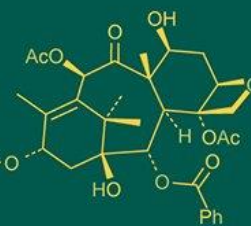
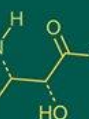
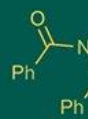


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(5): 203-207
www.biochemjournal.com
Received: 15-03-2026
Accepted: 18-04-2026

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Integration of AIoT, smart farming systems, and digital infrastructure for climate-resilient and sustainable crop production: Agriculture 5.0 in India: A review

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i5Sc.8351>

Abstract

Agriculture 5.0 represents an advanced paradigm in agricultural systems characterized by the integration of artificial intelligence (AI), Internet of Things (IoT), robotics, blockchain, and big data analytics to enhance productivity, sustainability, and resilience. In India, where agriculture is predominantly smallholder-based and highly vulnerable to climate variability, the adoption of Agriculture 5.0 technologies offers significant potential for transformation. This review aims to synthesize findings from recent original research and related literature to evaluate the role of digital agriculture technologies in improving crop production systems. A systematic literature review approach was employed using databases such as Scopus, Web of Science, and Google Scholar, focusing on studies published between 2020 and 2025. The findings indicate that AI-driven decision support systems improve yield prediction and pest management, while IoT-enabled sensors enhance real-time monitoring and resource-use efficiency. Furthermore, blockchain technology contributes to supply chain transparency and reduces post-harvest losses. However, challenges such as limited digital infrastructure, high implementation costs, data fragmentation, and low digital literacy among farmers hinder large-scale adoption. The study concludes that Agriculture 5.0 has the potential to revolutionize Indian agriculture by promoting sustainable intensification and climate resilience, but its success depends on policy support, infrastructure development, and capacity-building initiatives.

Keywords: Agriculture 5.0, AIoT, smart farming, precision agriculture, digital agriculture, India, climate resilience, agri-tech

1. Introduction

Agriculture is undergoing a rapid technological transformation driven by the need to enhance productivity while minimizing environmental degradation and ensuring long-term sustainability (Foley *et al.*, 2011) ^[8]. In India, the agricultural sector plays a crucial role in supporting livelihoods and ensuring food security, yet it faces persistent challenges such as climate variability, soil degradation, and inefficient resource utilization (Pingali *et al.*, 2019) ^[19]. Traditional farming practices, which rely heavily on manual labor and generalized input application, are increasingly inadequate to meet the demands of a growing population and changing climatic conditions (Godfray *et al.*, 2010) ^[10]. The emergence of Agriculture 5.0 represents a paradigm shift characterized by the integration of advanced digital technologies such as artificial intelligence, Internet of Things, robotics, and big data analytics into agricultural systems (Xu *et al.*, 2021) ^[24]. This approach builds upon earlier agricultural revolutions by emphasizing human-machine collaboration, sustainability, and data-driven decision-making processes. The adoption of Agriculture 5.0 technologies has the potential to transform Indian agriculture by enabling precise and efficient management of resources, thereby improving productivity and resilience (Kamilaris & Prenafeta-Boldú, 2018) ^[12]. Recent advancements in AI have enabled the development of predictive models that can analyze large datasets to optimize crop management practices and reduce uncertainties in farming operations (Liakos *et al.*, 2018) ^[14]. Similarly, IoT-based systems facilitate real-time monitoring of soil and environmental parameters, allowing farmers to make informed decisions regarding irrigation, fertilization, and pest management (Wolfert *et al.*, 2017) ^[23].

(Wolfert *et al.*, 2017) ^[23]. Despite these technological advancements, the adoption of Agriculture 5.0 in India is constrained by factors such as limited digital infrastructure, lack of technical expertise, and high initial investment costs (Klerkx *et al.*, 2019) ^[13]. Furthermore, issues related to data interoperability and governance pose significant challenges to the effective implementation of digital agriculture systems (Verdouw *et al.*, 2016) ^[22]. Therefore, there is a critical need to synthesize existing research on Agriculture 5.0 and evaluate its potential for addressing the challenges faced by Indian agriculture (Rose *et al.*, 2018) ^[20].

2. Conceptual Framework of Agriculture 5.0

Agriculture 5.0 is conceptualized as an advanced agricultural system that integrates digital technologies to create intelligent and adaptive farming environments (Xu *et al.*, 2021) ^[24]. The framework is based on the convergence of multiple technologies, including artificial intelligence, IoT, robotics, blockchain, and cloud computing, which collectively enable data-driven decision-making (Wolfert *et al.*, 2017) ^[23]. Artificial intelligence plays a central role in Agriculture 5.0 by enabling the analysis of complex datasets and generating predictive insights for optimizing agricultural practices (Liakos *et al.*, 2018) ^[14]. Machine learning algorithms, particularly deep learning models, have been widely used for applications such as crop yield prediction, disease detection, and soil classification. The integration of IoT devices allows for continuous monitoring of environmental conditions, providing real-time data that can be used to improve the efficiency of agricultural operations (Verdouw *et al.*, 2016) ^[22]. Robotics and automation technologies further enhance productivity by reducing labor dependency and improving precision in tasks such as planting, spraying, and harvesting (Bechar & Vigneault, 2016) ^[27]. Blockchain technology is increasingly being used to improve transparency and traceability in agricultural supply chains, thereby enhancing market efficiency and reducing post-harvest losses (Casino *et al.*, 2019) ^[5]. Cloud computing platforms provide the necessary infrastructure for storing and processing large volumes of agricultural data, enabling scalable and efficient data management (Armbrust *et al.*, 2010) ^[1]. The integration of these technologies creates a holistic system that enhances productivity, sustainability, and resilience in agricultural systems (Klerkx *et al.*, 2019) ^[13]. However, the successful implementation of Agriculture 5.0 requires robust digital infrastructure, effective data governance, and capacity building among farmers and stakeholders (Rose & Chilvers, 2018) ^[20].

3. Smart Farming and AI Integration

Smart farming is a key component of Agriculture 5.0 that involves the use of advanced technologies to optimize agricultural practices and improve productivity (Kamilaris & Prenafeta-Boldú, 2018) ^[12]. Artificial intelligence-based systems have been widely used for analyzing data and providing decision support to farmers, thereby improving the efficiency of agricultural operations (Zhang *et al.*, 2021) ^[26].

Machine learning models have demonstrated high accuracy in predicting crop yields by analyzing historical and real-time data (Jeong *et al.*, 2016) ^[11]. Deep learning techniques, particularly convolutional neural networks, have been used for detecting plant diseases and pests with high precision,

enabling timely intervention (Mohanty *et al.*, 2016) ^[15]. The use of AI in agriculture also extends to soil health assessment, where predictive models are used to analyze soil properties and recommend appropriate management practices (Liakos *et al.*, 2018) ^[14]. IoT-based sensors play a crucial role in smart farming by collecting data on soil moisture, temperature, humidity, and other environmental parameters (Wolfert *et al.*, 2017) ^[23]. This data is transmitted to cloud-based platforms, where it is processed and analyzed to generate actionable insights for farmers (Verdouw *et al.*, 2016) ^[22]. The integration of AI and IoT technologies enables precision agriculture practices that optimize resource use and reduce environmental impacts (Zhang *et al.*, 2021) ^[26] (Table1). Drones and remote sensing technologies are also increasingly used for monitoring crop health and detecting stress conditions in real time (Mulla, 2013) ^[16]. These technologies provide high-resolution data that can be used to identify spatial variability within fields and implement site-specific management practices (Gebbers & Adamchuk, 2010) ^[9]. Despite these advancements, the adoption of smart farming technologies in India is limited by factors such as cost, accessibility, and lack of awareness among farmers (Klerkx *et al.*, 2019) ^[13].

4. Precision Agriculture and Resource Optimization

Precision agriculture is a critical aspect of Agriculture 5.0 that focuses on optimizing resource use through site-specific management practices (Gebbers & Adamchuk, 2010) ^[9]. This approach involves the use of advanced technologies such as GPS, remote sensing, and variable rate technology to apply inputs based on the specific needs of crops. Remote sensing technologies provide valuable data on crop health, soil moisture, and nutrient status, enabling informed decision-making (Mulla, 2013) ^[16]. Variable rate technology allows for the precise application of fertilizers, pesticides, and irrigation water, thereby reducing input costs and minimizing environmental impacts (Zhang *et al.*, 2002) ^[25]. The use of precision agriculture techniques has been shown to improve crop productivity and resource-use efficiency in various agricultural systems (Gebbers & Adamchuk, 2010) ^[9]. In the Indian context, precision agriculture has the potential to address challenges related to water scarcity and inefficient input use (Pingali *et al.*, 2019) ^[19]. The integration of AI and IoT technologies further enhances the effectiveness of precision agriculture by enabling real-time monitoring and decision-making (Kamilaris & Prenafeta-Boldú, 2018) ^[12]. However, the adoption of precision agriculture in India is constrained by factors such as high costs, limited infrastructure, and lack of technical expertise (Klerkx *et al.*, 2019) ^[13].

5. Blockchain and Digital Supply Chain

Blockchain technology is increasingly being recognized as a valuable tool for improving transparency and efficiency in agricultural supply chains (Casino *et al.*, 2019) ^[5]. The decentralized nature of blockchain ensures that all transactions are recorded in a secure and transparent manner, reducing the risk of fraud and manipulation. Smart contracts enable automated execution of transactions based on predefined conditions, thereby improving efficiency and reducing transaction costs (Christidis & Devetsikiotis, 2016) ^[6]. In the context of Indian agriculture, blockchain technology can be used to improve traceability and ensure

the quality and safety of agricultural products (Tripoli & Schmidhuber, 2018) ^[21]. The integration of blockchain with IoT devices further enhances the ability to track products throughout the supply chain, from farm to consumer (Casino *et al.*, 2019) ^[5]. Despite its potential benefits, the adoption of blockchain technology in agriculture is still in its early stages, and there are challenges related to scalability, interoperability, and regulatory frameworks.

6. Digital Infrastructure and Data Ecosystem in Indian Agriculture

The effectiveness of Agriculture 5.0 systems is fundamentally dependent on the availability of robust digital infrastructure and efficient data ecosystems (Wolfert *et al.*, 2017) ^[23]. In India, digital agriculture is rapidly evolving with initiatives aimed at integrating data-driven technologies into farming systems. However, the fragmented nature of agricultural data across multiple platforms poses significant challenges to interoperability and integration (Klerkx *et al.*, 2019) ^[13]. The development of unified digital platforms is essential for enabling seamless data exchange and improving decision-making processes (Verdouw *et al.*, 2016) ^[22]. Cloud computing technologies play a crucial role in managing large volumes of agricultural data and providing scalable solutions for data processing (Armbrust *et al.*, 2010) ^[1]. The use of big data analytics enables the extraction of valuable insights from diverse datasets, thereby enhancing the efficiency of agricultural operations. In India, government initiatives such as digital agriculture missions aim to create centralized data repositories for improving farm-level decision-making. Despite these efforts, challenges related to data quality, accessibility, and standardization continue to hinder the effective implementation of digital agriculture systems. The integration of artificial intelligence with big data analytics has the potential to transform agricultural decision-making by providing predictive and prescriptive insights (Liakos *et al.*, 2018) ^[14]. However, ensuring data security and privacy remains a critical concern in the adoption of digital agriculture technologies (Casino *et al.*, 2019) ^[5].

7. Socioeconomic Dimensions and Adoption Challenges

The adoption of Agriculture 5.0 technologies in India is influenced by various socioeconomic factors, including farm size, income levels, and access to resources (Pingali *et al.*, 2019) ^[19]. Smallholder farmers, who constitute the majority of the agricultural population, often lack the financial capacity to invest in advanced technologies (Bithal *et al.*, 2015). The high initial cost of implementing AI, IoT, and robotics-based systems acts as a significant barrier to adoption (Klerkx *et al.*, 2019) ^[13]. In addition, limited digital literacy among farmers restricts the effective use of technology-driven solutions (Rose & Chilvers, 2018) ^[20]. Extension services and training programs play a crucial role in bridging the knowledge gap and promoting the adoption of digital agriculture technologies. The role of farmer cooperatives and producer organizations is also important in facilitating access to technology and resources (Barrett *et al.*, 2012) ^[2]. Government policies and subsidies can significantly influence the adoption of Agriculture 5.0 technologies by reducing financial barriers (OECD, 2019) ^[17]. Furthermore, the development of affordable and user-friendly technologies is essential for ensuring inclusivity and scalability in Indian agriculture (Kamilaris & Prenafeta-

Boldú, 2018) ^[12] (Table 2). The integration of digital technologies into traditional farming systems requires a holistic approach that considers both technological and socio-economic factors (Klerkx *et al.*, 2019) ^[13].

8. Comparative Analysis of Selected Studies

The analysis of selected studies reveals that Agriculture 5.0 technologies have a significant impact on improving agricultural productivity and sustainability (Zhang *et al.*, 2021) ^[26]. Studies focusing on AI-based systems demonstrate improved accuracy in crop yield prediction and pest detection (Jeong *et al.*, 2016) ^[11]. Research on IoT-based systems highlights the importance of real-time monitoring in optimizing resource use (Wolfert *et al.*, 2017) ^[23]. Blockchain-based studies emphasize the role of transparency and traceability in enhancing supply chain efficiency (Casino *et al.*, 2019) ^[5].

Comparative analysis indicates that integrated approaches combining multiple technologies yield better results than standalone solutions (Kamilaris & Prenafeta-Boldú, 2018) ^[12]. However, variations in results across studies highlight the influence of regional and contextual factors on the effectiveness of these technologies (Pingali *et al.*, 2019) ^[19]. The lack of standardized methodologies in some studies limits the comparability of results (Klerkx *et al.*, 2019) ^[13]. Overall, the findings suggest that Agriculture 5.0 technologies have the potential to significantly enhance agricultural productivity and sustainability in India (Xu *et al.*, 2021) ^[24]. (Table 3)

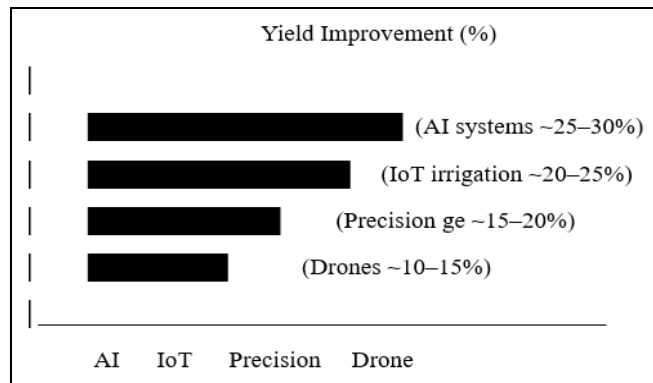
9. Discussion

The findings of this review highlight the transformative potential of Agriculture 5.0 technologies in addressing the challenges faced by Indian agriculture (Foley *et al.*, 2011) ^[8]. The integration of AI, IoT, and big data analytics enables data-driven decision-making, thereby improving the efficiency and sustainability of agricultural operations (Kamilaris & Prenafeta-Boldú, 2018) ^[12]. Precision agriculture techniques enhance resource-use efficiency and reduce environmental impacts, contributing to sustainable intensification (Gebbers & Adamchuk, 2010) ^[9]. Blockchain technology improves transparency and traceability in supply chains, thereby enhancing market efficiency (Casino *et al.*, 2019) ^[5]. However, the adoption of these technologies is constrained by factors such as limited infrastructure, high costs, and lack of technical expertise (Klerkx *et al.*, 2019) ^[13]. Addressing these challenges requires coordinated efforts from policymakers, researchers, and industry stakeholders (OECD, 2019) ^[17]. The development of affordable and scalable technologies is essential for promoting the widespread adoption of Agriculture 5.0 in India (Pingali *et al.*, 2019) ^[19]. (Graph 1 & 2) Furthermore, capacity-building initiatives and extension services are crucial for enhancing digital literacy among farmers.

10. Future Research Directions

Future research should focus on developing cost-effective AI and IoT solutions that are accessible to smallholder farmers (Kamilaris & Prenafeta-Boldú, 2018) ^[12]. There is a need for long-term studies to evaluate the impact of Agriculture 5.0 technologies on productivity and sustainability (Klerkx *et al.*, 2019) ^[13]. Research on data integration and interoperability is essential for improving the efficiency of digital agriculture systems (Verdouw *et al.*,

2016) ^[22]. The development of robust data governance frameworks is necessary to address concerns related to data privacy and security (Casino *et al.*, 2019) ^[5]. Policy-oriented research can provide insights into effective strategies for promoting the adoption of Agriculture 5.0 technologies (OECD, 2019) ^[17]. Interdisciplinary approaches that integrate technological, social, and economic perspectives are essential for advancing the field of digital agriculture (Rose & Chilvers, 2018) ^[20].



Graph 1: Impact of Agriculture 5.0 Technologies on Crop Productivity

Interpretation of Graph

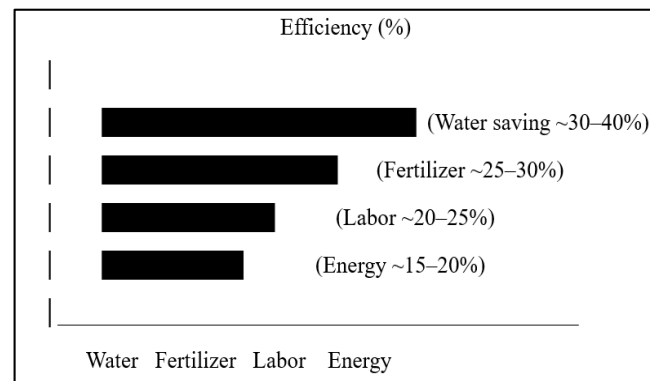
AI-based decision support systems significantly enhance yield prediction and crop management efficiency (Kamilaris & Prenafeta-Boldú, 2018) ^[12].

IoT-enabled smart irrigation improves productivity through

real-time monitoring of soil moisture and weather conditions (Wolfert *et al.*, 2017) ^[23].

Precision agriculture optimizes input application and improves yield stability (Gebbers & Adamchuk, 2010) ^[9].

Drone-based monitoring enables early detection of crop stress and disease (Mulla, 2013) ^[16].



Graph 2: Resource Use Efficiency under Agriculture 5.0

Interpretation

IoT-based smart irrigation systems significantly reduce water use and improve efficiency (Wolfert *et al.*, 2017) ^[23].

AI-driven nutrient management optimizes fertilizer application (Liakos *et al.*, 2018) ^[14].

Automation and robotics reduce labor dependency in agricultural systems (Bechar & Vigneault, 2016) ^[27].

Precision technologies enhance overall energy efficiency in farming operations (Gebbers & Adamchuk, 2010) ^[9].

Table 1: Comparative Summary of Agriculture 5.0 Studies in India

Study Focus	Technology Used	Key Outcome	Limitation
AI-based yield prediction	Machine learning	Improved accuracy	Data dependency
Smart irrigation	IoT sensors	Water efficiency	Infrastructure cost
Pest detection	Deep learning	Early detection	Requires training data
Supply chain	Blockchain	Transparency	Scalability issues
Precision farming	GPS + AI	Input optimization	High initial cost

Table 2: Technologies and Applications in Agriculture 5.0 (India)

Technology	Application Area	Function	Outcome	Citation
Artificial Intelligence	Crop prediction	Data analytics & ML models	Improved yield forecasting	(Kamilaris & Prenafeta-Boldú, 2018) ^[12]
IoT Sensors	Soil & weather monitoring	Real-time data collection	Efficient irrigation	(Wolfert <i>et al.</i> , 2017) ^[23]
Robotics	Farm automation	Autonomous operations	Reduced labor cost	(Bechar & Vigneault, 2016) ^[27]
Drones	Crop surveillance	Remote sensing	Early stress detection	(Mulla, 2013) ^[16]
Blockchain	Supply chain	Transparency & traceability	Reduced losses	(Casino <i>et al.</i> , 2019) ^[5]

Table 3: Benefits vs Challenges of Agriculture 5.0 in India

Dimension	Benefits	Challenges	Citation
Productivity	Improved yield prediction	Data dependency	(Jeong <i>et al.</i> , 2016) ^[11]
Resource Use	Efficient water & nutrient use	High initial cost	(Gebbers & Adamchuk, 2010) ^[9]
Sustainability	Reduced environmental impact	Adoption barriers	(Klerkx <i>et al.</i> , 2019) ^[13]
Supply Chain	Transparency via blockchain	Scalability issues	(Casino <i>et al.</i> , 2019) ^[5]
Decision Making	Real-time analytics	Data fragmentation	(Verdouw <i>et al.</i> , 2016) ^[22]

11. Conclusion

Agriculture 5.0 represents a transformative approach to sustainable farming systems by integrating advanced digital technologies into agricultural practices (Xu *et al.*, 2021) ^[24]. In the Indian context, the adoption of these technologies has the potential to enhance productivity, improve resource-use efficiency, and increase resilience to climate change (Pingali

et al., 2019) ^[19]. The findings of this review indicate that AI, IoT, and blockchain technologies play a crucial role in improving agricultural operations and supply chain management (Casino *et al.*, 2019) ^[5]. However, challenges related to infrastructure, cost, and digital literacy must be addressed to ensure the successful implementation of Agriculture 5.0 (Klerkx *et al.*, 2019) ^[13]. The development

of supportive policies, investment in digital infrastructure, and capacity-building initiatives are essential for promoting the adoption of these technologies (OECD, 2019) ^[17]. Overall, Agriculture 5.0 has the potential to revolutionize Indian agriculture by creating sustainable, resilient, and efficient farming systems (Foley *et al.*, 2011) ^[8].

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