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Artificial intelligence in agriculture: A review of applications, challenges and future directions

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Abstract
The integration of artificial intelligence (AI) in agriculture has the potential to revolutionize the way we produce, manage and distribute food. This review paper provides a comprehensive overview of the current state of AI applications in agriculture, highlighting its uses in crop management, livestock monitoring, precision farming and supply chain optimization. We discuss the various AI techniques employed including machine learning, deep learning and computer vision and examine their impact on agricultural productivity, efficiency and sustainability. The paper also explores the challenges and limitations of AI adoption in agriculture, including data quality, infrastructure and expertise. Finally, we outline future directions for research and development emphasizing the need for interdisciplinary collaboration, data sharing and tailored solutions for diverse agricultural contexts. This review aims to provide a valuable resource for researchers, policymakers and practitioners seeking to harness the power of AI in agriculture.

Keywords: FarmVibes.AI, CNN, Sowing App, ICRISAT, autonomous bots

1. Introduction

Artificial Intelligence (AI) is transforming agriculture, one practice of humanity's oldest, by augmenting farming knowledge with understandings driven by data and solutions automated. AI technologies are being integrated with agriculture so that farmers can increase efficiency, sustainability, and productivity, which helps solve climate change, resource scarcity, and rising global food demand. AI applications are transforming all aspects of crop management to livestock monitoring (Sivarethinamohan *et al*. 2021) [22]. Agriculture has undergone an outstanding transformation from manual practices, based on intuition, to operations driven by data, and improved by technology. This evolution represents a fundamental shift in the way how farmers approach cultivation, management of resources, and processes for decision-making.

1.1 From Traditional to Precision Agriculture

Farming practices of the customary kind, combined with manual labour, have been superseded via farming approaches with precision that leverage the technologies that are cutting-edge. Precision agriculture uses AI, machine learning, together with sensors, as well as data analytics in order to optimize crop management and resource utilization (Stock and Gardezi, 2021) [24]. This technological adventure has enabled a gradual incorporation of AI tools that empower farmers to make data-directed decisions instead of relying solely on experience or guesswork. As Microsoft's Ranveer Chandra notes, "Digital agriculture promises help to address many of the global challenges facing agriculture. Digitization of the food system, with data and AI, can enable greater efficiency, transparency, profitability and equity".

1.2 Yield Prediction and Crop Planning

AI has revolutionized yield prediction, enabling farmers to make better-informed decisions about planting, harvesting, and resource allocation. Using multimodal AI, which combines several types of data, farmers can receive advice about what to plant, when to plant it, when to provide fertilizers, and when to harvest. Tools like Microsoft's FarmVibes.AI offer features such as soil and yield maps and what-if analyses, allowing farmers to assess potential yields on their farms and plan effective growth strategies. Generative AI algorithms analyse vast amounts of historical data, including climate patterns, soil conditions, and crop characteristics, to accurately predict crop yields and help farmers optimize their operations. By considering variables such as temperature, rainfall, nitrogen levels, and disease prevalence, these AI models provide valuable insights that enable better planning and resource management.

2. Literature Review

India, being an agrarian economy, has seen a growing interest in integrating Artificial Intelligence (AI) into agricultural practices to address longstanding challenges such as unpredictable weather patterns, pest infestations, and inefficient resource use. In recent years, both government initiatives and private sector innovations have accelerated the deployment of AI-based solutions tailored to the Indian context.

2.1 Precision Agriculture in India has been a major focus of AI integration. According to Bijarniya *et al*. (2020) [3], AI models combined with remote sensing and GIS technologies have enabled site-specific nutrient management and optimal input use in crops like wheat and rice in Punjab and Haryana. Some new startups use AI and satellite data to provide actionable insights to farmers on crop health, water stress, and sowing times, especially in resource-constrained rural settings.

2.2 Crop Disease Detection is another key application area. A study by Patil and Patil (2021) [18] demonstrated the use of convolutional neural networks (CNNs) to identify the process of disease detection through images of the cotton plant. This new system with accuracy and efficiency turned out to be an improvement in the production of the crop.

2.3 Smart Irrigation and Water Management are critical for a water-stressed country like India. AI-powered systems are being used to optimize irrigation schedules by analysing data from soil moisture sensors, weather forecasts, and evapotranspiration rates.

2.4 Government and Industry Initiatives have further encouraged AI adoption. The Indian Council of Agricultural Research (ICAR) and the Ministry of Agriculture have partnered with tech companies to pilot AI-based projects in rural areas. Microsoft's AI Sowing App, developed in collaboration with International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), provided personalized sowing advisories to farmers in Andhra Pradesh, leading to a reported 30% increase in crop yield (Microsoft, 2018) [17].

3. Process of Artificial Intelligence in agriculture

The effectiveness of artificial intelligence (AI) in addressing agricultural challenges is largely dependent on the quality and accessibility of data. AI is increasingly regarded as a transformative technology with the potential to revolutionize agriculture. However, one significant challenge lies in acquiring relevant data at the farmer level. The integration of image classification techniques with both remote and local sensing data can revolutionize the efficiency of farm machinery—particularly in weed control, early disease detection, crop harvesting, and product grading. These AI-driven solutions enable continuous, round-the-clock monitoring of high-value crops.

Horticultural practices require meticulous monitoring throughout all stages of plant development. Leveraging data from precision agriculture software, soil sensors, analysis drones, and even smartphone images, AI systems can continuously evaluate soil nutrient levels. These insights are compared with historical data from high-yielding crops to determine optimal conditions. Additionally, AI can assess the environmental impact of varying fertilizer types and dosages, helping to identify the most sustainable and effective application methods. These practices contribute to more environmental friendly farming. As pollution and climate variability continue to rise, farmers face growing uncertainty, especially regarding optimal planting times. AI addresses these concerns by analysing the effects of weather, sunlight, wind, and precipitation on crop cycles, providing timely forecasts that support better planting decisions.

Technological advancements in computer vision, AI, and machine learning have enabled the development of remote sensing tools for the identification and management of crops, pests, weeds, and diseases. These technologies offer unprecedented opportunities for precision seeding and fertilization. AI tools assist farmers in minimizing waste, enhancing product quality, and ensuring quicker market access. Autonomous GPS-enabled tractors now prepare fields for planting and harvesting without human intervention, while drones collect real-time data, monitor crop health, and transmit vital insights.

AI systems can identify key plants in a field and support targeted pest management by recommending appropriate pesticide types and quantities. Drones further facilitate this by applying pesticides efficiently, saving time and reducing labour costs. Predictive analytics can also estimate precipitation and evapotranspiration. Combined with soil sampling and other data sources, machine learning models generate valuable insights into soil moisture, temperature, and condition. This enables more efficient irrigation, improving both environmental sustainability and farm profitability (Camarena, 2020) [27]. Such smart systems support automated monitoring of field conditions, resulting in a less labour-intensive and more resource-efficient agricultural model. By addressing variability within fields, these technologies ensure crops receive exactly what they need, optimizing yields, fertilizer use, and profitability. Precision agriculture not only boosts productivity and efficiency but also promotes sustainability and environmental conservation.

Globally, numerous companies are adopting AI to enhance the efficiency of agriculture-based industries. As societies transition from agrarian to urban lifestyles, labour shortages in farming have become increasingly prominent. Traditional agriculture requires human labour for tasks such as seeding, irrigation, harvesting, and weeding. AI addresses these issues through automation. Companies are developing autonomous bots to perform labour-intensive tasks, effectively augmenting the human workforce and delivering higher productivity, faster operations, reduced costs, and improved output quality.

AI applications in agriculture extend to disease prediction, soil retention assessment, pesticide and nutrient loss evaluation, and even poultry fertility monitoring (Javaid *et al*., 2023) [11]. The strategic use of AI offers farmers enhanced decision-making capabilities, leading to improved crop and livestock production. The success and reliability of AI in agriculture serve as indicators of progress in the sector, highlighting its potential for future growth.

Over the past decades, various industries have explored AI integration. However, its capacity to enhance agricultural decision-making has only recently gained significant recognition. As a relatively new but rapidly growing field, AI is proving vital in agricultural research by enabling data-driven insights and smarter farming practices. AI enhances human intellect through the development of theories, methodologies, algorithms, and practical applications. Given the vast scale and complexity of big data—often beyond the capabilities of conventional data-processing systems—AI leverages machine learning (ML) algorithms to extract valuable insights. These insights help in understanding crop growth patterns, identifying potential diseases, recommending specific fertilizers or pesticides based on disease profiles, and predicting diseases by analysing changes in leaf growth, plant size, or coloration. To facilitate this, AI systems utilize various sensors, including feed sensors, weight sensors, soil sensors, temperature sensors, light intensity sensors, and different types of cameras. These sensors can be integrated into machines such as low-flying drones or compact robots that navigate the fields, enabling real-time monitoring and data collection for informed agricultural decision-making.

4. Enhancing crop productivity with AI

AI is a crucial driver of future agricultural productivity, as it can greatly enhance farming efficiency. Specifically, AI contributes to genetic advancement, optimal resource utilization, and practical implementations, all of which boost crop yields while strengthening resistance to environmental stresses (Aijar *et al*., 2025) [1]. AI is playing an increasingly important role in crop breeding and genetic modification. It helps scientists develop crop varieties that are better equipped to handle diseases, pests, and extreme environmental conditions. By analysing large sets of genetic and environmental data, AI can predict which genetic modifications are most likely to succeed in improving crop yields. This speeds up the breeding process and increases the chances of producing viable, resilient crops (Hafeez *et al*., 2023) [10]. For example, AI can help identify genes linked to drought resistance, making it possible to engineer crops that thrive even in areas where agriculture was previously not feasible. This could significantly improve agricultural productivity. But drought resistance isn't the only target—AI also supports the discovery of traits like better nutrition, faster growth, and reduced need for fertilizers and pesticides. These advancements offer real hope for creating more sustainable and nutritious crops that can adapt to changing climates.

When combined with gene-editing tools like CRISPR, AI becomes even more powerful. Together, they can help develop crops that are not only high-yielding and climate-resilient but also tailored to meet the growing global demand for food. Beyond genetics, AI is revolutionizing how farmers manage resources. It improves the efficiency of using water, fertilizers and pesticides by using data from soil sensors, weather forecasts, and crop health indicators. For instance, AI-powered irrigation systems can automatically adjust water levels based on soil moisture, ensuring crops get exactly what they need without any wastage (Talaviya *et al*., 2020) [25].

AI also allows for the precise application of fertilizers and pesticides, reducing overuse and its negative effects on soil and water quality. With real-time data on soil nutrients and pest levels, AI can recommend exactly how much input is needed for each section of a field. This targeted approach not only conserves resources but also promotes more sustainable farming practices, helping to reduce the environmental footprint (Katiyar, 2022) [13]. As these technologies continue to evolve, AI will play an even greater role in balancing agricultural productivity with environmental sustainability, contributing to long-term global food security (Kugler, 2022) [14].

5. Agricultural AI in emerging Economies

AI-powered technologies are already well-established in wealthier countries, but they're also starting to gain traction in emerging economies (Cook and O'Neill, 2020) [6]. Farmers in these regions often struggle due to limited access to timely information—things like accurate weather forecasts, pest outbreaks, or market trends. AI tools can help bridge this gap by offering valuable insights and recommendations. These tools can guide farmers on managing risks, improving efficiency, reducing costs, and deciding the best times for planting and harvesting based on real-time market dynamics (Cook and O'Neill, 2020) [6]. This kind of support is especially helpful for small-scale farmers trying to compete in a complex marketplace.

There's growing optimism that AI will help level the playing field for farmers in emerging economies by reducing information imbalances in regional and global markets. AI systems that analyse external factors—like consumer demand, crop prices, and aesthetic preferences—can help farmers make better business decisions (Dharmaraj and Vijayanand, 2018) [7]. In fact, farmers in lower-income areas are already starting to benefit from AI-based mobile apps and platforms. While many AI devices are expensive, mobile apps are relatively affordable and more accessible for farmers with limited income (Mhlanga, 2021) [16]. These apps can support farmers with tasks like securing supply contracts, monitoring livestock health, and improving food safety. By collecting and analysing farm data, AI can offer personalized advice on what actions to take. It can also track product volume and quality throughout the supply chain—information that's particularly valuable for investors and lenders (Cook and O'Neill, 2020) [6]. This improved traceability allows farmers to access premium markets when their product quality meets required standards (Cook and O'Neill, 2020) [6].

Machine learning also plays a key role by generating credit scores and pricing models that reduce the knowledge gap between farmers and other stakeholders in the value chain. It even helps small farmers qualify for microloans and insurance (Cook and O'Neill, 2020) [6]. These systems assist lenders in evaluating a farmer's financial health and the sustainability of their operations. By reducing information and market asymmetries and tailoring solutions to local needs, AI has the potential to boost agriculture in emerging economies without putting extra strain on the environment.

Ultimately, AI can be a powerful tool for reducing poverty. It helps farmers grow more with fewer resources, improve the quality of their produce, and get products to market faster (Mhlanga, 2021) [16]. Research by Awasthi (2020) [2] found that planting at the right time—guided by AI—can increase yields by 30-40%. In India, introducing AI on 175 farms led to a 30% jump in yield per hectare (Dharmaraj and Vijayanand, 2018) [7].

AI apps can also make farming more inclusive. They often include features like translation, text-to-speech, and image analysis—making it easier for farmers to interact with technology regardless of literacy levels. For example, by uploading images of crops, farmers can receive advice on optimal sowing, irrigation, and harvesting schedules (Cook and O'Neill, 2020) [6].

However, the success of AI in agriculture depends heavily on infrastructure. Reliable internet access, transport networks, irrigation systems, and data protection are all necessary for AI tools to function effectively (Cook and O'Neill, 2020). In many poorer or remote areas, these resources are still lacking, which remains a significant barrier (Eli-Chukwu, 2019). Overcoming these challenges is essential for farmers in developing countries to fully benefit from AI.

6. Social and Ethical aspects of AI in agriculture

As artificial intelligence takes root in agriculture, it brings both promise and peril—reshaping farms in ways that could uplift or undermine the very people who feed us. While AI offers tools to boost yields and protect farmers from hazardous work, its ethical implementation remains thorny, demanding careful stewardship to ensure technology serves humanity, not the other way around.

AI can shield farmers from dangers—automating pesticide spraying to reduce chemical exposure (Rodzalan *et al*., 2020) [19] or preventing accidents with smart machinery (Vasconez *et al*., 2019) [26]. Yet these advances introduce new risks: hackers could sabotage digital farms (Carolan, 2020) [5], and distancing farmers from hands-on work might encourage riskier practices, like overusing pesticides because robots bear the immediate harm (Gardezi and Stock, 2021) [9]. Many farmers face a Faustian bargain when adopting AI. Restrictive contracts lock them into proprietary systems, forbidding repairs or modifications —a modern-day version of the "tractor monopoly" battles of the past. Worse, some are pressurized to surrender decision-making to algorithms, trusting AI's "scientific authority" over generations of hard-won intuition (Ryan, 2023) [21].

The digital revolution in farming risks leaving many behind-while big agribusinesses race ahead with smart tractors and AI analytics, small family farms struggle with expensive technologies as they can't afford or understand. Across the world, we are seeing the same old divides play out again: wealthy farms automate while poorer ones keep doing backbreaking work by hand, and women farmers-already overlooked-get pushed further to the margins. What's worse, the very data farmers generate about their own fields-soil health, crop yields, weather patterns-is being snatched up by corporations who profit from it while the farmers themselves lose control. Imagine working your land for decades only to have some algorithm tell you how to farm-and then charge you for the advice! But there's a better way: by putting farmers at the heart of designing these tools, fighting for their right to fix their own equipment, making technology affordable for all, and protecting farm data like the precious resource it is, we can ensure AI becomes a tool for empowerment rather than exploitation. After all, technology should serve those who feed us, not the other way around. AI should not be a force that dis-empowers farmers—it should be a tool they wield with confidence. As we navigate this transformation, the measure of success isn't just efficiency, but equity: technology must enrich the hands that feed the world, not strip away their dignity. The future of farming must be grown from human wisdom, not just algorithms.

7. The Future of Farming: When AI Meets Human Wisdom

The fields of tomorrow won't just be worked by human hands—they'll hum with intelligent machines. Research suggests that by 2030, nearly all manual pesticide application and repetitive farm labour could be automated (Rotz *et al*., 2019) [20]. But this is not just about replacing muscle with machinery. The real revolution lies in AI systems that can analyse, predict, and even make decisions—tasks we've always considered the exclusive domain of experienced farmers and agricultural experts. Yet for all their processing power, these systems still lack something vital: human judgment. The kind of wisdom that knows when to ignore the data—when a farmer's gut feeling about changing weather patterns trumps what the algorithm predicts, or when an advisor spots something in the soil that sensors miss. This is why, even as AI transforms agriculture, we're seeing new roles emerge that blend technical skills with deep agricultural knowledge.

The Changing Face of Farm Work

- **From Hands to Heads:** Farm jobs are shifting from backbreaking labour to roles requiring data literacy and tech skills. Workers who once spent days in fields now monitor drone feeds and interpret AI recommendations (Smith, 2020) [23].
- **The Rise of Digital Farm Coaches:** A new generation of advisors is emerging—part agronomist, part data scientist—who can translate AI insights into practical farming decisions (Lassoued *et al*., 2021) [15].
- **Bridging Language Barriers:** AI translation tools are making it easier for migrant workers to contribute, potentially creating more flexible labour markets (Smith, 2020) [23].

But this transition isn't without its challenges. As farms become more technologically advanced, they require workers who can operate complex systems—a steep learning curve for many in the agricultural workforce. And while AI creates new opportunities for skilled labour, we can't ignore those whose traditional jobs may disappear.

The Human Edge in an AI World

Even the most advanced farm robots still struggle with basic human competencies. Current AI lacks "object permanence"—the understanding that things exist even when we can't see them (Kakani *et al*., 2020) [12]. A self-driving tractor might navigate perfectly around visible obstacles, but can't account for what lies just beyond its sensors. This limitation becomes dangerous when dealing with living systems—where a momentary glitch could harm livestock or damage ecosystems. The future of farming is not about choosing between humans and AI—it's about finding the right balance. AI can handle repetitive tasks and process vast amounts of data, but we will always need human expertise to make ethical judgments when algorithms suggest questionable practices, adapt to unexpected situations which no training data could predict and to maintain the wisdom of generations of farming knowledge. As we stand at this technological crossroads, one thing is clear: the most successful farms of the future won't be those that replace humans with machines, but those that best combine artificial intelligence with human wisdom. The challenge before us isn't just technological—it's about ensuring this transition benefits all who work the land, from the tech-savvy farm manager to the seasonal worker learning to collaborate with robotic helpers.

8. Conclusion

While AI's transformative potential echoes across industries—from healthcare to manufacturing—its application in agriculture carries unique weight. As the foundation of human survival, farming demands an especially thoughtful integration of emerging technologies. Our research reveals how AI can revolutionize food production through precision agriculture, predictive analytics, and autonomous systems that optimize yields while conserving precious resources. Yet these technological advances arrive with complex challenges: the threat of corporate monopolies locking farmers into restrictive systems, valid concerns about data privacy and ownership, and the risk of widening disparities between high-tech agribusinesses and smallholder farmers. The stakes couldn't be higher—with climate change intensifying and global populations growing, we must implement agricultural AI through an interdisciplinary lens that balances innovation with equity. This requires technologists co-designing tools with farmers, policymakers safeguarding fair access, and researchers addressing gaps in livestock and fisheries applications. The impact will ripple far beyond fields and orchards, transforming entire supply chains from soil to supermarket. But technology alone won't solve our food security challenges—we need systems that empower farmers as stewards of both their land and their data. By combining cutting-edge AI with generations of agricultural wisdom, we can cultivate a future where sustainable farming practices nourish both people and the planet. The seeds of this transformation are being planted today; how they grow depends on our collective commitment to responsible innovation that serves all who depend on the land—farmers, consumers, and ecosystems alike.

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