Leveraging Artificial Intelligence for Transforming Agriculture: Need, Strategies and Challenges

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Abstract. The United Nations World Population Prospects 2024 report projects that the global population will reach 9.66 billion by 2050, necessitating a 60 percent increase in food production [1]. Agriculture is vital for livelihoods, food security, and economic growth. However, challenges such as rising food demand, shrinking farmlands, resource depletion, and unpredictable weather patterns threaten the sector. Adopting technology, especially Artificial Intelligence (AI), can transform agriculture from low-yield subsistence to high-yield market-oriented practices. AI applications include precision farming, crop monitoring with drones, predictive analytics for farm yields, and supply chain optimization. Despite its benefits, barriers remain, including reliance on traditional methods, high adoption costs for small farmers, inadequate rural infrastructure, and a shortage of skilled workers due to youth migration. The study investigates the impact of artificial intelligence (AI) on agriculture, highlighting its potential applications and strategies to enhance its adoption in the sector. It evaluates the challenges associated with integrating AI into agricultural practices and provides an overview of India's institutional framework, which sets the stage for future technology interventions. These interventions aim to transform the agricultural landscape, ushering in a new era of sustainability that seeks to improve food and nutritional security for all.

Keywords: Artificial Intelligence, Food and Nutritional Security, Agricultural landscape, Technology interventions, Sustainability.

1 Introduction

"The integration of artificial intelligence in agriculture marks a transformative shift from intuition-based to data-driven decision-making, enhancing productivity, sustainability, and resilience across the agri-food system."
— FAO (2022), The State of Food and Agriculture: Leveraging Automation in Agriculture

Nobel laureate Theodore W. Schultz asserted that, in many low-income countries, agriculture is not merely one sector among others but rather the essential foundation for broader welfare improvements. In his renowned lecture, "The Economics of Being Poor," he remarked, "Most people in the world are poor. Most of the world's poor

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people earn their living from agriculture. If we knew the economics of agriculture, we would know much of the economics of being poor." Schultz contended that advancements in agricultural productivity can elevate incomes, reduce poverty, and stimulate overall economic growth. Consequently, for Schultz, improving agriculture is not merely a policy option but an essential solution to myriad socioeconomic challenges [2].

Agriculture has always played a crucial role in human civilization and national development, particularly in agrarian economies such as India. At its core, agriculture ensures food and nutritional security for the population by supporting consistent access to adequate food for all [3]. Beyond providing sustenance, agriculture underpins economic growth. A significant portion of India's population depends on agriculture for their livelihoods. The agriculture sector accounts for approximately 20 percent of the nation's Gross Value Added (GVA) and employs nearly 45 percent of the workforce, underscoring its critical role in supporting livelihoods and ensuring food security [4,5].

Agriculture in India largely focuses on raw production, which limits opportunities for adding value [6]. This reliance on traditional farming practices results in low productivity and inefficiencies, ultimately failing to meet increasing food demand [7]. Farmers often experience tighter profit margins and income that fluctuates more than in non-farming sectors. Agricultural productivity is six times lower than that of manufacturing and services, underscoring the significant potential for agricultural productivity to evolve toward more productive roles [8].

The objective of enhancing agricultural yield encounters multiple challenges. A significant issue is the decline in arable land resulting from urbanization and industrial development. Furthermore, the land available for agriculture is often small and fragmented, complicating efforts to implement larger and more efficient farming practices that could increase productivity. The unsustainable depletion of water and soil resources has led to approximately 40 percent of agricultural land degraded [9]. Compounding these difficulties, climate change introduces shifting patterns and unpredictable weather events that negatively impact crop yields and disrupt traditional farming practices [10].

Among rural youth, agriculture is the primary occupation, with 42.2 percent of those aged 15-29 employed in it. However, in the past six years, young men have shifted from agriculture to construction, with agricultural employment declining by nearly eight percentage points [11]. Rural youth increasingly perceive agriculture as a less prestigious and less innovative sector. A report by the Global Opportunity Youth Network et al. [12] emphasized that 70-85 percent of over 5,000 individuals surveyed across rural India prefer employment opportunities in small manufacturing, retail, or business sectors. This underlines the urgent need for strategies to retain young talent within the agricultural sector.

Across the globe, technology has invigorated the agriculture sector, ushering in a new era of efficiency and productivity. Cutting-edge innovations are transforming the age-old practices of labour-intensive, subsistence farming into streamlined, high-yield systems [13] that are not only modernized but also tailored to meet market demands. This evolution is turning farming into a smart, forward-thinking enterprise that thrives

on precision and sustainability, bridging the gap between tradition and the future of food production [14]. In this environment, Artificial Intelligence has emerged as a revolutionary technology with the potential to redefine the future of agriculture.

Artificial Intelligence has emerged as a significant tool for addressing the most pressing challenges in agriculture. By leveraging advanced technology, the sector enhances efficiency, fosters inclusivity, and promotes sustainability [15]. This innovative tool is transforming farming practices, making them smarter and more resource-efficient, ultimately paving the way for a resilient and productive agricultural landscape and fostering an entrepreneurial, knowledge-driven sector.

Recognizing the profound impact of artificial intelligence on agricultural transformation, this study endeavours to explore its diverse applications and innovative strategies, while identifying the barriers to successful implementation. It aims to deepen our understanding of how AI can play a pivotal role in advancing sustainable food systems and fostering resilient agricultural futures, ultimately contributing to global food security and environmental sustainability.

2 Theoretical Framework and Literature Review

When human insight collaborates with mechanical assistance, we can effectively tackle challenges and enhance processes. The idea of machines thinking for themselves, known as "artificial intelligence" (AI), enables automated tasks such as learning and problem-solving [16,17]. AI has evolved from rule-based systems to machine learning and deep learning, creating new possibilities in various fields, particularly agriculture. In the Indian context, where agriculture continues to support a significant share of livelihoods while facing structural inefficiencies, AI is increasingly viewed as a transformative tool capable of enhancing productivity, resilience, and farmers' income.

Several theoretical frameworks support the use of AI in agriculture. Systems theory views agriculture as a complex interplay of biological, environmental, and economic factors [18]. The Technology Acceptance Model (TAM) suggests that farmers' acceptance of AI is driven by perceptions of usefulness and ease of use [19]. Venkatesh and Davis [20] expanded TAM to include social influence and facilitating conditions. The Unified Theory of Acceptance and Use of Technology (UTAUT) by Venkatesh et al. [21] further explores farmers' technology acceptance. Sood et al. [22] found that AI enhances decision-making in agriculture but emphasized the need for trust in these technologies. Khanna et al. [23] noted that AI-enabled technologies can transform agriculture by improving practices and promoting sustainability, aligning with the UN Sustainable Development Goals. This approach also builds resilience to the effects of climate change [24], as supported by Sustainability Theory. Additionally, the Socio-Technical Systems framework highlights that effective use of AI requires farmers to possess digital skills and supportive structures [25].

A considerable amount of research highlights the role of AI in boosting farm productivity and resource efficiency [26-30]. Studies show that AI techniques, particularly machine learning (ML) and deep learning (DL), enhance prediction and detection tasks that are vital to agricultural decision-making. Reviews of crop yield

prediction reveal that ML models (e.g., random forests and neural networks) and increasingly sophisticated DL architectures, trained on diverse data sources (satellite, weather, soil, management), significantly outperform traditional statistical models in forecasting [31,32].

Another prominent stream of literature highlights that precision agriculture is a management approach that uses AI to analyze variability in crops and livestock, aiming to optimize inputs such as water, fertilizers, and pesticides to enhance productivity and sustainability [33]. Smart farming integrates AI, IoT, and data analytics to enhance agricultural operations through automated irrigation, drone-based surveillance, and predictive analytics [34]. By collecting and analyzing data from sensors and satellites, AI algorithms can identify patterns and provide actionable insights [35].

Research highlights AI's role in improving market access and price discovery for farmers by providing price forecasts and marketing recommendations [36]. It is integrated into public extension systems, crop insurance, and supply chain management through initiatives like digital agriculture missions. While AI can enhance traditional extension services with personalized and timely advisories, studies indicate that success depends on governance frameworks, data ownership, and public–private coordination—not solely on technology [37].

The integration of AI into agriculture offers numerous advantages, yet several critical perspectives highlight challenges that impede its broader adoption. Factors such as insufficient preparedness [38], concerns over data privacy, algorithmic bias [34], the digital divide, and infrastructural limitations [39-41] often pose significant barriers to implementation. Additionally, issues such as resistance to new technologies, youth migration, and the sidelining of indigenous knowledge systems further complicate matters [42]. The high initial costs of deploying AI technologies create additional barriers to access [43,44].

While existing research has shed light on the transformative potential of AI in Indian agriculture, there remains a noticeable gap in comprehensive analyses. To harness the multifaceted benefits of AI adoption and its ability to enhance productivity, it is essential to create more integrated studies in this area. The research indicates that India stands to gain significantly from developing tailored strategies to effectively implement AI in agriculture. By proactively tackling potential challenges, these strategies could be essential in nurturing a more resilient and innovative agricultural sector.

3 Objectives of the study

- To examine the need for integrating Artificial Intelligence into agriculture.
- To identify and evaluate the strategies and technological interventions in agriculture.
- To analyze the challenges hindering the adoption of Artificial Intelligence in agriculture.

4 Imperative of Artificial Intelligence Adoption in Agriculture

The rise of artificial intelligence presents a remarkable opportunity to improve agricultural practices and transform farming into a more productive, efficient, and resilient system. Agriculture currently faces a twofold challenge: ensuring global food security while reducing environmental degradation, particularly as the population continues to grow [40]. AI is becoming increasingly vital in boosting agricultural productivity and spreading knowledge among farmers. AI-powered advisory systems provide valuable recommendations for various farming activities, which is especially beneficial for those who lack access to official extension services [34]. By delivering insights into crucial areas such as planting, irrigation, and harvesting, AI helps farmers make informed decisions that can significantly enhance their production. Furthermore, when paired with Internet of Things sensors, AI analytics improve farm monitoring and enable timely interventions, further optimizing agricultural practices [45].

Agricultural landscapes are often characterized by challenges such as resource and factor scarcity, climate variability, and market imbalances. While traditional knowledge is valuable, it may fall short in terms of speed, scalability, and predictive insight. This is where AI-based strategies come into play, offering innovative solutions that can significantly enhance agricultural practices. By leveraging these technologies, farmers can better respond to the intricate challenges they face. Importantly, AI should be viewed not as a replacement for indigenous knowledge but as a powerful complement to it, enhancing existing capabilities. AI systems can digitally encode indigenous knowledge by mapping it into datasets, validating traditional practices, preserving intergenerational experiences, and providing region-specific guidance over time. This integration of AI fosters a more proactive approach to addressing contemporary agricultural risks. Furthermore, by adopting AI, we can promote sustainable farming practices that protect the environment, thereby ensuring a healthier planet for future generations [46,47].

Advanced economies are leveraging artificial intelligence technologies to enhance agricultural practices. India has emerged as the world's third-most competitive nation in the global artificial intelligence landscape, propelled by rapid advancements in digital technologies, greater data availability, and a strategic emphasis on innovation within policy frameworks [48]. While the country excels in AI across various sectors, its potential in agriculture remains largely untapped. Key focus areas include increasing staple productivity, diversifying crops, enhancing farm worker productivity, and expanding food systems [49]. For India to excel in the global agricultural market, it's vital to adopt advanced AI tools to boost efficiency, crop yields, and data-driven decision-making. Investing in AI is essential for transforming India's agricultural landscape.

5 Strategies for Effective AI Integration in Agriculture

Agriculture encompasses essential activities for bringing crops to market, including soil preparation, sowing seeds, applying fertilizers, irrigating, and protecting crops from

pests. Post-harvest, proper storage and marketing are key to successful sales. Integrating artificial intelligence can enhance efficiency by providing customized strategies. Successful AI incorporation requires well-designed approaches that combine technology, stakeholder involvement, infrastructure development, and data-driven decision-making.

The initial phase of soil preparation includes evaluating the soil, ploughing, levelling, and applying manure. AI technologies enable autonomous machinery for ploughing and levelling [50]. Soil health prediction tools help identify essential nutrients, while geospatial analysis with satellite imagery assesses soil health [51]. The AI-powered Crop Selection Method (CSM) aids in choosing the best crop [52]. By analyzing various data sources, AI can improve yields and reduce costs. Precision agriculture leverages AI-driven sensors and UAVs to monitor soil health, select seeds, and determine water requirements, enabling farmers to make informed decisions to improve yield quality [35,53].

Choosing the right seeds is just the beginning; the next step is sowing. AI can help determine the best sowing times for optimal germination and yield. Automated methods, such as AI-enabled seed drills, use GPS for accurate seed placement, improving precision and lowering labour costs. These systems also assess nutrient levels, pH, and soil texture, using predictive analytics to monitor humidity, temperature, and soil quality [54]. Mobile AI chatbots, such as Plantix and KisanGPT, assist farmers with sowing guidance in local languages.

Adequate water is crucial for healthy crops, making irrigation essential in farming. Farmers use various irrigation sources, including wells, ponds, and canals. Traditional methods can be labor-intensive and time-consuming. However, advances in artificial intelligence have enhanced water conservation and crop growth, thereby increasing irrigation efficiency. Smart systems that use weather forecasts improve water management, while AI-powered controllers adjust watering automatically. Technologies such as smart drip and sprinkler systems deliver water directly to the roots more effectively, and AI can identify water stress, dry spots, or leaks. Apps like FarmAI, CropX, and IBM's Watson Decision Platform provide tailored irrigation practices for farmers [55].

There is a significant link between food and the health of individuals and communities, highlighting the growing importance of nutrition research. AI aids in identifying plant diseases, suggesting effective pest control, and recommending essential nutrients for optimal growth [56]. It minimizes errors typical of traditional methods and monitors soil and crops using drones, IoT, and satellite imagery. AI analyzes data to support targeted agricultural interventions, helping farmers achieve higher yields and make informed decisions [57-60]. Mobile agriculture apps also facilitate real-time tracking of farm operations, allowing for automated decision-making [61].

The harvesting phase involves the cutting and gathering of mature crops. While this process has traditionally been labor-intensive, the introduction of machinery (tractors and cultivators) has significantly boosted efficiency. Furthermore, AI-driven autonomous harvesting robots and advanced sensors streamline the process by precisely

identifying and harvesting ripe crops, helping to address labor shortages and improve agricultural practices [62,63].

The post-harvest phase is vital for maintaining crop quality and extending shelf life. By harnessing artificial intelligence, supply chain management can be significantly improved. AI helps to streamline logistics, reduce spoilage, and facilitate real-time inventory tracking. This means that fresh produce can reach the market quickly and in the best condition, benefiting both farmers and consumers. These innovations bolster food safety by monitoring freshness, improving hygiene, and reducing waste [64,65]. Ultimately, this leads to a more transparent supply chain, which reduces the need for human intervention [66].

Artificial Intelligence has demonstrated remarkable potential for optimizing a wide range of agricultural processes [67]. By harnessing AI-enabled technologies, farmers can significantly enhance crop productivity while simultaneously minimizing labour-related errors and reducing input costs [26,28,68]. Furthermore, these advanced systems improve operational timeliness, ensuring that agricultural practices keep pace with the ever-changing environmental conditions. Through precise forecasting, AI can effectively contribute to reducing greenhouse gas emissions. A dynamic AI model can adeptly schedule and respond to anticipated shocks, bolstering the resilience of agricultural systems [69]. To fully realize the transformative potential of AI in agriculture, a collaborative, multi-stakeholder approach is essential, as it can ensure that AI integration not only boosts agricultural production but also promotes sustainability and resilience within the sector [70,71].

6 Challenges of Artificial Intelligence Adoption in Agriculture

Although AI possesses significant potential to transform agriculture, its implementation is constrained by various structural, economic, and technical obstacles [72,18]. Comprehending these challenges is essential to formulating inclusive and sustainable frameworks for AI-driven agricultural advancements.

A significant barrier to the adoption of AI in agriculture is the lack of adequate digital infrastructure in rural areas. Many agricultural communities grapple with issues such as poor internet connectivity, inconsistent electricity supply, and the cost of smart devices [40], which can lead to low returns on investment [41]. Unfortunately, small and marginal farmers often struggle to afford these systems and have limited access to affordable loans, making it challenging for them to adopt AI solutions [73]. Additionally, digital illiteracy impedes access to these technologies, contributing to a digital divide that prevents many individuals from reaping the benefits AI can offer in agricultural practices [39].

Farmers' reliance on traditional agricultural practices has been identified as a significant barrier to the adoption of artificial intelligence in the sector [43,44]. Many view agriculture as a low-tech industry, which contributes to a lack of awareness and low levels of digital readiness among farmers. This reluctance to embrace new technologies is further exacerbated by a skills gap in operating and maintaining AI tools, which reduces confidence in using these advancements. Without targeted

capacity-building initiatives, the benefits of AI in agriculture may accrue primarily to larger-scale or more technologically adept farmers, potentially leaving others behind [74].

Large-scale AI integration requires institutional support and an extensive policy framework that provides clear rules for the use of AI, robust data governance, and ethical considerations. Challenges related to algorithmic bias, data manipulation [34], and the environmental sustainability of extensive automation have also emerged. Integrated policy measures are crucial for building trust and ensuring equal access to AI advancements among farmers [35].

Young, educated individuals are increasingly leaving agricultural communities in search of better opportunities [75,76]. As these young people migrate, the agricultural sector loses a vital group that is typically more willing to adopt new technologies and skilled in digital tools. Research indicates that 55.83 percent of rural youth are partially migrated, meaning they temporarily relocated for work—often during the off-peak agricultural seasons—before returning to their villages. In contrast, 44.17 percent have fully migrated, having permanently left their family's agricultural enterprise for urban areas, with non-agricultural employment as their primary source of income [77]. This shift leads to labor shortages during critical agricultural seasons, such as planting and harvesting, and to higher wage rates in rural areas [78]. The ongoing outmigration is contributing to the ageing of agricultural communities and creating a knowledge and expertise gap.

Tackling these challenges demands a united effort and shared commitment from agricultural communities, businesses, research institutions, and governments. The integration of indigenous knowledge with artificial intelligence is complex, and to forge a more inclusive and sustainable path for AI-driven agricultural advancements, we must prioritize investments in infrastructure, education, and regulatory frameworks.

7 Institutional Framework for AI Integration in Indian Agriculture

The integration of artificial intelligence into agriculture has emerged as a strategic priority for India in response to persistent challenges. The Government of India has increasingly embedded AI within its digital agriculture agenda through the creation of data-driven public infrastructure, AI-enabled advisory services, pest- and crop-surveillance systems, and precision farming initiatives. These interventions reflect an emerging policy architecture that seeks to integrate data, analytics, and institutional coordination to enhance productivity, sustainability, and farmer welfare [70].

The Government of India has launched a series of strategic initiatives to integrate artificial intelligence into the agricultural sector as part of its broader digital transformation agenda [79]. At the heart of these efforts is the Digital Agriculture Mission, which aims to establish robust digital public infrastructure through platforms such as AgriStack and the Krishi Decision Support System (KDSS). This initiative also encompasses integrated databases for farmers and land, facilitating data-driven policymaking and personalized advisory services [80].

To address information gaps, AI-powered tools, such as the Kisan e-Mitra chatbot, have been introduced, providing real-time, multilingual assistance to farmers on schemes, subsidies, crop insurance, and best practices. Furthermore, the National Pest Surveillance System (NPSS) employs AI and image analytics for the early detection of crop pests and diseases, thereby significantly reducing yield losses [81].

The government is also promoting AI-driven weather forecasting and climate advisory systems to enhance resilience against climate change and support informed decisions regarding sowing and irrigation. To further advance precision agriculture, initiatives employing drone-based monitoring, remote sensing, soil health mapping, and predictive analytics are encouraged to optimize resource use and enhance productivity [69,28].

Support for these initiatives is bolstered by the establishment of AI Centres of Excellence, public-private partnerships, and the overarching IndiaAI Mission, which demonstrates a significant national commitment to fostering a comprehensive indigenous AI ecosystem [79]. Together, these initiatives signify a coordinated effort by the government to leverage AI for improving productivity, sustainability, risk management, and farmer welfare across Indian agriculture.

8 Conclusion

India, home to approximately 18 percent of the world's population, faces low food production [82]. This highlights the need for new farming technologies, such as AI-driven precision agriculture and smart irrigation, to improve food security and farmers' incomes. However, barriers such as poor digital infrastructure, high costs, and skill gaps hinder their adoption.

Social norms influence farmers' decisions [83]. Engaging communities and strengthening Self-Help Groups (SHGs) and Farmer Producer Organizations (FPOs) can help. Better communication and sharing agricultural information can also boost AI adoption [84,85].

Training programs can teach farmers modern methods and tools [86]. Involving youth and providing financial support, such as subsidies and easier credit, are crucial for encouraging AI adoption and investment. Ongoing monitoring ensures these efforts benefit farmers and support economic growth.

Digital technologies are transforming agriculture [87], improving productivity and sustainability. A collaborative strategy involving farmers, tech providers, researchers, and policymakers is crucial for creating a future-ready agricultural ecosystem. Promoting AI adoption in agriculture requires financial support, knowledge integration, community engagement, and the attraction of young talent.

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