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A Comprehensive Review on Future of Smart Farming and Its Role in Shaping Food Production

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Author's contribution

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

ABSTRACT

The advent of smart farming represents a pivotal shift in agricultural practices, integrating advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, and gene editing to enhance food production efficiency, sustainability, and global food security. This comprehensive review explores the multifaceted dimensions of smart farming, including its

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implementation across diverse global contexts, the profound impacts on food production, the challenges and concerns associated with its adoption, and the prospective future directions shaped by emerging technologies and innovations. By analyzing case studies and current research, the review highlights how precision agriculture, IoT sensors, and data analytics have significantly increased crop yields and resource use efficiency, underscoring the role of smart farming in promoting sustainable agricultural practices and reducing environmental footprints. However, the adoption of smart farming technologies is not without challenges, including technical limitations, data privacy and security concerns, socio-economic and ethical considerations, such as job displacement and animal welfare. The review also discusses the crucial role of government policy, international collaboration, and education in facilitating the adoption of smart farming technologies and addressing these challenges. As the agricultural sector stands on the brink of a technological revolution, this review emphasizes the need for continuous innovation, robust support frameworks, and inclusive strategies to ensure that the benefits of smart farming are realized equitably across the global agricultural landscape, paving the way for a more sustainable and secure food future.

Keywords: Smart farming; sustainability; IoT; robotics; precision agriculture; gene editing.

1. INTRODUCTION

The evolution of agriculture from traditional practices to smart farming is a testament to human innovation in pursuit of efficiency and sustainability. Traditional farming, characterized by manual labor, rudimentary tools, and empirical knowledge of farming practices, has been the backbone of agriculture for millennia. Over time, the agricultural sector has witnessed significant transformations, notably the Agricultural Revolution and the Green Revolution, which introduced mechanized tools, chemical fertilizers, and improved crop varieties to increase food production [1]. However, these advancements also brought challenges, including environmental degradation, increased use of non-renewable resources, and social inequalities. Smart farming represents the next leap in agricultural evolution, integrating Information and Communication Technology (ICT) into farming practices. Defined as the application of IoT, AI, robotics, and digital technologies in agriculture, smart farming aims to enhance productivity, sustainability, and profitability [2]. IoT devices, such as sensors and drones, collect data on soil moisture, crop health, and environmental conditions. AI and machine learning algorithms analyze this data to inform decisions on planting, watering, and harvesting. Robotics automates labor-intensive tasks, reducing the need for human labor and increasing precision in activities such as planting, weeding, and harvesting. The significance of smart farming extends beyond mere technological advancement; it addresses pressing global challenges. With the world population projected to reach 9.7 billion by 2050, food production must increase significantly to meet demand [3]. Smart farming offers a pathway to increase food production while minimizing environmental impacts. By optimizing resource use and reducing waste, smart farming practices contribute to sustainability and climate change mitigation efforts. Additionally, smart farming technologies can enhance food security by increasing crop yields and reducing losses due to pests, diseases, and environmental factors.

2. SMART FARMING TECHNOLOGIES

2.1 Precision Agriculture

Precision agriculture (PA) represents a farm management concept focused on observing, measuring, and responding to inter and intra-field variability in crops. The goal of PA is to optimize returns on inputs while preserving resources. It encompasses precision planting, irrigation, and fertilization techniques [4]. The benefits of precision agriculture include enhanced efficiency in the use of water, fertilizers, and pesticides, which in turn can lead to increased yields and reduced environmental impact. Technologies like GPS-guided tractors, variable rate technology (VRT), and soil and yield mapping allow for the precise application of inputs based on the specific needs of each part of the field. For example, VRT adjusts the amount of inputs applied to different areas, optimizing the growth conditions for crops [5].

2.2 IoT and Sensor Technologies

The Internet of Things (IoT) and sensor technologies have become integral to modern agriculture, enabling real-time monitoring and management of agricultural environments. [6]. The use of IoT and sensors facilitates precision agriculture by providing detailed, real-time information about the conditions of crops and their environment. This data-driven approach allows for more accurate and timely decisions regarding irrigation, fertilization, and pest control, leading to more efficient resource use and improved crop yields.

2.3 Robotics and Automation

Robotics and automation in agriculture include the use of drones, autonomous tractors, and robotic harvesters. These technologies are revolutionizing farming by reducing the need for manual labor and increasing the efficiency and precision of agricultural tasks. Drones, for example, are used for aerial imaging, crop monitoring, and even targeted pesticide application, while autonomous tractors and robotic harvesters can perform planting, weeding, and harvesting with minimal human intervention [8]. The adoption of robotics and automation in agriculture can lead to significant labor cost savings and improvements in operational efficiency. These technologies also have the potential to increase crop yields and reduce waste by optimizing the timing and execution of agricultural tasks.

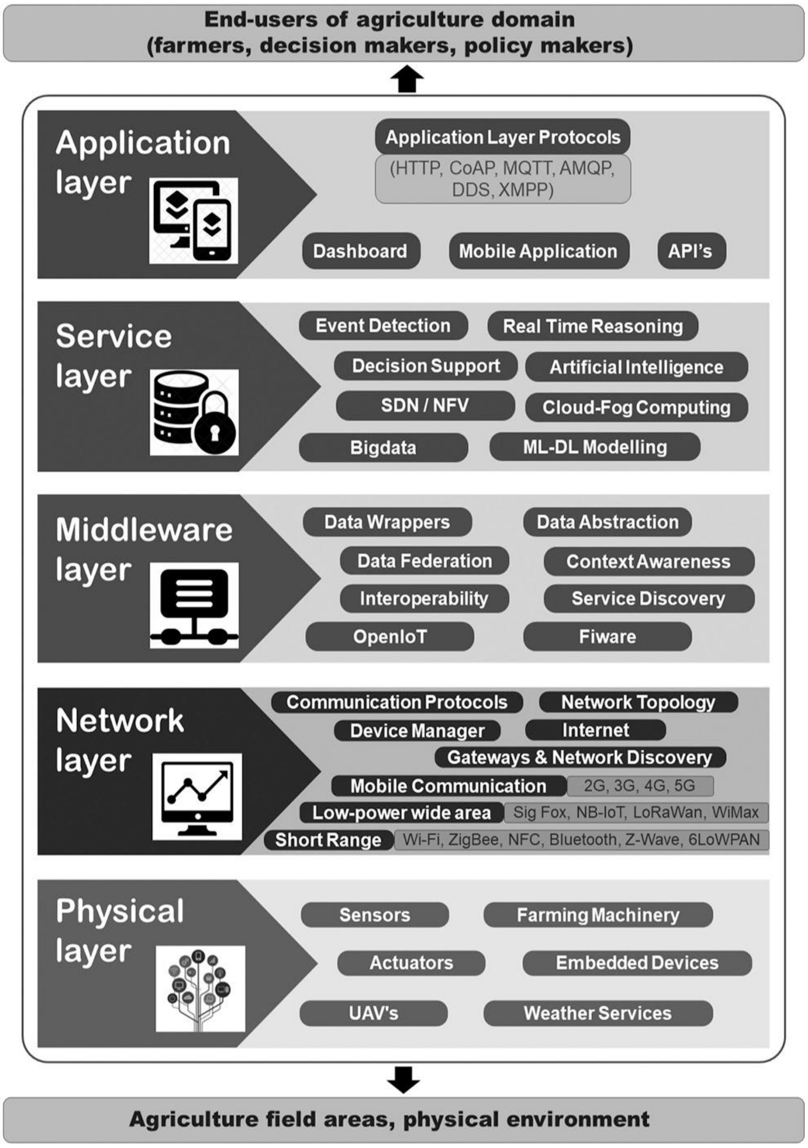

Fig. 1. Layered architecture of agriculture internet of things [7]

Table 1. Smart Farming Technologies

Technology	Description	Benefits	Applications
Precision Agriculture	Utilizes GPS, sensors, and data analytics to optimize farm management and crop production.	Increases yield, reduces waste, improves resource efficiency.	Soil sampling, yield mapping, variable rate application.
IoT and Sensors	Network of physical devices embedded with sensors, software, and other technologies.	Real-time monitoring of environmental conditions, crop health.	Soil moisture tracking, climate control in greenhouses.
Robotics and Automation	Machines and systems that perform tasks without human intervention.	Reduces labor costs, increases precision and efficiency in farming operations.	Autonomous tractors, drones for spraying, robotic harvesters.
Data Analytics and AI	Advanced algorithms that analyze data from various sources to make predictions and inform decisions.	Optimizes decision-making, enhances productivity, predicts trends.	Crop prediction, pest detection, yield optimization.
Blockchain	Distributed ledger technology for transparent and secure transaction recording.	Enhances traceability and transparency in the supply chain, increases trust and efficiency.	Supply chain management, smart contracts, product traceability.

2.4 Data Analytics and AI

Big data and artificial intelligence (AI) are being increasingly utilized in agriculture for predictive analytics. By analyzing large datasets collected from IoT devices and other sources, AI algorithms can predict optimal planting times, identify potential pest invasions, and recommend precise amounts of water and nutrients needed for crops [9]. The use of data analytics and AI in agriculture supports more informed decision-making, leading to improved crop management, pest control, and yield optimization. Predictive analytics can also help in mitigating risks associated with weather and changing climate conditions, enhancing the resilience of agricultural systems.

2.5 Blockchain for Supply Chain Management

Blockchain technology offers a novel approach to enhancing traceability and transparency in the agricultural supply chain. By providing a secure and immutable ledger for recording transactions, blockchain can help in tracking the production, processing, and distribution of agricultural products [10]. The implementation of blockchain in the agricultural supply chain can lead to increased consumer trust, as it provides verifiable information on the origin and safety of food products. Furthermore, it can improve efficiency in the supply chain by reducing paperwork and streamlining transactions, potentially leading to cost savings for farmers and suppliers.

3. IMPLEMENTATION AND CASE STUDIES

3.1 Global Implementation

In the United States, the adoption of precision agriculture has been propelled by the need to increase efficiency and reduce costs. Technologies such as GPS-guided tractors and drones for aerial imaging have become commonplace. For instance, the use of Variable Rate Technology (VRT) has allowed farmers to apply fertilizers and water precisely where they are needed, significantly reducing waste and environmental impact [11]. In Europe, smart farming technologies are being integrated into the agricultural sector with a strong emphasis on sustainability and reducing the carbon footprint. The European Union’s Horizon 2020 program has funded projects like IoF2020, which explores the use of IoT in farming across various European regions. In India, digital technologies are revolutionizing agriculture through initiatives like Digital India. Mobile apps and remote sensing technologies are used for soil health monitoring and crop advisories, directly impacting smallholder farmers' productivity [12].

In Africa, projects like the Precision Agriculture for Development (PAD) are leveraging mobile technology to provide farmers with actionable agricultural advice, showing significant improvements in yields and income [13].

3.2 Success Stories

In California, the use of sensor networks for vineyard management has led to a 25% reduction in water usage while maintaining the same level of crop yield. This is a prime example of how precision irrigation can lead to significant water savings in agriculture [14]. In Kenya, smallholder farmers have increased their maize yields by up to 30% through the adoption of precision farming techniques facilitated by the Connected Farmer Alliance, a partnership between Vodafone, USAID, and Techno Serve. The use of drones in Brazil for crop monitoring and pesticide application has reduced costs by up to 20% and increased yields, demonstrating the potential of UAV technology in large-scale farming operations [15].

3.3 Barriers to Adoption

The initial investment required for smart farming technologies can be prohibitive for small to medium-sized farms. High costs associated with purchasing and maintaining advanced equipment like drones or autonomous tractors can limit their adoption [16]. There is a significant knowledge gap in operating sophisticated farming technologies, particularly in regions where education and training opportunities are limited. Farmers must be trained to interpret data collected from sensors or to operate automated machinery effectively. Adequate infrastructure, such as reliable internet connectivity and electricity, is crucial for the successful implementation of smart farming technologies. In many rural areas, especially in developing countries, this infrastructure is lacking or non-existent [17].

4. IMPACT ON FOOD PRODUCTION

4.1 Increased Efficiency and Productivity

Precision agriculture technologies, such as GPS-guided equipment and variable rate technology (VRT), allow for the precise application of water, fertilizers, and pesticides, reducing waste and increasing the efficiency of resource use. Studies have shown that precision agriculture can significantly increase crop yields by ensuring that crops receive exactly what they need for optimal growth [18]. IoT devices and sensors monitor crop health and environmental conditions in real-time, allowing for timely interventions that can prevent crop failures and enhance productivity. For example, soil moisture sensors can optimize irrigation schedules, leading to better water use efficiency and higher yields. AI and machine learning algorithms analyze vast amounts of data to make predictions and provide recommendations for crop management. This can lead to optimized planting schedules, improved pest and disease management, and ultimately higher yields [19].

4.2 Sustainability and Environmental Benefits

Smart farming technologies contribute to the conservation of vital resources. For instance, precision irrigation techniques can significantly reduce water usage in agriculture, contributing to water conservation efforts [20]. By precisely targeting the application of fertilizers and pesticides, smart farming reduces the volume of chemicals released into the environment, lowering the risk of pollution and protecting biodiversity. Smart farming practices can contribute to reducing the carbon footprint of agriculture by optimizing farm operations and reducing the need for mechanical soil tillage, thus lowering greenhouse gas emissions [21].

4.3 Economic Implications

The adoption of smart farming technologies often requires significant initial investment, but the increase in efficiency and productivity can lead to substantial returns. For instance, the implementation of precision agriculture has been shown to increase profitability through higher yields and reduced input costs [22]. The integration of automation and robotics in farming can lead to changes in the agricultural labor market. While some manual labor jobs may be reduced, there is an increasing demand for skilled workers who can operate and maintain advanced technologies [23]. Small and medium-sized farms may face challenges in adopting expensive smart farming technologies, potentially leading to increased market consolidation. However, cooperative models and government subsidies can help in leveling the playing field [24].

5. CHALLENGES AND CONCERNS

5.1 Technological Limitations and Compatibility Issues

Despite rapid advancements, smart farming technologies face limitations in terms of scalability, reliability, and durability under various environmental conditions. The integration of new technologies into existing farm systems often presents compatibility issues, necessitating additional modifications or upgrades [25]. The need for continuous innovation is imperative to overcome these challenges. However, this requires significant ongoing investment in research and development (R&D), which can be a barrier for small to medium-sized enterprises (SMEs) and developing countries with limited resources [26].

5.1.1 Data privacy and security

The collection and use of data in smart farming raise significant privacy and security concerns. Questions about data ownership, control, and sharing remain largely unresolved, leading to potential conflicts between farmers, technology providers, and third parties [27]. The risk of cyber-attacks on agricultural data systems can have far-reaching consequences, from the loss of critical operational data to the disruption of food supply chains. Ensuring the security of these systems against such threats is a major challenge [28].

6. FUTURE DIRECTIONS

The next generation of AI models is poised to offer unprecedented predictive analytics, enabling more precise crop management, disease prediction, and yield optimization. Advanced AI could automate decision-making processes, analyzing data from various sources to provide real-time, actionable insights to farmers [29]. Gene editing technologies, like CRISPR/Cas9, offer the potential to revolutionize crop breeding by making plants more resistant to pests and diseases, tolerant to adverse environmental conditions, and capable of higher yields. This could significantly contribute to food security while reducing the need for chemical inputs [30].

6.1 Policy and Regulation

Effective government policies are crucial for fostering the adoption of smart farming technologies. Policies can provide the necessary infrastructure, financial incentives, and regulatory frameworks to encourage farmers to invest in new technologies. For example, subsidies for precision farming equipment or tax incentives for sustainable farming practices can lower the barriers to entry for small-scale farmers [31]. International collaboration can play a significant role in addressing global challenges such as food security and climate change. Collaborative efforts can facilitate the exchange of knowledge, technologies, and best practices. Initiatives like the Global Open Data for Agriculture and Nutrition (GODAN) support the sharing of agricultural and nutritional data across borders to enhance global food security [32].

6.2 Education and Training

As smart farming technologies become increasingly sophisticated, the need for specialized education and training programs becomes more critical. Farmers and agricultural professionals must understand how to integrate and utilize these technologies effectively to maximize their benefits. This includes not only technical skills but also data analysis and decision-making skills [33]. Educational institutions, in collaboration with industry and government agencies, should develop and offer training programs focused on the latest agricultural technologies and practices. Online platforms and mobile applications can also provide accessible learning resources, ensuring that farmers in remote areas have the opportunity to upgrade their skills [34].

7. CONCLUSION

The future of smart farming heralds a transformative era for agriculture, promising enhanced efficiency, sustainability, and food security through the integration of advanced technologies, supportive policies, and comprehensive education and training. Emerging technologies like AI, gene editing, and IoT will drive unprecedented precision in farming practices, while government policies and international collaboration are essential in overcoming adoption barriers and addressing global challenges. Moreover, education and skill development will empower farmers and agricultural professionals to leverage these technologies fully. As we navigate this evolving landscape, a balanced approach that considers the technical, ethical, and social implications is crucial to ensuring that the benefits of smart farming are realized equitably across the globe, marking a significant step forward in our quest for sustainable agriculture and food systems.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Kansanga M, Andersen P, Kpienbaareh D, Mason-Renton S, Atuoye K, Sano Y, Luginaah I. Traditional agriculture in transition: Examining the impacts of agricultural modernization on smallholder farming in Ghana under the new Green Revolution. International Journal of Sustainable Development & World Ecology. 2019;*26*(1):11-24.
2. Javaid M, Haleem A, Singh RP, Suman R. Enhancing smart farming through the applications of Agriculture 4.0 technologies. International Journal of Intelligent Networks. 2022;3:150-164.
3. Plesse M. Global food and water security in 2050: Demographic change and increased demand. Future Directions International; 2020.
4. Evett SR, O'Shaughnessy SA, Andrade MA, Kustas WP, Anderson MC, Schomberg HH, Thompson A. Precision agriculture and irrigation: Current US perspectives. Trans. ASABE. 2020;63(1):5 7-67.
5. Fabiani S, Vanino S, Napoli R, Zajíček A, Duffková R, Evangelou E, Nino P. Assessment of the economic and environmental sustainability of Variable Rate Technology (VRT) application in different wheat intensive European agricultural areas. A Water energy food nexus approach. Environmental Science & Policy. 2020;114, 366-376.
6. Zhang L, Dabipi IK, Brown Jr WL. Internet of Things applications for agriculture. Internet of things A to Z: technologies and applications. 2018;507-528.
7. Patel B, Bhatia J. A comprehensive review of internet of things and cutting-edge technologies empowering smart farming. Current Science. 2024;00113891:126(2).
8. Tsouros, DC, Bibi S, Sarigiannidis PG. A review on UAV-based applications for precision agriculture. Information. 2019;1 0(11):349.
9. Javaid M, Haleem A, Khan IH, Suman R. Understanding the potential applications of Artificial Intelligence in Agriculture Sector. Advanced Agrochem. 2023;2(1):1 5-30.
10. Salah K, Nizamuddin N, Jayaraman R, Omar M. Blockchain-based soybean traceability in agricultural supply chain. Ieee Access. 2019;*7*:73295-73305.
11. Bongiovanni R, Lowenberg-DeBoer J. Precision agriculture and sustainability. Precision Agriculture. 2004; 5:359-387.
12. Cole S, Harigaya T, Killeen G, Krishna A. Using satellites and phones to evaluate and promote agricultural technology adoption: Evidence from smallholder farms in India; 2020.
13. Fabregas R, Kremer M, Schilbach F. Realizing the potential of digital development: The case of agricultural advice. Science, 2019;366(6471):eaay303 8.
14. Mirás-Avalos JM, Araujo ES. Optimization of vineyard water management: Challenges, strategies, and perspectives. Water. 2021;13(6):746.
15. Hassler SC, Baysal-Gurel F. Unmanned aircraft system (UAS) technology and applications in agriculture. Agronomy. 2019;9(10):618.
16. Parmaksiz O, Cinar G. Technology Acceptance among Farmers: Examples of Agricultural Unmanned Aerial Vehicles. Agronomy. 2023;13(8):2077.
17. Mavalankar DV, Ramani KV, Patel A, Sankar P. Building the Infrastructure to Reach and Care for the Poor: Trends, Obstacles and Strategies to overcome them; 2005.
18. Bongiovanni R, Lowenberg-DeBoer J. Precision agriculture and sustainability. Precision agriculture. 2004;5:359-387.
19. Elbasi E, Zaki C, Topcu AE, Abdelbaki W, Zreikat AI, Cina E, Saker L. Crop prediction model using machine learning algorithms. Applied Sciences. 2023;13(16): 9288.
20. Bwambale E, Abagale FK, Anornu GK. Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. Agricultural Water Management. 2022;260:107324.
21. Rahman MM, Aravindakshan S, Hoque MA, Rahman MA, Gulandaz MA, Rahman

J, Islam MT. Conservation tillage (CT) for climate-smart sustainable intensification: Assessing the impact of CT on soil organic carbon accumulation, greenhouse gas emission and water footprint of wheat cultivation in Bangladesh. Environmental and Sustainability Indicators. 2021;10:10 0106.
22. Karunathilake EMBM, Le AT, Heo S, Chung YS, Mansoor S. The path to smart farming: Innovations and opportunities in precision agriculture. Agriculture. 2023;13 (8):1593.
23. Acemoglu D, Autor D. Skills, tasks and technologies: Implications for employment and earnings. In Handbook of labor Economics. 2011;4:1043-1171). Elsevier.
24. Mizik T. How can precision farming work on a small scale? A systematic literature review. Precision agriculture. 2023;24(1):3 84-406.
25. Darnhofer I, Bellon S, Dedieu B, Milestad R. Adaptiveness to enhance the sustainability of farming systems. A review. Agronomy for Sustainable Development. 2010;30:545-555.
26. Hvolkova L, Klement L, Klementova V, Kovalova M. barriers hindering innovations in small and medium-sized enterprises. Journal of competitiveness. 2019;11(2).
27. Gupta M, abdelsalam M, khorsandroo S, Mittal S. Security and privacy in smart farming: Challenges and opportunities. IEEE Access. 2020;8:3456 4-34584.
28. Ali I, Govindan K. Extenuating operational risks through digital transformation of agri-food supply chains. Production Planning & Control. 2023;34(12):1165-1177.
29. Evans KJ, Terhorst A, Kang BH. From data to decisions: Helping crop producers build their actionable knowledge. Critical Reviews in Plant Sciences. 2017;36(2):71-88.
30. Beddington J. Food security: Contributions from science to a new and greener revolution. Philosophical Transactions of the Royal Society B: Biological Sciences. 2010;365(1537):61-71.
31. Kendall H, Clark B, Li W, Jin S, Jones GD., Chen J, Frewer LJ. Precision agriculture technology adoption: A qualitative study of small-scale commercial family farms located in the North China Plain. Precision Agriculture. 2022;1-33.
32. Allemang D, Teegarden B. A global data ecosystem for agriculture and food. F1000 Research, 2017;6(1844):1844.
33. Hoffmann, V., Probst, K., & Christinck, A. Farmers and researchers: How can collaborative advantages be created in participatory research and technology development?. Agriculture and Human Values. 2007;24:355-368.
34. Mapiye O, Makombe G, Molotsi A, Dzama K, Mapiye C. Information and communication technologies (ICTs): The potential for enhancing the dissemination of agricultural information and services to smallholder farmers in sub-Saharan Africa. Information Development. 2023;39 (3):638-658.

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