

Adoption of Emerging Technologies for Precision Farming in Nigeria: Challenges and Prospect

**Anene Ndubisi Kelvin, Ohanu Victor Chibueze,
& Joan Nneamaka Eze (Ph.D)**

Department of Agricultural Education
Federal College of Education (Technical)
P.M.B. 1044, Asaba Delta State, Nigeria

For correspondence, email: ndubisianene63@gmail.com

Abstract

The global agriculture sector is faced with critical challenges in achieving sustainable food production and environmental sustainability. This study investigates how precision farming through upcoming technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), remote sensing, robotics, and blockchain has the potential to transform agricultural production towards sustainability. Through a scrutiny of the coupling of these technologies, the study investigates how precision farming optimizes resource utilization, enhances crop defense, and maximizes soil condition and water utilization. The research highlights the technologies that facilitate information-based, place-specific farming and minimize input losses and environmental damage. Even with the evident advantages, precision farming has hurdles to face, ranging from high capital requirements to technical intensity, human skill deficiencies among farmers, and privacy and cybersecurity issues around data. In addition, insufficient strong infrastructure, like stable internet and power, particularly in rural settings, slows the large-scale application of these technologies. Through case studies in such markets as Sub-Saharan Africa, as in Ghana's e-Soko and Nigeria's Hello Tractor, the study emphasizes the potential for localized adoption of precision farming technologies. The paper recommended that the major strategies for overcoming these barriers, including government support through policy frameworks, public-private partnerships, investment in infrastructure, and capacity building. It also offers future directions, such as combining digital twins, bioinformatics, and quantum computing, which will further revolutionize farm practices.

Keywords: AI, Emerging technologies, IoT, Precision farming, Sustainable agriculture.

INTRODUCTION

The global agri-food industry is at a crossroads, being faced with the challenging mission of increasing food production to feed a rapidly increasing world population projected at more than 9.7 billion by 2050, while concurrently ensuring environmental sustainability (FAO, 2021; United Nations, 2022). Traditional agriculture practices characterized by the deployment of standardized input applications, land-intensive use, and reactive decision-making are unable to sustainably support the worldwide food chain during the occurrence of climatic variation, soil deterioration, and limited availability of inputs (Pretty et al., 2018; Loboguerrero et al., 2019). Precision farming or precision agriculture (PA), here, is also increasingly becoming a popular advanced, efficient input application, and sustainable agriculture. It uses data analytics, spatial variation, and automation to enhance farm productivity and reduce environmental impacts (Zhang et al., 2020; Rains et al., 2021).

Precision farming is defined by its capacity to provide the right input (water, fertilizer, pesticide, etc.) at the right time, place, and quantity, tailored to the specific requirements of the individual plant or field zones (Mulla, 2018; Gebbers & Adamchuk, 2021). This farm-level crop management system depends on the application of multiple digital technologies—e.g., Geographic Information Systems (GIS), Global Positioning Systems (GPS), drone and satellite-based remote sensing, and smart sensor networks—providing real-time data for evidence-based decision-making (Pierpaoli et al., 2018; Zhang et al., 2023). Moreover, recent advancements in Artificial Intelligence (AI), machine learning, Internet of Things (IoT), blockchain, and robotics are dramatically transforming farm management and the processing, tracing, and transportation of agricultural goods through value chains (Wolfert et al., 2017; Jha et al., 2019; Rejeb et al., 2022). These technologies promise not just to maximize production and minimize wastage of resources, but also to maximize traceability, transparency, and efficiency throughout the entire agri-food system.

Despite the immense potential of digital technologies and precision agriculture, they remain unevenly adopted across various regions, particularly in low- and middle-income countries (LMICs), due to infrastructural limitations, low digital literacy, high costs, and policy gaps (Eastwood et al., 2019; Rose et al., 2021). Even though developed countries such as the United States, Germany, and the Netherlands have made considerable progress in using digital technology in agriculture, the majority of developing nations are still struggling with the fundamentals, including electricity, internet, and human capital (Kamilaris et al., 2017; van der Burg et al., 2020). In addition, smallholder farmers, who make up the majority of agricultural producers in the world, tend to be short of capital and information to shift to precision-based practices, widening technological gaps (Aubert et al., 2021; World Bank, 2023).

Several earlier studies have explored the benefits of individual technologies in farm settings (e.g., AI for forecasting pests, IoT for irrigation), but very little integrated research has been done to study how these technologies collectively impact sustainable agricultural farming and processing in an integrated precision farming system (Shamshiri et al., 2018; Klerkx & Rose, 2020). Additionally, existing literature has mainly concerned itself with the production side of things, ignoring the post-harvest and processing sides where new technologies have the

potential to greatly enhance food preservation, quality, and value addition (Feng et al., 2021). Also lacking is sufficient scholarly attention to policy design, ethical considerations, farmer-led innovation, and environmental sustainability in the long term. These lacunas underscore the need for an integrated, inter-disciplinary conceptual framework that will ensure synergetic complementarities between precision farming and emerging technologies for the whole agriculture value chain.

This study aims to bridge the above mentioned gaps by synthesizing existing knowledge on how precision farming supported by emerging technologies can produce sustainable agricultural processing and production. It not only explores the technical and operational aspects of precision agriculture, but also analyzes its environmental, economic, social, and social effects.

Lastly, as the world strives to achieve the United Nations Sustainable Development Goals (SDGs)—specifically SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action)—it is essential to revitalize agriculture through precision and innovation (UNDP, 2023). This study highlights precision farming and emerging technologies as more than just operational tools; they serve as transformative forces capable of reshaping the future of global food systems. By embracing these innovations, agriculture can be adapted to meet the evolving challenges of sustainability, efficiency, and resilience.

LITERATURE REVIEW

Emerging Technologies in Agriculture

Artificial Intelligence (AI) and Machine Learning

Artificial Intelligence (AI) is transforming precision agriculture by enabling smart, data-driven farming systems. Through predictive analytics, AI models can forecast crop yields, weather patterns, pest infestations, and disease outbreaks using both historical and real-time data (Liakos et al., 2018; Kamilaris & Prenafeta-Boldú, 2018). This integration supports informed decision-making, reduces waste input, and improves productivity. Yield forecasting, aided by satellite imagery and climatic data, helps in planning logistics and market strategies (Jha et al., 2019). Machine Learning (ML), a subset of AI, enhances adaptability by recognizing data patterns and improving decisions over time (Singh et al., 2020). Both supervised and unsupervised algorithms are used to detect plant diseases, monitor soil health, and manage irrigation. Convolutional Neural Networks (CNNs) achieve high accuracy in diagnosing plant diseases from images (Ferentinos, 2018), while reinforcement learning aids in resource optimization amid environmental uncertainty (Kamilaris et al., 2021), making AI vital for resilient, market-responsive agriculture.

Internet of Things (IoT)

The Internet of Things (IoT) involves interconnected machines and sensors that collect, transmit, and process agricultural data continuously. Key components like soil sensors, temperature-humidity sensors, and automated irrigation systems enable real-time monitoring and communication across farm operations (Wolfert et al., 2017; Verdouw et al., 2018). Smart

irrigation systems, for example, use IoT to tailor watering based on soil and climate conditions, reducing water use by up to 30% without harming crop health (Patil et al., 2020). Beyond resource efficiency, IoT promotes automation and situational awareness. Biometric sensors and RFID tags help monitor livestock health and movement, while IoT-equipped machines perform tasks like planting and spraying autonomously (Zhang et al., 2023). Integration with edge analytics and cloud computing allows these devices to process data locally, reacting promptly to environmental changes for precise input application and risk reduction (Mekonnen et al., 2021). These scalable and cost-effective tools drive agriculture's digital transformation.

Remote Sensing and Geographic Information Systems (GIS)

Remote sensing technologies, including satellite imagery and Unmanned Aerial Systems (UASs), offer comprehensive monitoring of crop fields by assessing crop health, soil moisture, and nutrient variability. Equipped with multispectral and hyperspectral cameras, these tools detect early signs of plant stress, enabling timely interventions against pests, diseases, and water stress (Mulla, 2018; Tmušić et al., 2020). Geographic Information Systems (GIS) enhance remote sensing by analyzing and mapping spatial data to support zone-specific fertilization, pesticide application, and field variability management (Khosla et al., 2019). GIS-driven precision farming improves input efficiency, yield reliability, and reduces environmental harm. Furthermore, integrating GIS with crop simulation models and weather forecasts strengthens scenario planning and promotes climate-smart agriculture (Velásquez et al., 2022). Combined, these technologies enable farmers to shift from reactive to proactive strategies in crop management.

Robotics and Automation

Robotics is transforming agriculture by automating labor-intensive tasks such as seeding, spraying, weeding, and harvesting with high precision and minimal human input (Shamshiri et al., 2018; Bechar & Vigneault, 2017). These robots, powered by AI and sensors, adapt to various crops and field conditions. For example, vision-enabled robotic harvesters delicately pick ripe fruits, reducing post-harvest damage. Automation also extends to greenhouse and vertical farming, where climate, lighting, and nutrient delivery are optimized for maximum crop growth. Such smart farms ensure consistent yields with minimal resource use and are ideal for urban and peri-urban areas (Shamshiri et al., 2018; Koirala et al., 2022). Although initial investment in robotics is high, their benefits in labor savings, precision, and scalability make them valuable in precision agriculture, especially in countries facing labor shortages and rising production costs.

Blockchain Technology

Blockchain technology offers a decentralized, tamper-evident ledger that enhances transparency, accountability, and traceability across the agricultural value chain. It secures data on seed origin, fertilizer use, harvest volumes, storage, and transport, fostering trust from farm to fork (Tripoli & Schmidhuber, 2018; Tian, 2017). This system allows buyers, regulators, and certifiers to verify food origins and safety, especially in organic and export-based agriculture. Additionally, blockchain supports smart contracts—automated agreements that trigger actions

once conditions are met—improving payment systems, insurance processing, and subsidy distribution, thereby reducing bureaucracy and boosting financial inclusion for smallholder farmers (Rejeb et al., 2022; Kamilaris et al., 2021). When integrated with IoT and AI, blockchain offers enhanced digital traceability, enabling real-time monitoring of agricultural inputs and outputs. This integration supports data-driven governance and minimizes fraud, contamination, and breaches in the supply chain.

Precision Farming

Precision farming, also known as precision agriculture or site-specific crop management, is a technology-driven approach that integrates advanced digital tools with agricultural practices to enable site-specific, data-driven decision-making. It comprises three core components: data capture, data interpretation, and data application. Data collection involves gathering spatial and temporal information from farms using tools such as GPS-enabled devices, drones, multispectral and hyperspectral sensors, soil sensors, weather stations, and IoT devices (Pierpaoli et al., 2018; Zhang et al., 2023). The collected data is interpreted using machine learning, decision support systems (DSS), and geospatial analysis to assess crop health, soil variability, nutrient needs, and pest threats (Shamshiri et al., 2018; Jha et al., 2019; Heidari et al., 2022).

The application phase translates these insights into actionable interventions like variable rate application (VRA) of fertilizers, targeted irrigation, and precise pesticide use to improve productivity, reduce input waste, cut costs, and conserve natural resources (Wolfert et al., 2017; Khosla et al., 2019). This data-driven cycle includes feedback loops that allow continual adaptation and learning, essential for sustainable production. Technologies such as AI, blockchain, robotics, and cloud computing enhance automation, traceability, and decentralized farm operation control (Rejeb et al., 2022; Wang et al., 2021).

The framework also acknowledges critical off-farm adoption drivers such as farm size, cost of technology, digital literacy, regulations, and socio-economic factors like farmer attitudes and institutional support (Eastwood et al., 2019; Aubert et al., 2021). Precision farming extends into post-harvest phases, using sensors and IoT to monitor quality, prevent spoilage, and optimize logistics (Feng et al., 2021).

Ultimately, precision farming embodies the principle of “doing the right thing, at the right place, at the right time,” enhancing efficiency while reducing environmental impact (Loboguerrero et al., 2019; Heidari et al., 2022). It represents a paradigm shift toward sustainable intensification, aiming to achieve greater productivity with fewer inputs and minimal environmental degradation, aligning with goals of economic efficiency and global food security (FAO, 2021; Fielke et al., 2022; Gebbers & Adamchuk, 2021).

Sustainable Agricultural Production through Precision Farming

Resource Optimization

Precision agriculture transforms farming by optimizing resource use through digital technologies and data-driven methods. Central to this is site-specific crop management

(SSCM), which ensures inputs like water, fertilizers, and pesticides are applied precisely when and where needed, reducing waste, cost, and environmental impact (Basso & Antle, 2020; Zhang et al., 2022). Tools such as GPS, GIS, and yield monitors help assess field variability for better resource allocation. Machine learning further enhances efficiency by analyzing data to optimize input timing and quantity (Liakos et al., 2018). Innovations like UAVs and remote sensing offer high-resolution crop health imagery, enabling variable-rate applications of agrochemicals. AI-enabled precision sprayers can cut herbicide use by up to 90% (Zhang et al., 2023). Additionally, IoT-based soil sensors detect nutrient deficiencies, allowing targeted fertilization. Overall, precision agriculture boosts productivity, ecological resilience, and supports climate-smart agriculture (Gebbers & Adamchuk, 2019; Wang et al., 2024).

Nutrient Management and Soil Health

Maintaining soil health is essential for sustainable agriculture, and precision agriculture introduces innovative nutrient management strategies. Technologies like soil nutrient sensors, electrical conductivity mapping, and proximal sensing enable real-time soil assessments and targeted fertilizer application (Ziliani et al., 2019; Yao et al., 2021). These tools identify spatial variability in soil fertility, allowing for site-specific fertilization. Variable Rate Technology (VRT) enhances this process by preventing over-fertilization and reducing nutrient leaching (Shanahan et al., 2020). Furthermore, AI-powered Decision Support Systems (DSS) integrate historical and current data to create optimal nutrient management plans, enhancing soil health while minimizing environmental impact. By combining sensor data with models like DSSAT, farmers can simulate various input scenarios and select the most effective one (Tey & Brindal, 2017; Jones et al., 2022). These technologies improve crop yield and soil quality, including organic matter, pH, and microbial activity, thus supporting resilient and regenerative agroecosystems (Khosla et al., 2019; Zhang et al., 2025).

Water Management

Precision agriculture improves water management through IoT-based intelligent irrigation systems that utilize real-time data from soil moisture sensors, weather stations, and satellite imagery to optimize irrigation schedules and volumes (Zhang et al., 2021; Ali et al., 2023). Smart drip and sprinkler systems target plant root zones, minimizing evaporation and runoff. Machine learning models predict water needs based on evapotranspiration, crop stages, and weather, enabling proactive planning (Jain et al., 2022). Decision Support Tools (DSTs) like AquaCrop and SWAT aid in selecting efficient irrigation strategies for different soils and crops by modeling soil water flow, preventing over-irrigation and related issues such as waterlogging and nutrient leaching (Pereira et al., 2020). Precision water management enhances climate resilience by conserving freshwater and maintaining productivity during droughts, supporting the UN's Sustainable Development Goal 6 on clean water and sanitation (FAO, 2022; Wu et al., 2024).

Crop Protection and Disease Management

Precision agriculture revolutionizes crop protection by integrating AI, remote sensing, and image recognition for early detection of pests and diseases (Kamilaris & Prenafeta-Boldú,

2018; Mahlein et al., 2021). AI platforms analyze aerial and ground imagery to identify early biotic stress indicators, enabling timely interventions such as targeted pesticide use and biological control. The fusion of AI with GIS allows mapping of disease and pest patterns, enhancing outbreak prediction (Chlingaryan et al., 2018). Drones with hyperspectral/multispectral sensors detect subtle stress signals, facilitating site-specific actions. Cloud-based systems aggregate data across farms to detect emerging insect threats and guide community-level responses (Steenbergen et al., 2022). Machine learning models further assess disease severity and suggest effective treatments based on historical trends. These technologies improve Integrated Pest Management (IPM) by combining ecological and digital strategies, thereby reducing crop loss, minimizing chemical use, and promoting sustainable farming practices (Ferentinis, 2018; Li et al., 2023).

Environmental Sustainability

The environmental effects of precision agriculture are crucial for addressing climate change, biodiversity, and sustainable land use. Key benefits include reducing chemical inputs like fertilizers and pesticides, which helps lower greenhouse gas emissions, water pollution, and soil loss (Rose et al., 2021; Hockridge et al., 2023). It also enhances conservation agriculture by improving soil structure and carbon sequestration. Techniques such as precision land leveling, contour farming, and controlled traffic reduce soil erosion and improve moisture retention, supporting healthier ecosystems (Lal, 2020). Technological advances like blockchain also promote environmental stewardship by verifying sustainable practices (Tripoli & Schmidhuber, 2018; Kumar et al., 2024). Precision agriculture facilitates biodiversity tracking through GIS and remote sensing, guiding conservation efforts. Overall, it contributes to environmentally sustainable food systems, balancing productivity and ecological health (Pretty et al., 2020; FAO, 2025).

Technological Innovations in Agricultural Processing

Smart Packaging

Smart packaging uses IoT technologies, biosensors, and smart materials to monitor food quality and extend shelf life by detecting changes in temperature, pH, humidity, gas content, and microbial growth (Ribeiro-Santos et al., 2021; Prasad et al., 2020). Time-temperature indicators (TTIs), RFID, and NFC enhance product traceability, improving freshness and reducing food spoilage (Sharma et al., 2022). These technologies not only boost food safety but also minimize food loss throughout the supply chain. Additionally, intelligent packaging aids sustainability by ensuring customers receive fresh products and preventing food waste. Sensors notify consumers and retailers when food reaches spoilage points, facilitating timely consumption or disposal (Silvestre et al., 2021). IoT-enabled packaging is increasingly linked with blockchain for better transparency and traceability, enhancing consumer confidence, regulatory compliance, and efficient recall processes (Kamble et al., 2020).

Automation in Processing

Food processing automation uses advanced technologies like robotics, computer vision, AI, and machine learning to sort, grade, and package products with high speed and accuracy, ensuring

consistent quality (Verdouw et al., 2018; Moghimi et al., 2022). This reduces reliance on human labor, especially during shortages or crises like COVID-19 (Manzini & Accorsi, 2020). Automation enhances safety, hygiene, and productivity by eliminating repetitive tasks. It also enables real-time monitoring of product quality, minimizing errors and ensuring consistent batch quality. The integration of robotics and AI has led to customized food production, such as personalized nutrition and allergen-free packaging (Shukla et al., 2021). Additionally, automation supports waste removal, operational efficiency, and energy savings, contributing to more sustainable production. Industry 4.0 technologies like cyber-physical systems and digital twins are also being used to optimize production and reduce costs (Chaudhary et al., 2023).

Supply Chain Digitalization

The digitalization of the food supply chain involves adopting technologies like blockchain, cloud computing, big data analytics, and artificial intelligence to enhance transparency, traceability, and responsiveness (Tian, 2017; Min et al., 2019). These technologies enable tracking from farm to table, providing visibility of each stage of production, transportation, and distribution. Cloud systems promote real-time coordination and data sharing, reducing transaction costs and improving supply chain coordination (Rejeb et al., 2021). This network allows just-in-time delivery, minimizes stockouts, and optimizes logistics. Digitalization also empowers decision-makers with predictive analytics for handling disruptions such as climate change or market shocks (Kamble et al., 2020; Tripathi et al., 2023). Blockchain ensures product quality, origin verification, and ethical sourcing, vital for food safety, regulatory compliance, and consumer trust. Additionally, digital supply chains support sustainability by monitoring carbon footprints and material optimization, promoting eco-friendly practices (Tsao et al., 2022).

Global Trends and Case Studies

Precision agriculture (PA) has gained global traction, with leading nations like the Netherlands, Israel, and the United States making significant strides through investments in research, advanced technologies, and coordinated policies. The Netherlands employs high-tech greenhouses, satellite imagery, and crop monitoring to achieve high yields despite limited arable land (Meijerink & Bindraban, 2020). Israel's innovations, such as drip irrigation and soil sensors, help maximize water usage and improve yields in arid conditions (Zhang et al., 2021). In the U.S., GPS-guided tractors, variable rate technology, drones, and data analysis have enhanced productivity while promoting environmental sustainability (Rotz et al., 2019; Khanal et al., 2020). These examples show how integrating policy, private investment, and technological advancements can promote smart agriculture.

In contrast, sub-Saharan Africa faces challenges like poor infrastructure and illiteracy in digital tools, yet innovative PA applications are helping smallholder farmers. Ghana's e-Soko platform provides real-time market information and agronomic advice via mobile phones (Aker et al., 2021), while Nigeria's Hello Tractor connects farmers with tractor owners through a GPS-enabled app, improving productivity and reducing labor costs (Bello-Bravo et al., 2022). These initiatives highlight the potential of context-specific technologies and mobile connectivity in advancing agriculture in resource-poor regions (FAO, 2024; World Bank, 2023).

Challenges in Adopting Emerging Agricultural Technologies

High Upfront Capital Expenditure

The primary barrier to adopting precision farming technology is the high upfront capital expenditure, which includes costly tools like drones, sensors, autonomous tractors, and AI-based software. These technologies are often unaffordable for smallholder farmers, particularly in low-income economies (Finger et al., 2019; Klerkx et al., 2019). In developing regions, agriculture is largely subsistence-based, and while some industrialized nations offer government subsidies, support programs are lacking or insufficient in the Global South, widening the digital divide (Carolan, 2020). Additionally, the financial burden of infrastructure costs, such as cloud data storage, equipment, and software subscriptions, further exacerbates the issue (Eastwood et al., 2019). The unclear return on investment makes it hard for small-scale farmers to justify the expense. While cooperative ownership models may work in some cases, they face organizational challenges and lack widespread acceptance (Walter et al., 2021). Without new financing mechanisms and policy incentives, precision agriculture will remain inaccessible.

Technical Complexity and Skill Gaps

Precision farming depends on users' ability to interpret and make decisions based on real-time data analysis, a skill many global farmers lack. Smallholders and aging farmers often lack the digital skills necessary for managing and interpreting large agricultural datasets (Paustian & Theuvsen, 2017; Fielke et al., 2020). Operating GPS-equipped tractors, managing data platforms, and responding to alerts require specialized training, which is often inconsistent and inadequate in many farming areas. This lack of digital literacy results in ineffective use of technology, with some abandoning it due to perceived inefficiency. The rapid pace of technological change leads to skill obsolescence, further exacerbated by insufficient continuous extension services and tailored digital literacy programs for rural farmers (Barrett & Rose, 2022). Addressing this requires capacity building through experiential training, mobile learning, and peer-to-peer knowledge sharing. Collaboration among farming institutions, technology providers, and cooperatives is essential for a sustainable and competent digital farming community.

Data Privacy and Cybersecurity

The implementation of cloud-based software, GPS, IoT, and mobile applications in agriculture has raised concerns about data cybersecurity and privacy. Farmers generate sensitive data, such as crop yields and soil conditions, which, if mishandled, could lead to economic loss or a competitive disadvantage (Bronson & Knezevic, 2019; Wiseman et al., 2019). Data ownership remains poorly regulated, raising ethical and legal issues regarding third-party control by tech firms and agribusinesses (Wolfert et al., 2017). Inadequate data governance exposes farmers to cyber threats and data tampering, especially in regions with weak cybersecurity infrastructure (Carbonell, 2018). Many farmers lack understanding of how their data are stored and shared, eroding trust in digital platforms. To address these issues, measures like open data policies, enhanced user ownership, and rural cybersecurity education are crucial. Governments and

industry stakeholders should also collaborate to establish global data standards that protect farmers' rights and foster innovation.

Infrastructure Shortfalls

The deployment of precision agriculture heavily depends on infrastructure such as electricity, broadband internet, and transport, which are lacking in many rural areas globally. Without reliable power, automation, sensors, and drones cannot operate effectively, while poor internet connectivity disrupts real-time data and cloud computing (Deichmann et al., 2016; Ayre et al., 2019). These infrastructure gaps deepen the digital divide, especially in Sub-Saharan Africa, South Asia, and parts of Latin America, where rural electrification and connectivity are major challenges. Additionally, inadequate transport infrastructure hampers the movement of goods, limiting the support for high-tech agricultural equipment. Delays in repairs, unavailable suppliers, and limited agri-tech presence in rural areas slow digital agriculture progress. To address these issues, governments, donors, and businesses must invest in rural infrastructure and integrate digital readiness into agricultural development plans to prevent precision technologies from becoming obsolete in tackling agricultural challenges.

Policy and Institutional Frameworks

Robust policy and institutional frameworks are crucial for the adoption of precision agriculture technologies. Governments should create policies that promote research, innovation, and capacity building (Lowder et al., 2021). Subsidies, tax rebates, and grants can help reduce barriers to technology adoption, particularly in developing countries. Regulations must ensure the technologies are secure and align with national goals like food security, sustainability, and economic growth. Empowering agricultural research institutes and fostering collaboration with universities, technology companies, and international bodies will bridge knowledge gaps (Ashraf et al., 2020). Public-private partnerships (PPPs) are vital in accelerating digital farming adoption, with governments providing regulatory support and subsidies, and the private sector contributing innovation and low-cost solutions (Gürbüz & Çevik, 2021). In regions like Sub-Saharan Africa and South Asia, where smallholder farmers face challenges, PPPs can help improve access to technology and training. Governments must also improve rural infrastructure, including internet and electricity, to support digital agriculture (Deichmann et al., 2016).

Future Directions and Innovations

The future of precision agriculture will be revolutionized by advanced technologies, particularly the development of digital twins. These virtual replicas of real-world farms simulate, predict, and optimize farming operations using data from IoT sensors, remote sensing, and other digital tools, enabling farmers to make better decisions (Jin et al., 2023). Bioinformatics will also enhance precision farming by improving plant genetics, pest resistance, and disease protection. Quantum computing will process vast data quickly, enabling improved predictive models and better agricultural efficiency (Chen et al., 2021). The convergence of AI, IoT, big data analytics, and robotics in smart farming systems will push productivity and sustainability limits. However, significant advancements in infrastructure,

such as data storage and processing, are necessary. Coordinated efforts between academia, industry, and governments will be crucial, with policy playing a central role in equitable innovation (Kumar et al., 2022). Education and training will also be essential for farmers to maximize the benefits of these technologies, helping to achieve food security and environmental sustainability (Tian, 2020).

CONCLUSION AND RECOMMENDATIONS

In conclusion, the integration of new technologies in agriculture, including Artificial Intelligence (AI), the Internet of Things (IoT), remote sensing, and blockchain, offers great potential to transform sustainable agriculture production and processing. These technologies can enhance productivity, resource efficiency, and environmental sustainability. However, their successful implementation relies on collaboration among governments, private sector actors, research organizations, and farmers. A crucial aspect of ensuring equitable benefits from these technologies is inclusivity, particularly for smallholder farmers who face challenges such as high initial costs, lack of technical knowledge, and inadequate infrastructure.

To fully realize the potential of precision farming, investments must be made in rural infrastructure, including reliable internet, electricity, and transportation networks. These are essential for the deployment of IoT-based sensors and AI decision support systems, especially in rural or remote areas. Additionally, training and capacity-building programs are necessary to equip farmers with the skills to effectively use and maintain these technologies. Policymakers must focus on creating supportive frameworks, offering incentives, and fostering public-private partnerships to encourage technology adoption. This comprehensive approach will ensure that the benefits of these technologies are widely shared, improving food security, reducing environmental impact, and enhancing global agricultural resilience (Jin et al., 2023; Lowder et al., 2021).

REFERENCES

- Aker, J. C., Ghosh, I., & Burrell, J. (2021). The promise (and pitfalls) of ICT for agriculture initiatives. *World Development*, 146, 105572.
- Ashraf, S., Khan, S. A., & Sattar, S. (2020). Leveraging public-private partnerships to accelerate the adoption of precision agriculture technologies in developing countries. *Agricultural Systems*, 177, 102686.
- Aubert, B. A., Schroeder, A., & Grimaudo, J. (2021). IT as enabler of sustainable farming: An empirical analysis of farmers' adoption decision of precision agriculture technology. *Technological Forecasting and Social Change*, 162, 120346.
- Basso, B., & Antle, J. (2020). Digital agriculture to design sustainable agricultural systems. *Nature Sustainability*, 3(4), 254–256.
- Bechar, A., & Vigneault, C. (2017). Agricultural robots for field operations: Current status and future trends. *Biosystems Engineering*, 149, 94–111.
- Bronson, K., & Knezevic, I. (2019). Big Data in food and agriculture. *Big Data & Society*, 6(1), 205395171984944.

Anene, Ohanu & Eze. *Adoption of emerging technologies for precision farming in Nigeria ...*

Chaudhary, R., Yadav, G., Singh, A. R., & Mishra, A. R. (2023). Role of Industry 4.0 in food processing sector: An overview. *Journal of Food Engineering*, 336, 111248. <https://doi.org/10.1016/j.jfoodeng.2022.111248>

Deichmann, U., Goyal, A., & Mishra, D. (2016). Will digital technologies transform agriculture in developing countries? *World Bank Policy Research Working Paper*, 7669.

Eastwood, C., Klerkx, L., Ayre, M., & Dela Rue, B. (2019). Managing socio-ethical challenges in the development of smart farming: From a fragmented to a comprehensive approach for responsible innovation. *Journal of Agricultural and Environmental Ethics*, 32, 741–768.

FAO & ITU (2022). *E-agriculture strategy guide: Piloted in Asia-Pacific countries*. Rome: Food and Agriculture Organization and International Telecommunication Union.

FAO and ITC. Verdouw, C. N., et al. (2018). Smart agri-food logistics: Research challenges and opportunities. *Logistics*, 2(3), 20.

FAO. (2021). *The State of Food and Agriculture: Making Agrifood Systems More Resilient to Shocks and Stresses*.

Ferentinos, K. P. (2018). Deep learning models for plant disease detection and diagnosis. *Computers and Electronics in Agriculture*, 145, 311–318.

Fielke, S., Taylor, B., & Jakku, E. (2022). Digitalisation of agricultural knowledge and advice networks: A state-of-the-art review. *Agricultural Systems*, 195, 103304.

Finger, R., Swinton, S. M., El Benni, N., & Walter, A. (2019). Precision farming at the nexus of agricultural production and the environment. *Annual Review of Resource Economics*, 11, 313–335.

Gebbers, R., & Adamchuk, V. I. (2021). Precision agriculture and food security: A technological perspective. *Agronomy Journal*, 113(2), 1020–1035.

Gürbüz, H., & Çevik, S. (2021). Policy and institutional frameworks for digital transformation in agriculture: A global perspective. *Agricultural Economics Review*, 22(2), 57–70.

Jha, K., Doshi, A., Patel, P., & Shah, M. (2019). A comprehensive review on automation in agriculture using artificial intelligence. *Artificial Intelligence in Agriculture*, 2, 1–12.

Jin, X., Jiang, Y., & Li, C. (2023). Prospects of digital twin and AI in sustainable precision agriculture. *Computers and Electronics in Agriculture*, 205, 107591.

Kamble, S. S., Gunasekaran, A., & Dhone, N. C. (2020). Industry 4.0 and lean manufacturing practices for sustainable organizational performance in Indian manufacturing companies. *International Journal of Production Economics*, 231, 107861.

Kamilaris, A., & Prenafeta-Boldú, F. X. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*, 147, 70–90.

- Kamilaris, A., Kartakoullis, A., & Prenafeta-Boldú, F. X. (2017). A review on the practice of big data analysis in agriculture. *Computers and Electronics in Agriculture*, 143, 23–37.
- Khanal, S., Fulton, J., & Shearer, S. (2020). An overview of precision agriculture technologies in the U.S. and their adoption barriers. *Biosystems Engineering*, 193, 39–54.
- Khosla, R., Mulla, D. J., & Robert, P. C. (2019). Precision agriculture in practice: The way forward. *Precision Agriculture*, 20(4), 727–748.
- Klerkx, L., & Rose, D. (2020). Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways? *Global Food Security*, 24, 100347.
- Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors*, 18(8), 2674. <https://doi.org/10.3390/s18082674>
- Loboguerrero, A. M., Rodríguez, J., & Morales, S. (2019). Impact of climate change on agriculture and food security. *Agricultural Systems*, 170, 70-83. <https://doi.org/10.1016/j.agsy.2019.01.004>
- Lowder, S. K., Skoet, J., & Raney, T. (2021). The role of public policy in the development of precision agriculture: Trends, challenges, and future directions. *Food Policy*, 98, 101775.
- Manzini, R., & Accorsi, R. (2020). The food cold chain: Modeling and simulation. *Springer*.
- Mekonnen, D., Gebreslassie, M., & Kassahun, A. (2021). IoT-based smart agriculture: Trends, issues, and future directions. *Journal of King Saud University – Computer and Information Sciences*.
- Min, H., Zacharia, Z. G., & Smith, C. D. (2019). Blockchain technology for enhancing supply chain resilience. *Business Horizons*, 62(3), 329-340.
- Moghimi, A., Khalilian, A., & Navid, H. (2022). Robotic systems in food processing: A review. *Journal of Food Process Engineering*, 45(2), e13907.
- Mulla, D. J. (2018). Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering*, 114(4), 358–371.
- Patil, R. A., Kulkarni, R. V., Patil, R. A., & Patil, P. B. (2020). Smart irrigation system using IoT. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 5(2), 1–4.
- Paustian, M., & Theuvsen, L. (2017). Adoption of precision agriculture technologies by German crop farmers. *Precision Agriculture*, 18(5), 701–716.
- Pierpaoli, E., Carli, G., Pignatti, E., & Canavari, M. (2018). Drivers of precision agriculture technologies adoption: A literature review. *Procedia Technology*, 8, 61–69.

Anene, Ohanu & Eze. *Adoption of emerging technologies for precision farming in Nigeria ...*

- Prasad, P., Kochhar, G. S., Vashisht, R., Dhawan, A., & Singh, A. (2020). Intelligent packaging: Trends and applications in food safety. *Trends in Food Science & Technology*, *105*, 414–426. <https://doi.org/10.1016/j.tifs.2020.09.020>
- Pretty, J., Norton, L., & Williams, A. (2018). *Sustainable agriculture: A global perspective on challenges and solutions*. Oxford University Press.
- Rejeb, A., Rejeb, K., Simske, S. J., & Keogh, J. G. (2022). The role of blockchain in agriculture: Applications, challenges and future directions. *Technology in Society*, *70*, 101983.
- Ribeiro-Santos, R., Andrade, M., Melo, N. R., & Sanches-Silva, A. (2021). Smart packaging in food applications: A review. *Trends in Food Science & Technology*, *104*, 132–149. <https://doi.org/10.1016/j.tifs.2020.08.008>
- Rose, D. C., Lyons, K., Chilvers, J., & Kuzma, J. (2021). Policy perspectives on emerging agricultural technologies. *Nature Food*, *2*(2), 92–97. <https://doi.org/10.1038/s43016-020-00211-1>
- Rotz, S., Gravely, E., Mosby, I., Duncan, E., Finnis, E., Horgan, M., LeBlanc, J., Martin, R., Neufeld, H. T., Nixon, A., Pant, L., & Shalla, V. (2019). Automated pastures and the digital divide: How agricultural technologies are shaping labor and rural communities. *Journal of Rural Studies*, *68*, 112–122. <https://doi.org/10.1016/j.jrurstud.2019.01.023>
- Shamshiri, R. R., Kalantari, F., Ting, K. C., Thorp, K. R., Hameed, I. A., Weltzien, C., Ahmad, D., & Shad, Z. M. (2018). Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. *International Journal of Agricultural and Biological Engineering*, *11*(1), 1–22. <https://doi.org/10.25165/j.ijabe.20181101.3210>
- Sharma, R., Kumar, S., & Singh, M. (2022). Role of smart packaging systems in food preservation: Innovations and future directions. *Food Control*, *130*, 108400.
- Shukla, P., Jain, R., & Dubey, R. (2021). AI-driven personalized food: Emerging trends and ethical considerations. *Trends in Food Science & Technology*, *113*, 160–169.
- Silvestre, C., Duraccio, D., & Cimmino, S. (2021). Food packaging materials: Recent advances and future challenges. *Comprehensive Reviews in Food Science and Food Safety*, *20*(4), 3402–3443.
- Singh, A., Patil, A., Rane, S., & Kotecha, K. (2020). Machine learning in agriculture: A comprehensive review. *Computers and Electronics in Agriculture*, *180*, 105894. <https://doi.org/10.1016/j.compag.2020.105894>
- Tian, F. (2017). A supply chain traceability system for food safety based on blockchain. *International Conference on Service Systems and Service Management*, 1–6.
- Tripoli, M., & Schmidhuber, J. (2018). Emerging opportunities for the application of blockchain in the agri-food industry. *FAO & ICTSD Discussion Paper*.

- UNDP (2023). *Sustainable Development Goals Report*. United Nations Development Programme.
- Velásquez, M. A., Peña, A., Rodríguez, D. A., & Zambrano-Barragán, P. X. (2022). Climate-smart GIS applications in smallholder agriculture. *Climate Risk Management*, 35, 100404. <https://doi.org/10.1016/j.crm.2022.100404>
- Verdouw, C., Wolfert, S., Beulens, A., & Rialland, A. (2018). Digital twins in smart farming. *IFAC-PapersOnLine*, 51(17), 831–836.
- Wang, Y., Han, J., & Zhang, X. (2021). Integration of artificial intelligence and blockchain in agriculture: A framework and applications. *Computers and Electronics in Agriculture*, 189, 106413.
- Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M.-J. (2017). Big data in smart farming—A review. *Agricultural Systems*, 153, 69–80.
- Zhang, J., Wang, Q., Liu, H., Li, Y., & Zhao, X. (2021). Smart irrigation systems for sustainable agriculture. *Water*, 13(5), 641. <https://doi.org/10.3390/w13050641>
- Zhang, Q., Chen, L., Wang, Y., Liu, H., & Zhao, X. (2020). Precision agriculture technology for crop farming. *Journal of Agricultural and Food Chemistry*, 68(21), 5975–5984. <https://doi.org/10.1021/acs.jafc.0c00720>
- Zhang, Y., Jiang, H., & Wang, C. (2023). Next-generation precision agriculture: Integrating AI and spatial analytics for sustainable crop management. *Computers and Electronics in Agriculture*, 205, 107612.
- Ziliani, M. G., Piras, M., Adamchuk, V. I., & Romboli, Y. (2019). Soil sensors for sustainable agriculture. *Sensors*, 19(19), 4321. <https://doi.org/10.3390/s19194321>