ha) or per unit of production (e.g., L/t of grain). The advanced powertrains, improved engine-transmission systems, and precise control technologies can reduce the fuel consumption keeping machines operating at most efficient conditions and avoiding unnecessary power demands (Jensen *et al.,* 2024).

The smart machinery and variable-rate technologies further improve the energy efficiency by applying inputs with adjusting working depth, speed, and application rates according to farm conditions. For example, the reduced-tillage systems combined with suitable machinery can lower the draft requirements and fuel consumption. The telematics systems can also monitor the fuel consumption, allowing the farmers to compare the performance across fields, operators, and machine settings.

6.3 Labour and Operating Cost

The labour and operating costs include wages, supervision, fuel or electricity, maintenance, repairs, reduction, and interest on machinery investments. The automation and robotics can also reduce the need of manual labour. In automatic system a single operator can monitor and manage the multiple machines or robots. Hence automation changs the role of direct machine operator to monitor and planner (Dhatterwal *et al.,* 2023).

However, the advanced machining systems have higher initial costs and require more technical skills for operation, setup, troubleshooting, and maintenance. Therefore, economic evaluation should consider the total cost of ownership over the machine's lifetime, considering the purchase price, use of machine, service life, residual value, and savings in labour and fuel. the cost-benefit analysis and the partial budgeting can help to determine the payback period and productivity.

The overall, performance and economic evaluation can also provide a useful basis for deciding whether to adopt a smart, autonomous, and energy-efficient farm machine. A properly selected and managed technology can reduce the operating costs, improve the timeliness of the farm operations, with lower environmental impacts. However, their benefits depend on the local conditions, and management skills.

7. Challenges and Future Perspectives

The shift toward smart, autonomous, and energy-efficient farm machinery provides important technical and environmental benefits. However, its adoption also faces several practical, economic, and social challenges. Understanding these challenges is important for developing suitable adoption strategies and identifying future research and policy needs.

7.1 Technical and Operational Challenges

A major challenge is maintaining the reliability and performance of smart farm machinery under changing field conditions. Sensors, actuators, and electronic control systems must operate effectively in dust, moisture, vibration, and extreme temperatures. Autonomous and robotic machines also need reliable systems for sensing and navigation in complex fields with uneven boundaries, obstacles, and changing soil and crop conditions.

Interoperability between different machines, implements, and digital platforms is another important challenge. Different manufacturers often use their own data formats and communication systems, making it difficult to integrate equipment and manage machine fleets effectively. Advanced machinery also depends on reliable connectivity, such as GNSS and mobile networks, which may be limited or unavailable in many rural areas.

Maintenance and repair of electronic and software-based machinery can also be more difficult than for traditional equipment. Fault diagnosis may require specialized tools, software updates, and trained technicians. Such technical support is not always easily available, particularly for small farms and remote agricultural areas.

7.2 Economic and Structural Barriers

The high initial investment in the way of adoption of smart and advanced farm machinery is one of the major barriers, particularly for small and medium farms. The electric tractors, and autonomous robots are much more precious than that of traditional machinery. Although the adoption of technological advancement results in the savings in fuel, labour, and the reduction of overall cost. The payback period is an uncertain parameter and depends upon number of factors such as working time, fuel prices, and the market conditions.

The size of farm, cropping patterns, and the level of automation can also affect the economic feasibility of modern technologies. The automated equipment's designed for large and medium size farms may not be economically suitable for small farms. In addition to this the resale value of new technologies is also uncertain because of the rapid technological development and limitations of second-hand markets. One of another major concern towards the automation is the dependency on limited number of manufacturers and service providers.

7.3 Human, Social, and Skills-Related Issues

The adoption of smart and autonomous machinery needs special skills and training required in farming. The operators must have the knowledge of digital tools, data analysis, and basic programming, along with traditional agricultural and mechanical skills. This seems to be very challenging in areas where training and technical support are limited.

The automation is also concerns about job displacement, especially for the regions where agriculture field provides employment to large part of the population. Thus, the automation can reduce labour requirement and physically demanding work, it may also eliminate the requirement of low-skilled workers. Therefore, measurable change in the policies is required for training, and creating alternative rural employment opportunities. The generation of farmers' trust on new technologies is another important factor. They may be hesitant to the adoption of autonomous or highly digital systems for critical farm operations until they get confident about their reliability and availability of service supports.

7.4 Environmental and Regulatory Considerations

Although the energy-efficient and low-emission machinery can reduce the environmental impact. But the its overall benefits depend on number of factors, such as sources of energy, efficiency of machine, operating conditions, maintenance, resource use, and the end-of-life management. In battery production, the use of critical raw materials, and the disposal or recycling of electronic components raise an important concern about the resource conservation and the waste management. Similarly, the installation of renewable energy systems should be planned very carefully to navigate and to avoid negative effects on land, landscape, and biodiversity.

Clear and effective policies are required to define responsibility in accidents, data misuse and to determine its accessibilities. The standards for interoperability and cybersecurity will also play an important role in ensuring the safe and widespread adoption of smart agricultural technological upgradation.

8. Future Perspectives

The futuristic farm machinery will be likely to become more modular, connected, and easier to use. All smaller and autonomous machines may work together in groups for the replacement of large machines. This can reduce the compaction of soil, improve flexibility, and provide greater reliability. The common data and its communication standards can also allow the machines to interact with each other and to work together.

Advances in artificial intelligence, machine vision, and edge computing will definitely improve the real-time monitoring and decision-making. These technologies would work automatically according to the properties of crop, soil, and weather. The integration with farm-management systems and the data sources can further improve the perform of farm logistics.

The financial incentives, cooperative ownership, and the machinery-sharing services could help to the small and medium farmers to access advanced technologies. The investment in rural farmer’s training is very important for the wider adoption of smart machinery.

Conclusion

The sustainable and smart farm equipment’s can transform all agricultural operations by using combined auction of automation, and digital technologies. These technologies have the precise guidance, monitoring, and decision-making capability to improve the operational efficiencyand to reduce running costs.

However, the economic benefits also depend on the selection of right technology for the right task. The major challenges are the high initial costs, technical complexity, and the limited availability of support and services. The future development will require cooperation among manufacturers, researchers, policymakers, and end users. The smart and sustainable machinery can play an important role in the development of a climate-resilient, resource-efficient, and economically viable agricultural systems.

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WEST BENGAL AGRICULTURE AT A CROSSROADS: CLIMATE CHANGE, LAND DEGRADATION AND STRATEGIES FOR SUSTAINABLE TRANSFORMATION

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Abstract

West Bengal's agriculture, sustaining a majority of the state's rural population, faces a convergence of climatic, ecological and socio-economic pressures. Rising temperatures, erratic monsoons, frequent cyclones and storm surges, recurrent northern floods and western drought are disrupting cropping calendars and degrading the resource base. Soil erosion, waterlogging and coastal salinization are eroding land quality, while groundwater over-abstraction and arsenic contamination compromise irrigation sustainability. These pressures are compounded by a narrowing of agricultural biodiversity, as traditional rice landraces are displaced by a few high-yielding varieties, and by the vulnerability of predominantly small and marginal holdings. This chapter synthesises recent scientific literature, government data and field assessments to examine these threats region by region, distinguishing the hill and Terai-Dooars tracts, the western lateritic plateau, the Gangetic plains, and the coastal Sundarbans, each requiring distinct responses. It develops a framework combining climate-resilient varieties, diversification, sustainable soil and water management, and agrobiodiversity conservation with equity-conscious deployment of precision agriculture, remote sensing, GIS, IoT and artificial intelligence, arguing that traditional knowledge and modern science are complementary. The chapter concludes that durable transformation depends on integrating ecological restoration, farmer-centred institutions and calibrated technology within a coherent policy architecture.

Keywords: West Bengal Agriculture, Climate Change, Land Degradation, Agrobiodiversity, Coastal Salinity, Climate-Smart Agriculture, Precision Agriculture, Sustainable Transformation.

Introduction

Agriculture anchors West Bengal's rural economy, contributing roughly a fifth of gross value added and supporting a majority of the population directly or indirectly (NITI Aayog, 2025). The state leads India in rice and vegetable production, with rice output reaching approximately 171 lakh tonnes in 2025-26, and contributes close to a quarter of national tea production from the Darjeeling, Terai and Dooars belts (IBEF, 2026). This diverse cropping system, spanning jute, potato, pulses, oilseeds, mango and vegetables across contrasting agro-ecologies, rests on an agrarian structure dominated by small and marginal holdings, making it acutely sensitive to weather, water and price shocks.

The climatic and environmental foundations of this system have grown visibly less stable. District-level assessment shows significant, spatially uneven shifts in temperature and rainfall, with measurable rice-yield declines in the most exposed districts (Das & Goswami, 2023). Cyclones Aila (2009), Bulbul (2019), Amphan (2020), Yaas (2021) and Remal (2024) have repeatedly breached embankments and driven saline water into southern deltaic farmland, while catastrophic floods and landslides struck North Bengal in October 2025, damaging dozens of tea gardens (Down To Earth, 2025a, 2025b). Groundwater-dependent boro paddy expansion has simultaneously drawn down aquifers and exposed populations across nine districts to arsenic-contaminated irrigation water (Chakraborti *et al.,* 2009).

This chapter argues that West Bengal agriculture stands at a genuine crossroads: continued reliance on input-intensive intensification of a narrow varietal base is increasingly mismatched with a destabilising climate. Sustainable transformation requires a deliberate shift toward agriculture that is resilient, climate-smart, resource-efficient, biodiversity-friendly, technology-enabled and farmer-centred. The chapter examines the major threats, maps their uneven regional distribution, and develops an evidence-based adaptation framework balancing ecology, technology, traditional knowledge, institutions and policy.

Agricultural Landscape of West Bengal

West Bengal's agro-ecology divides into seven zones. The Himalayan hill region (Darjeeling, Kalimpong) supports tea, cardamom and terraced horticulture on landslide-prone slopes. The Terai-Dooars belt (Jalpaiguri, Alipurduar, parts of Cooch Behar) combines tea with rice, jute and maize on fertile but flood-prone alluvium. The North Bengal plains (Cooch Behar, the Dinajpurs, Malda) grow rice, jute, mango and maize on the flood-affected Teesta-Mahananda system. The western lateritic plateau fringe (Purulia, Bankura, Jhargram, Paschim Bardhaman, parts of Birbhum) has coarse, low-fertility, poorly water-retentive soils and is chronically drought-prone (Barman & Roy, 2024). The Gangetic alluvial plains (Murshidabad, Nadia, Hooghly, Howrah, parts of Bardhaman) are the most intensively cultivated tract but also the most arsenic-affected. The coastal/deltaic zone (East and West Midnapore, coastal 24 Parganas) faces recurrent cyclones and episodic salinity, while the Sundarbans, the southernmost fringe of the 24 Parganas, is structurally constrained by tidal salinity, embankment fragility and extreme cyclone exposure.

Small and marginal holdings (below two hectares) dominate operational landholding across all zones, limiting capital investment and risk-bearing capacity (NITI Aayog, 2025). Table 1 summarises the principal regions.

Table 1: Major agro-ecological regions of West Bengal

Region	Representative Districts	Dominant Soils	Major Crops	Key Constraint
Himalayan hill region	Darjeeling, Kalimpong	Mountain, acidic	Tea, cardamom, vegetables	Landslides, erosion
Terai-Dooars	Jalpaiguri, Alipurduar	Alluvial, acidic	Tea, rice, jute, maize	Flash floods, siltation
North Bengal plains	Cooch Behar, Malda, Dinajpurs	New alluvium	Rice, jute, mango, maize	Riverine flooding
Western lateritic plateau	Purulia, Bankura, Jhargram	Red/lateritic	Rainfed rice, millets, pulses	Drought, low water retention
Gangetic alluvial plains	Murshidabad, Nadia, Hooghly	Old/new alluvium	Rice, jute, potato, vegetables	Arsenic-laden groundwater
Coastal/deltaic zone	E & W Midnapore, coastal 24 Parganas	Coastal alluvium	Rice, betel vine, fisheries	Cyclones, salinity
Sundarbans	South 24 Parganas blocks	Saline, tidal	Salt-tolerant rice, aquaculture	Tidal salinity, embankment breach

Barman and Roy (2024), Das and Goswami (2023)

Major Threats to Agriculture in West Bengal

A. Climate Change and Temperature Rise

District-level analysis (2015-2024) shows rising minimum temperatures across the Gangetic plains alongside heterogeneous coastal trends, decreasing maximum temperature at Contai and Diamond Harbour but rising at Digha and Sagar Island (Barman & Roy, 2024). Warmer nights shorten rice grain-filling and depress spikelet fertility, while flowering-stage heat stress affects vegetables, pulses and mango, desynchronising cropping calendars tuned to historical monsoon timing.

B. Changing Rainfall Patterns

Rainfall variability, more than any decline in total precipitation, threatens agriculture: annual rainfall shows inter-annual standard deviations exceeding 75 mm in monsoon-dependent zones, with rising frequency of intense short-duration events interspersed with longer dry spells (Barman & Roy, 2024; Das & Goswami, 2023). In the lateritic west, rising annual rainfall coincides with declining May rainfall and increased October-November rainfall, disrupting kharif sowing and rabi harvesting alike (Mukherjee & Banerjee, 2009).

C. Flooding and Waterlogging

North Bengal's Himalaya- and Bhutan-fed rivers are prone to sudden flooding. October 2025 rainfall triggered floods and nearly a hundred landslides across Darjeeling, Jalpaiguri, Cooch Behar and Alipurduar, killing at least 28 people and damaging over 30 tea gardens, with losses exceeding Rs 50 crore in tea alone (Down To Earth, 2025a, 2025b). Prolonged waterlogging delays transplanting and leaches nutrients, effects aggravated by unregulated riverbed sand mining and upstream deforestation that raise riverbeds through siltation (Down To Earth, 2025a).

D. Cyclones and Coastal Vulnerability

The Sundarbans is among South Asia's most cyclone-exposed agricultural landscapes: 35 recorded cyclones struck between 1891 and 2002, and eight more since 2019 alone (IndiaSpend, 2025). Cyclone Amphan damaged an estimated 925 hectares of standing crops across three assessed Sundarbans blocks, with about 63 per cent of the affected area showing significant post-flood vegetation-index decline (ScienceDirect, 2025). Storm surges breach embankments and drive saline water into paddy fields, sometimes suppressing cultivation for years, a key driver of large-scale outmigration; National Centre for Coastal Research data indicate 60.5 per cent of West Bengal's coastline is actively eroding (IndiaSpend, 2025).

E. Drought and Water Stress

Purulia and Bankura remain chronically drought-prone despite moderate rainfall (1,100-1,500 mm annually), because coarse lateritic soils retain little moisture and generate rapid run-off (Roy *et al.,* 2024). Purulia's precipitation anomaly index shows a persistent downward trend in sowing-season moisture availability since 1992, converting meteorological deficits into recurrent agricultural drought (Roy *et al.,* 2024).

F. Soil and Land Degradation

Degradation takes different forms across zones: erosion on the lateritic plateau, waterlogging in flood-prone plains, and salinization on the coast. Nationally, land degradation affects an estimated 187.8 million hectares, including 162.4 million hectares of soil erosion and 10.1 million hectares of salt-affected soils (Kumar *et al.,* 2023). In Bankura, expanding barren land and exposed sandbars reflect intensifying degradation from lateritic soils, drought, upland deforestation and riverbank erosion along the Damodar (Mahato & Ghosh, 2023).

G. Groundwater, Salinity and Irrigation

Groundwater arsenic contamination affects nine districts spanning about 38,865 sq. km and 50 million people, with contamination above national standards recorded in 3,417 villages across 107 blocks (Chakraborti *et al.,* 2009). Boro paddy expansion since the 1980s, sustained by shallow tubewells, has carried arsenic into soils and rice grain (Chakraborti *et al.,* 2009; Bhattacharya & Sen, 2022). Along the coast, tidal intrusion, storm surges and capillary rise of brackish groundwater drive soil salinity that peaks pre-monsoon, restricting nutrient uptake and depressing rice yields (Mandal *et al.,* 2026).

H. Loss of Agricultural Biodiversity

West Bengal once cultivated over 5,500 distinct rice landraces, part of a subcontinental pool exceeding 100,000 (Sharma & Deb, 2021). High-yielding varieties now cover over 90 per cent of rice area, displacing most landraces (Ghosh, 2018). This matters agronomically: traditional lateritic-zone varieties have historically shown more stable yields under drought and flood stress and greater pathogen resistance than modern cultivars, resilience traits a volatile climate now requires (Ghosh, 2018).

I. Emerging Pests, Pathogens and Weeds

Warmer, more humid conditions are reported to be shifting pest, pathogen and weed pressure in eastern India, including North Bengal's tea belt, where growers report more frequent outbreaks and rising, often unaffordable, reliance on chemical sprays (Down To Earth, 2025c).

J. Socioeconomic Challenges

Small, fragmented holdings, rising input costs, thin markets, inadequate storage, and uneven access to credit and extension compound these threats. In the Sundarbans, roughly three-quarters of families report at least one member migrating for work, driven largely by salinity-induced loss of cultivable seasons (Sharma & Deb, 2021; Adaptation Fund, 2021).

Table 2: Major threats, affected regions and vulnerability

Threat	Most Affected Region(s)	Principal Consequence	Vulnerability
Temperature rise	State-wide; coastal belt heterogeneous	Reduced fertility, shortened grain-fill	Moderate-High
Erratic/intense rainfall	Western plateau, Gangetic plains	Disrupted sowing/harvest windows	High
Riverine flooding	North Bengal plains, Terai-Dooars	Crop submergence	High
Cyclones/storm surge	Sundarbans, coastal 24 Parganas	Salinization, crop loss, migration	Very High
Drought	Purulia, Bankura, Jhargram	Reduced sowing area	High
Groundwater arsenic	Nine Gangetic-plain districts	Grain contamination	High
Coastal soil salinity	Sundarbans, coastal Midnapore	Suppressed rice yield	Very High
Agrobiodiversity loss	State-wide, esp. lateritic zone	Reduced stress resilience	Moderate-High

Climate Change Hotspots and Vulnerable Regions

West Bengal cannot be managed as agro-climatically uniform. A composite agricultural scenario index across all districts (2001-2012) found South 24 Parganas, Cooch Behar and Purulia most vulnerable, reflecting coastal, northern-flood and western-drought risk respectively (Das & Goswami, 2023). District-level assessment separately identified the western-southwestern Gangetic plains, the deltaic Sundarbans coast, and the sub-Himalayan foothills as the three climatically most vulnerable zones (Das & Goswami, 2023). Within the coast itself, an Integrated Agricultural Livelihood Vulnerability Index found Gosaba block a pronounced hotspot even relative to neighbouring Sundarbans blocks (Das *et al.,* 2025). These findings imply spatially targeted adaptation: salinity-tolerant cultivars and embankment resilience for the coast; water harvesting and drought-tolerant crops for the west; flood-tolerant varieties and slope stabilisation for the north.

Consequences for Crop Production and Food Security

Rice shows the clearest documented sensitivity: district analysis attributes 3-22 per cent production falls in the most vulnerable districts, with Paschim Medinipur worst affected (Barman & Roy, 2024). State aggregate rice output continues rising (about 171 lakh tonnes in 2025-26), but this masks sub-state divergence between underperforming vulnerable districts and intensifying better-endowed ones (IBEF, 2026). Jute shows marked drought-linked volatility and a longer-term area decline as farmers diversify (Roy *et al.,* 2024). Darjeeling tea production fell from about 12 million kg in 2014 to roughly 6 million kg in 2024, attributed to erratic rainfall, rising temperatures and the closure of about 40 gardens across the Terai, Dooars and hills (Down To Earth, 2026). Potato and vegetables, though buoyed by the state's national leadership in output, remain exposed to heat stress and the same water-quality constraints affecting cereals. Food security risk in West Bengal is therefore increasingly a matter of spatial and seasonal distribution rather than aggregate scarcity.

Strategies for Sustainable Agricultural Transformation

a. Climate-Smart Agriculture

Climate-smart agriculture balances productivity, resilience and mitigation as complementary rather than competing goals (AIF, 2024). For West Bengal this means pairing balanced nutrient management with stress-tolerant varieties and water harvesting, and mitigation measures such as reduced tillage and improved rice water management that also lower methane emissions.

b. Crop Diversification

Diversifying away from rice monoculture, particularly where diversification remains low in the western plateau (Das & Goswami, 2023), spreads climatic risk. Promising options include short-duration pulses and oilseeds in the lateritic zone, millets on marginal uplands, integrated vegetable-fruit systems in the Gangetic plains, and continued Sundarbans diversification toward salinity-tolerant crops and aquaculture.

c. Climate-Resilient Crop Varieties

Public breeding has produced submergence-, drought- and salinity-tolerant rice suited to different zones; wider dissemination alongside traditional stress-tolerant landraces (Section 3.8) offers a practical route to yield stability (Ghosh, 2018). In the Sundarbans, salt-tolerant varieties show adaptation success though yields remain below conventional cultivars and seed availability is constrained (Zero Carbon Analytics, 2025).

d. Sustainable Soil Management

Conservation agriculture, reduced tillage, organic matter incorporation, green manuring, biofertilizers and soil-test-based balanced fertilisation can arrest fertility decline. GIS-based land suitability mapping already applied in Purulia's Kashipur and Chhatna blocks could be extended across the wider lateritic zone to guide conversion of marginal uplands to agroforestry (Barman & Roy, 2024).

e. Sustainable Water Management

Water strategies must be zone-specific: farm ponds, check dams and watershed harvesting in the drought-prone west; deficit irrigation and alternate wetting-and-drying in the arsenic-affected plains to cut both drawdown and arsenic uptake (Bhattacharya & Sen, 2022); and rainwater harvesting, pond rehabilitation and saline/freshwater land-shaping in the Sundarbans (Sharma & Deb, 2021).

f. Integrated Farming Systems

Combining crop, livestock, fisheries and horticulture spreads risk and recycles nutrients, particularly valuable for small holdings. In the Sundarbans, rice-aquaculture integration has emerged organically in response to salinity, though expanding aquaculture can itself accelerate permanent conversion of paddy land (Zero Carbon Analytics, 2025).

g. Agroforestry and Nature-Based Approaches

Agroforestry on degraded western uplands reduces erosion and diversifies income, while mangrove restoration and bioshields along the Sundarbans coast complement, rather than replace, engineered embankments that have repeatedly failed under cyclone impact (Zero Carbon Analytics, 2025).

h. Conservation of Agricultural Biodiversity

Reversing genetic erosion (Section 3.8) requires community seed banks and participatory on-farm conservation, building on existing documentation of Bengal's traditional and aromatic folk rice (Ghosh, 2018; Sharma & Deb, 2021). Because small and marginal farmers are the principal keepers of these landraces, conservation succeeds best when linked to improved market value and yield stability.

Smart and Next-Generation Agriculture

Precision agriculture, variable-rate fertiliser and water application guided by soil testing and remote sensing, can reduce input over-application even on small plots (Sangeetha *et al.,* 2024). Satellite remote sensing and GIS, already used nationally for crop-acreage estimation, flood/drought mapping and disaster damage assessment, have direct application to West Bengal's flood-prone north and drought-prone west (Kumar *et al.,* 2023); Sentinel-1A-derived flood maps used to assess Amphan and Yaas in the Sundarbans, where about 63 per cent of affected area was identified through vegetation-index change, illustrate this potential (ScienceDirect, 2025).

Table 3: Smart farming technologies, applications and limitations

Technology	Application	Potential Benefit	Limitation For Small Farmers
Remote sensing / GIS	Flood/drought mapping, crop-area estimation	Faster response, better targeting	Needs institutional interpretation capacity
IoT soil/weather sensors	Automated irrigation scheduling	Water efficiency, less salinity intrusion	Upfront cost, rural connectivity gaps
Precision nutrient application	Variable-rate fertiliser	Lower cost, less soil degradation	Equipment access, plot-size mismatch
AI/ML pest & yield tools	Image-based disease detection	Early warning, less pesticide overuse	Limited state validation, data cost
Drones	Damage assessment, spraying	Rapid assessment when roads are cut	High cost; best as shared service
Digital advisory (AgriStack)	Weather, scheme access, MSP	Wider credit, insurance, DBT access	Literacy, language, device gaps

Sangeetha *et al.* (2024), Kumar *et al.* (2023), Government of India (2026)

IoT soil-moisture and weather sensors linked to scheduled irrigation can improve water-use efficiency in both the drought-prone west and salinity-prone coast, where timed irrigation limits capillary rise of saline groundwater (Kumar *et al.,* 2023). AI/ML applications for disease detection, yield prediction and irrigation optimisation are being piloted across Indian agriculture, though state-specific validation remains limited (Sangeetha *et al.,* 2024). Drones offer crop-health monitoring and rapid post-disaster assessment when roads are cut. Digital advisory systems, including the AgriStack platform launched under India's Digital Agriculture Mission, aim to unify farmer access to credit, insurance and Minimum Support Price procurement; West Bengal's rollout includes Pradhan Mantri Fasal Bima Yojana coverage for an estimated 1.1 crore farmers across roughly 30 lakh hectares (Government of India, 2026).

These tools are not a universal solution. Adoption in India correlates strongly with farm size, with smallholders lagging because of cost, connectivity and digital-literacy gaps (International

Journal of Agriculture Sustainable Farming, 2025). Given West Bengal's predominantly small holdings, smart agriculture risks widening inequity unless deliberately designed for shared access, community sensor networks, cooperative drone services via Krishi Vigyan Kendras, and Bengali-language, low-bandwidth advisories.

Integrating Traditional Knowledge with Modern Science

Traditional and modern approaches are complementary rather than substitutable. Lateritic-zone rice landraces show yield stability under drought and flood stress that many modern cultivars lack, having evolved under sustained local selection pressure (Ghosh, 2018); these landraces can serve as a genetic resource base for participatory or marker-assisted breeding of new stress-tolerant cultivars. Similarly, indigenous Sundarbans water-management practices, land-shaping to separate saline and freshwater zones and community embankment maintenance, can be strengthened using GIS-based hydrological modelling rather than displaced by purely engineered solutions (Zero Carbon Analytics, 2025). Evidence-based integration, linking community seed systems to formal gene banks and cross-validating farmer observation against sensor and satellite data through Krishi Vigyan Kendra extension, offers the most credible pathway to resilience.

Policy and Institutional Strategies

A substantial policy architecture already exists, though its reach is uneven. PM-KISAN has delivered cumulative disbursements exceeding Rs 15,000 crore to West Bengal since 2019 (Global Agriculture, 2026), alongside the state's own Krishak Bandhu scheme and a 2026 Pradhan Mantri Fasal Bima Yojana relaunch targeting roughly 50 lakh farmers across 14 lakh hectares (Business Upturn, 2026). The state's 2026-27 budget allocated Rs 10,463 crore to agriculture and allied activities, including Rs 3,938 crore for crop insurance (IBEF, 2026). The National Mission on Natural Farming, launched November 2024, is rolling out 346 natural farming clusters covering 17,300 hectares and about 43,250 farmers under the 2026-27 state action plan (Global Agriculture, 2026). AgriStack, under the Digital Agriculture Mission, was extended to West Bengal in 2026 to unify credit, insurance, DBT and MSP procurement access (Government of India, 2026), and the Pradhan Mantri Dhan-Dhaanya Krishi Yojana has begun implementation in four low-productivity districts (Government of India, 2026). Krishi Vigyan Kendras, under ICAR's Agricultural Technology Application Research Institutes, continue to anchor research and extension alongside the state's agricultural universities (Krishi Vigyan Kendra, n.d.).

Significant gaps remain: schemes centre on income support, insurance and input subsidy rather than the ecological restoration and embankment resilience the Sundarbans and North Bengal specifically require; extension and digital-advisory systems continue to favour better-connected farmers; and no scheme yet compensates farmers for conserving traditional landraces despite their documented resilience value. Closing these gaps requires dedicated coastal and flood-plain infrastructure financing, stronger KVK integration into landrace conservation and geospatial advisory delivery, and platforms explicitly designed for low-literacy, low-connectivity users.

A Proposed Framework for Sustainable Transformation

This chapter proposes an eleven-stage, iterative transformation pathway: Climate Risk Assessment Feeds Vulnerability Mapping (demonstrated for Gosaba block and the state's western and coastal hotspots; Das *et al.,* 2025; Das & Goswami, 2023), which informs targeted Resilient Crops matched to each hotspot's dominant stress, alongside Soil and Water Restoration. These create the basis for Crop Diversification and Integrated Farming, reinforced by Agrobiodiversity Conservation as both resilience reserve and breeding resource. Smart Technology is layered onto this ecological foundation, but only where Farmer Institutions, cooperatives, FPOs and KVK networks, mediate equitable access. Value Addition and Markets convert improved production into stable income, while Policy Support finances and sequences the pathway, producing Resilient Agricultural Landscapes that feed back into renewed Climate Risk Assessment. A conceptual figure summarising this pathway is specified below (Figure 2).

Future Research Priorities

Key gaps include: block-level (not only district-level) vulnerability mapping to replicate the Gosaba approach state-wide; crop-specific climate modelling for rice, jute, potato and tea; long-term soil carbon monitoring and systematic salinity mapping linked to cyclone projections; farmer-managed field trials of arsenic- and salt-tolerant cultivars; independent, West Bengal-specific validation of AI-enabled pest and yield forecasting; research on smallholder digital-extension adoption barriers and the socio-economic determinants of adaptation; and systematic on-farm inventories and genetic characterisation of remaining traditional rice landraces given the pace of erosion documented in this chapter.

Conclusion

West Bengal's agriculture has reached a genuine inflection point. Productivity gains built on a narrow genetic base, expanding groundwater extraction and a stable climate are increasingly difficult to sustain against more erratic rainfall, intensifying cyclones, chronic western drought, arsenic-compromised groundwater and accelerating coastal salinization. Yet the state retains a rich reservoir of traditional crop genetic diversity, a growing body of locally grounded vulnerability research, an expanding policy architecture spanning income support, crop insurance, natural farming and digital agriculture, and a widening set of remote sensing, IoT and AI tools already demonstrating relevance to flood, drought and salinity management.

Realising this potential requires a deliberate transition from input-intensive to knowledge-intensive agriculture, treating climate resilience, biodiversity conservation and equitable technology access as organising principles rather than add-ons. Ecology, economics, institutions, traditional knowledge and technology must advance together, with adaptation calibrated to each zone's specific hazard profile rather than applied uniformly. Pursued in this integrated, spatially differentiated way, West Bengal's agricultural future can move from vulnerability toward durable resilience, securing both farmer livelihoods and the food security of one of India's most agriculturally significant states.

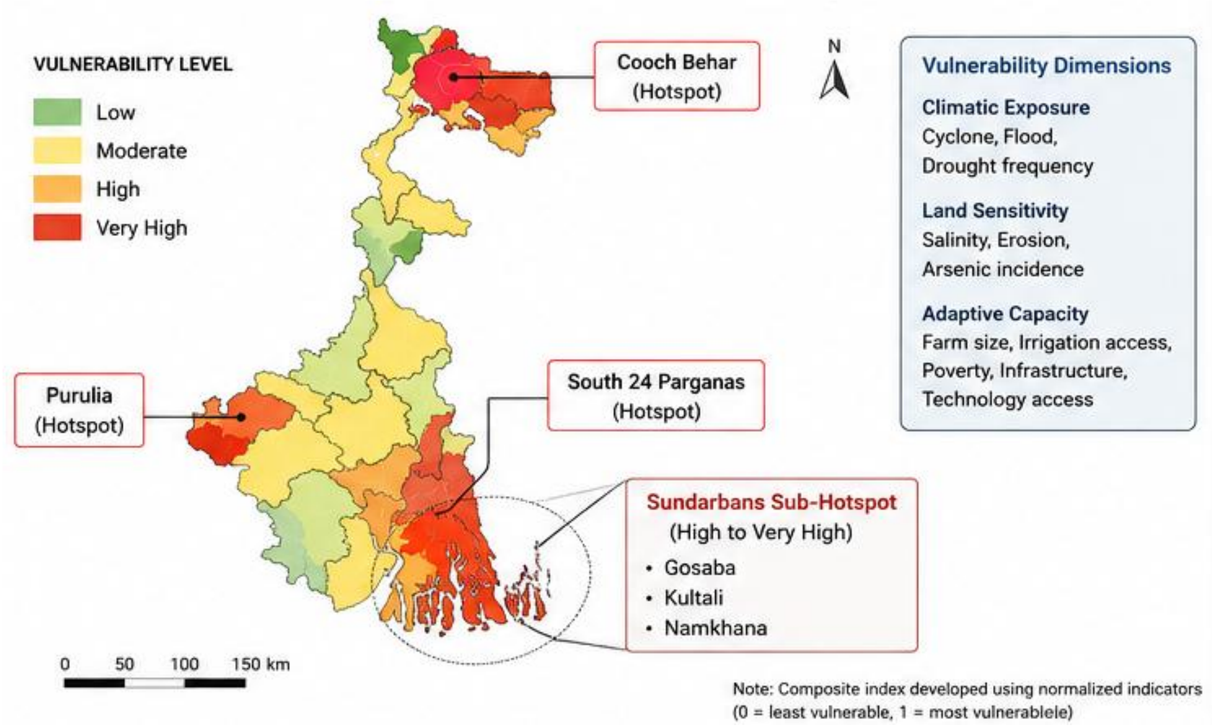

Figure 1: Agricultural vulnerability across West Bengal

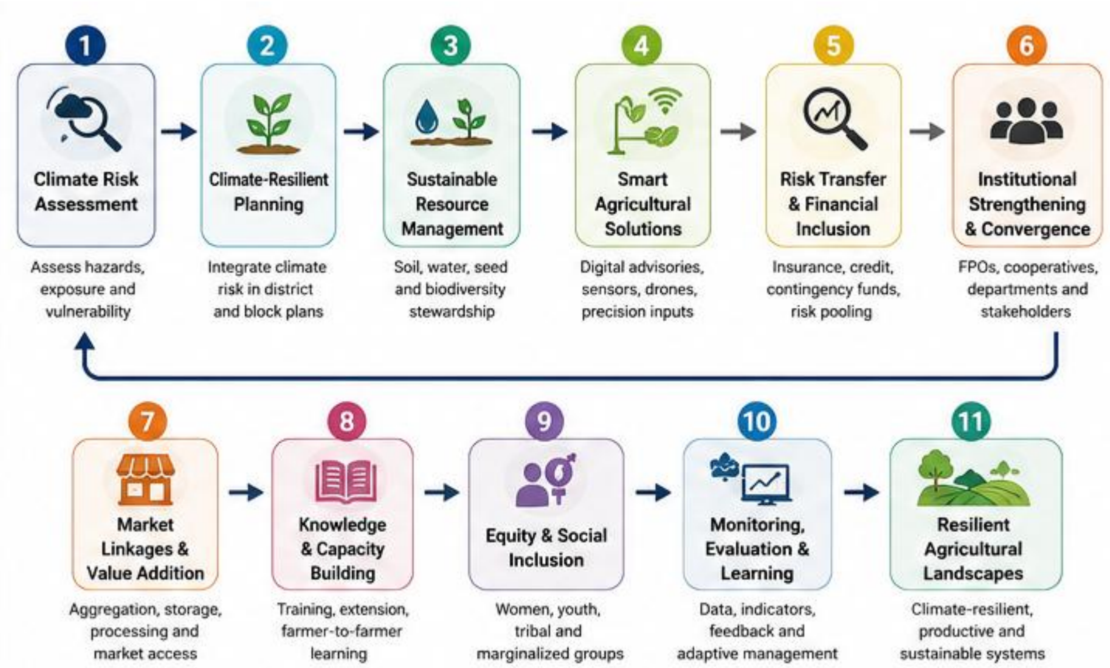

Figure 2: Conceptual transformation framework

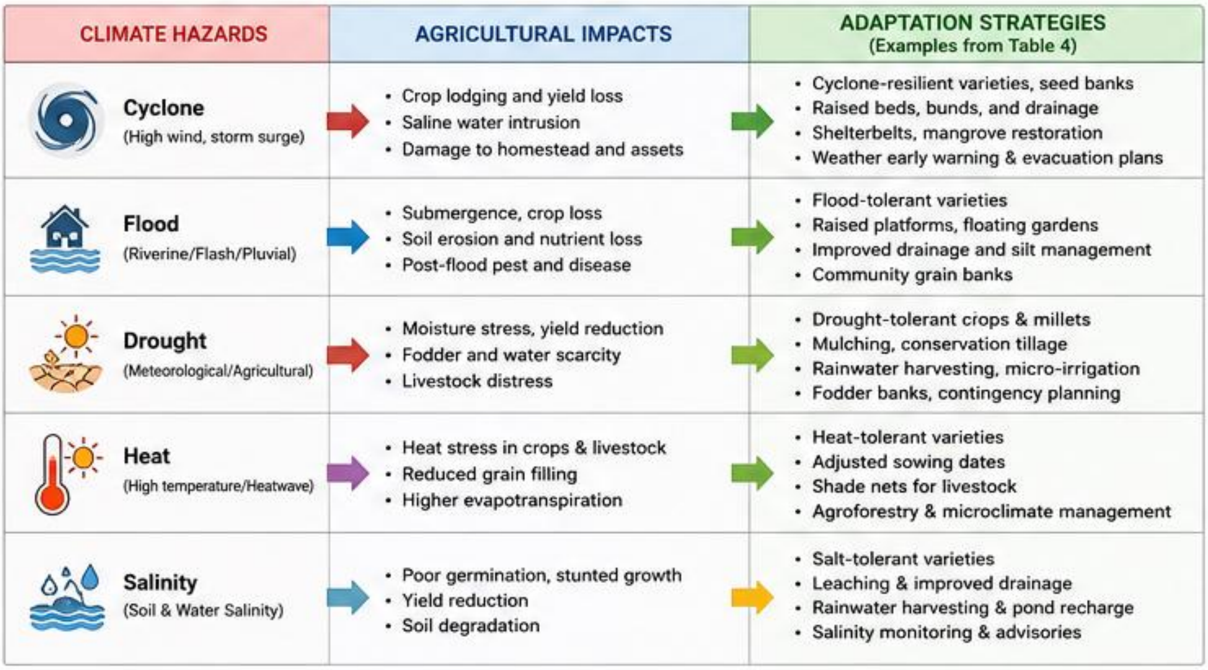

Figure 3: Climate risk to impact to adaptation pathway (specification)

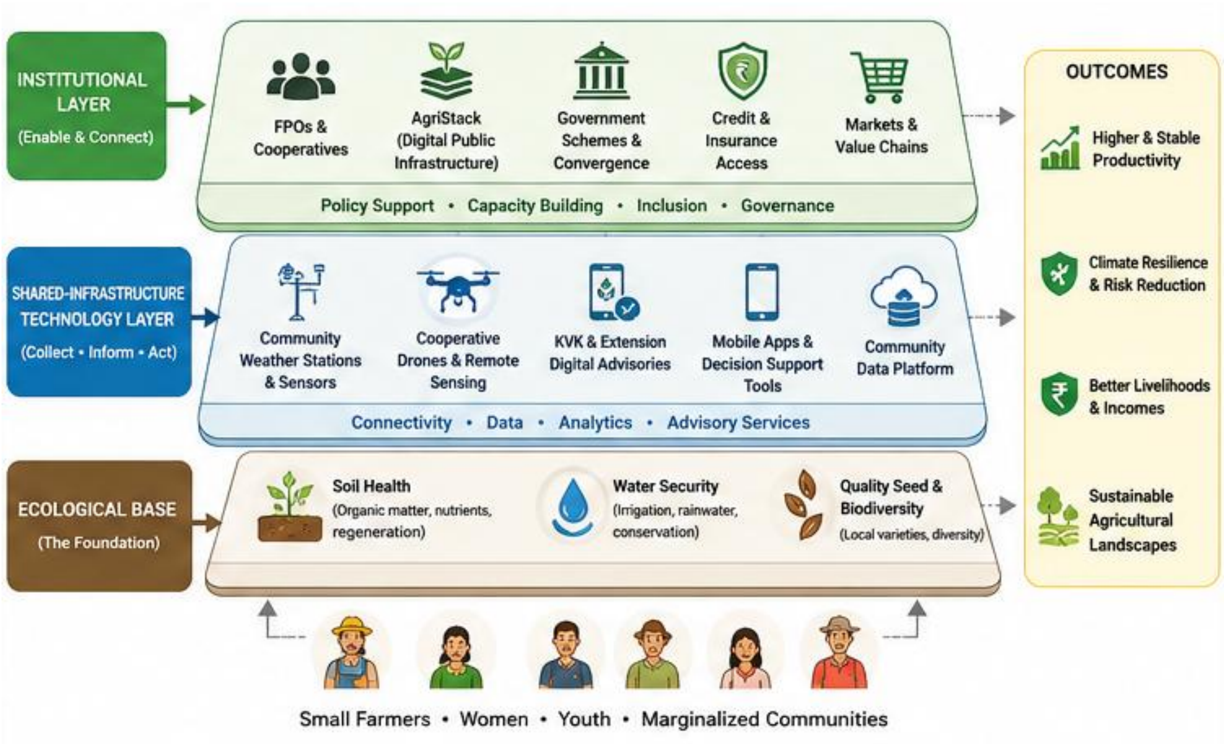

Figure 4: Smart agriculture framework for small farmers

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GREEN CHEMISTRY APPROACHES FOR ORGANIC CROP PRODUCTION: ADVANCING SUSTAINABLE AGRICULTURE THROUGH ECO-FRIENDLY INNOVATIONS

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Abstract

The increasing environmental concerns associated with intensive conventional agriculture have accelerated the adoption of sustainable farming systems worldwide. Organic crop production has emerged as an environmentally responsible approach that minimizes dependence on synthetic fertilizers, pesticides, and growth regulators while promoting ecological balance and soil health. Green chemistry complements organic farming by providing environmentally benign technologies and processes that reduce waste generation, improve resource efficiency, and minimize hazardous chemical use throughout agricultural practices. The integration of green chemistry principles into organic crop production offers innovative solutions such as biofertilizers, biopesticides, botanical pesticides, biodegradable formulations, compost-based nutrient management, biochar amendments, and nanotechnology-enabled green materials. These approaches enhance soil fertility, improve nutrient cycling, promote beneficial microbial activity, and increase crop resilience against pests, diseases, and abiotic stresses without compromising environmental quality. Continued research, technological innovation, supportive policies, and interdisciplinary collaboration are essential for developing efficient and economically viable green agricultural practices. This chapter discusses the fundamental principles of green chemistry in organic crop production, major eco-friendly technologies, current applications, challenges, and future prospects for achieving sustainable agricultural development while ensuring environmental protection, food security, and long-term ecosystem resilience.

Keywords: Green Chemistry, Organic Farming, Organic Crop Production, Biofertilizers, Biopesticides, Biochar, Sustainable Agriculture, Soil Health.

Introduction

Global agriculture has experienced remarkable intensification over the past several decades to meet the food demands of a rapidly growing population. Although conventional farming practices have substantially increased agricultural productivity, excessive dependence on synthetic fertilizers, pesticides, herbicides, and growth regulators has resulted in numerous environmental and health-related concerns. Continuous application of these chemicals has contributed to soil degradation, groundwater contamination, biodiversity loss, greenhouse gas emissions, pesticide resistance, and accumulation of toxic residues in agricultural products.

Consequently, sustainable alternatives that ensure food security while preserving environmental integrity have become an international priority [1].

Organic crop production represents one of the most effective approaches to sustainable agriculture. It emphasizes ecological balance by utilizing naturally derived inputs, enhancing soil biological activity, conserving biodiversity, and avoiding synthetic agrochemicals. Organic farming promotes nutrient recycling, crop diversification, integrated pest management, and biological soil fertility, thereby improving long-term agricultural sustainability. However, maintaining high productivity under organic cultivation requires innovative scientific approaches capable of improving nutrient availability, pest management, and resource utilization without compromising organic principles [2]. Rather than relying solely on pollution control after contamination occurs, green chemistry focuses on preventing pollution at its source through intelligent chemical design and sustainable manufacturing processes [3].

The application of green chemistry in organic crop production has significantly expanded during the past decade. Eco-friendly innovations including microbial biofertilizers, plant-derived biopesticides, biodegradable nanoformulations synthesized through green methods, biochar, vermicompost, compost extracts, amino acid-based biostimulants, microbial inoculants, and natural growth-promoting compounds are increasingly replacing conventional agricultural chemicals [4]. In addition, advances in biotechnology, nanotechnology, precision agriculture, and artificial intelligence are creating opportunities for integrating green chemistry into modern organic farming systems, enabling site-specific nutrient management, environmentally friendly pest control, and improved crop productivity [5].

Despite these advancements, several challenges remain, including inconsistent field performance of biological products, limited commercialization, regulatory complexities, higher production costs, and inadequate farmer awareness. Addressing these limitations requires multidisciplinary research, supportive governmental policies, public-private partnerships, and widespread extension programs to facilitate technology transfer and large-scale adoption [6]. This chapter explores the fundamental principles of green chemistry and their applications in organic crop production.

Principles of Green Chemistry in Organic Crop Production

Green chemistry is founded on the concept of designing chemical products and processes that minimize or eliminate the use and generation of hazardous substances while maximizing resource efficiency and environmental sustainability. The twelve principles of green chemistry, introduced by Paul T. Anastas and John C. Warner, provide a scientific framework for developing environmentally benign technologies that support sustainable agriculture. These principles closely complement the philosophy of organic crop production, where ecological balance, biodiversity conservation, soil regeneration, and human health are considered integral components of agricultural management [7].

One of the primary principles applicable to organic farming is waste prevention. Green chemistry encourages preventing waste generation rather than treating waste after its formation. In organic crop production, agricultural residues such as crop straw, fruit peels, vegetable waste, livestock manure, and food-processing by-products are converted into compost, vermicompost, biochar, and liquid organic fertilizers. This circular utilization of biomass minimizes environmental pollution while returning valuable nutrients to the soil, thereby improving soil fertility and reducing dependence on external inputs [8].

Another important principle is the use of renewable feedstocks. Organic agriculture relies predominantly on renewable biological resources instead of petroleum-derived synthetic chemicals. Plant extracts, microbial cultures, algae, seaweed, agricultural biomass, and naturally occurring minerals serve as sustainable raw materials for producing biofertilizers, biostimulants, and botanical pesticides. Such renewable resources contribute to long-term agricultural sustainability while minimizing depletion of non-renewable natural resources [9].

Green chemistry also promotes the design of safer chemicals and products. Instead of toxic synthetic pesticides that may persist in the environment and harm non-target organisms, organic crop production utilizes biodegradable biopesticides derived from plants, beneficial microorganisms, fungi, bacteria, and naturally occurring metabolites. These environmentally compatible products exhibit high target specificity while reducing ecological risks and pesticide residues in food products [10].

The principle of energy efficiency plays an increasingly important role in sustainable agriculture. Green chemistry encourages chemical processes that require lower temperatures, reduced energy consumption, and minimal greenhouse gas emissions. Composting, microbial fermentation, enzymatic transformations, and biological nitrogen fixation operate under ambient environmental conditions, making them significantly more energy-efficient than the industrial production of synthetic fertilizers and pesticides [11].

Another essential principle involves the use of catalysts instead of stoichiometric reagents. In agricultural systems, naturally occurring enzymes, soil microorganisms, and microbial inoculants function as biological catalysts that accelerate nutrient cycling, decomposition of organic matter, phosphorus solubilization, and nitrogen fixation without generating harmful by-products. These biological catalysts improve nutrient availability and soil biological activity while enhancing overall crop productivity [12].

Green chemistry further emphasizes the development of biodegradable products that do not accumulate in ecosystems after use. Organic farming increasingly employs biodegradable mulch films, natural polymer-based seed coatings, biodegradable pesticide formulations, and environmentally friendly packaging materials. These innovations reduce plastic pollution while supporting sustainable agricultural production [13].

Green Chemistry Approaches for Organic Crop Production

Biofertilizers are eco-friendly microbial formulations that enhance soil fertility through biological nitrogen fixation, phosphate solubilization, potassium mobilization, and production of plant growth-promoting substances. Microorganisms such as *Rhizobium*, *Azotobacter*, *Azospirillum*, *Bacillus*, and *Pseudomonas* improve nutrient availability while reducing dependence on synthetic fertilizers. They also enhance soil microbial diversity, improve root development, and increase crop tolerance to environmental stresses. As renewable and biodegradable agricultural inputs, biofertilizers exemplify the principles of green chemistry by promoting sustainable nutrient cycling, reducing greenhouse gas emissions, and improving long-term soil health and agricultural productivity [14].

Compost, vermicompost, and biochar are sustainable soil amendments produced from agricultural and organic wastes through environmentally friendly processes. Compost and vermicompost enrich soil with organic matter, beneficial microorganisms, and essential nutrients, whereas biochar improves soil structure, water retention, nutrient availability, and carbon sequestration. These materials enhance microbial activity, reduce nutrient leaching, and restore degraded soils without introducing harmful chemicals. Their production converts agricultural residues into valuable resources, supporting waste minimization and circular bioeconomy principles. Consequently, these amendments significantly improve soil fertility, crop productivity, and environmental sustainability in organic farming systems [15].

Botanical pesticides and biopesticides provide environmentally safe alternatives to conventional synthetic pesticides. Plant-derived compounds from neem, garlic, pyrethrum, and essential oils, together with microbial agents such as *Bacillus thuringiensis*, *Trichoderma*, and *Beauveria bassiana*, effectively control insect pests, weeds, and plant pathogens. These biodegradable products exhibit high target specificity, lower toxicity toward beneficial organisms, and minimal environmental persistence. Their application reduces pesticide residues in food and prevents ecological contamination. Green chemistry promotes the development of such natural pest-control strategies to ensure safe, sustainable, and residue-free organic crop production [16].

Microbial biostimulants enhance plant growth by stimulating natural physiological processes rather than supplying nutrients directly. Plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, seaweed extracts, and amino acid-based formulations improve nutrient uptake, root development, photosynthesis, and stress tolerance. They strengthen plant defense mechanisms against drought, salinity, and diseases while enhancing crop quality and yield. Produced from renewable biological resources, these biostimulants reduce dependence on synthetic agrochemicals and contribute to sustainable crop management. Their environmentally benign nature makes them an important component of green chemistry-based organic farming practices [17]. Green nanotechnology involves the eco-friendly synthesis of nanomaterials using plant extracts, microorganisms, or other biological resources. Green-synthesized nanoparticles can serve as efficient nano-fertilizers, nano-biopesticides, and nutrient delivery systems that improve nutrient-use efficiency while minimizing environmental contamination. Their controlled-release properties reduce fertilizer losses and enhance crop productivity using smaller quantities of active ingredients. Biologically synthesized nanomaterials avoid hazardous chemicals commonly used in conventional nanoparticle production, making them compatible with sustainable agriculture. Continued research is required to establish their environmental safety and regulatory acceptance in certified organic farming systems [18].

Green chemistry promotes the conversion of agricultural residues into valuable products rather than treating them as waste. Crop residues, fruit peels, animal manure, and food-processing by-products can be transformed into compost, biochar, biofertilizers, biogas, and biodegradable materials through sustainable biological and thermochemical processes. Waste valorization reduces environmental pollution, conserves natural resources, and generates renewable agricultural inputs. This circular bioeconomy approach minimizes waste generation while improving soil fertility, reducing production costs, and supporting sustainable resource management, thereby strengthening the environmental and economic sustainability of organic crop production [19].

Recent advances in artificial intelligence, sensors, drones, satellite imaging, and Internet of Things (IoT) technologies are improving the efficiency of organic farming. Precision agriculture enables real-time monitoring of soil nutrients, crop health, irrigation, and pest outbreaks, allowing site-specific application of biofertilizers and biopesticides. This targeted approach minimizes resource wastage, reduces environmental impact, and enhances crop productivity. When integrated with green chemistry principles, smart farming technologies promote efficient utilization of renewable agricultural inputs, improve decision-making, and contribute to climate-resilient, sustainable, and economically viable organic crop production systems [20].

Challenges and Future Perspectives

Despite significant advancements, the widespread adoption of green chemistry approaches in organic crop production faces several challenges. Biological inputs such as biofertilizers and biopesticides often exhibit variable field performance due to differences in soil properties, climate, and microbial survival. Their shorter shelf life, limited commercial availability, and slower action compared to synthetic agrochemicals can discourage farmers from adopting these alternatives. In addition, the higher initial costs of organic inputs, inadequate technical knowledge, lack of standardized quality control, and complex certification procedures remain major barriers, particularly for small-scale farmers. Limited investment in research, insufficient extension services, and regulatory uncertainties regarding emerging technologies, including green nanomaterials, further restrict their large-scale implementation [21].

Future research should focus on developing highly efficient, stable, and cost-effective bio-based agricultural inputs through advances in biotechnology, microbial engineering, and green nanotechnology. Integration of artificial intelligence, precision agriculture, remote sensing, and Internet of Things (IoT) technologies can optimize the application of organic inputs, improve resource-use efficiency, and enhance crop productivity. Strengthening public awareness, farmer training programs, supportive government policies, and international collaborations will accelerate the transition toward sustainable agriculture. Continued interdisciplinary research combining chemistry, biology, environmental science, and agricultural engineering will be essential for designing innovative green solutions that ensure food security while preserving natural ecosystems for future generations [22].

Green chemistry provides a scientifically sound and environmentally responsible framework for advancing organic crop production. By replacing hazardous synthetic agrochemicals with renewable, biodegradable, and biologically derived alternatives, green chemistry promotes sustainable nutrient management, eco-friendly pest control, improved soil fertility, and efficient utilization of natural resources. Approaches such as biofertilizers, biopesticides, compost, biochar, microbial biostimulants, green nanotechnology, and agricultural waste valorization contribute significantly to reducing environmental pollution while enhancing agricultural productivity and food quality. Although challenges related to cost, standardization, commercialization, and farmer awareness remain, continuous technological innovations and supportive policies are expected to overcome these limitations. The successful integration of green chemistry principles with modern precision agriculture and organic farming practices offers a promising pathway toward climate-resilient agriculture, improved ecosystem health, sustainable food production, and long-term environmental conservation. Adopting these green approaches will play a vital role in achieving global sustainability goals while ensuring agricultural productivity for present and future generations.

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