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**REVIEW ARTICLE**

# Emerging Technologies in Agriculture: Opportunities and Challenges for Future Perspective in Nigeria

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## ABSTRACT

The rapid evolution of emerging technologies is reshaping global agriculture, transitioning it from traditional practices to data-driven, technology-enabled systems. Tools such as artificial intelligence, the internet of things, robotics, blockchain, drones, and biotechnology are enhancing precision farming, resource optimization, and sustainability. These innovations not only improve productivity but also contribute to food security, climate resilience, and economic transformation. However, challenges such as high costs, poor infrastructure, limited digital literacy, and inadequate policy frameworks constrain adoption, particularly in developing countries like Nigeria, where smallholder farmers dominate. This review highlights the opportunities, challenges, and future perspectives of emerging technologies in agriculture, emphasizing their role in strengthening food systems, supporting rural development, and ensuring sustainable practices. It suggests that deliberate investments in research, training, infrastructure, and regulatory reforms are essential for Nigeria and other developing nations to harness these technologies for inclusive growth and food security.

**Key words:** Agriculture, artificial intelligence, emerging technologies, food security, Nigeria, precision farming

## INTRODUCTION

The agricultural sector is being transformed by advanced information and communication technologies, particularly the Internet of Things (IoT). The rapid rise of these innovations has redefined nearly every industry, including farming, shifting practices from traditional statistical methods to data-driven quantitative approaches. This shift has replaced older techniques and introduced new opportunities alongside a range of challenges (Khan *et al*., 2021). With increasing reliance on cloud-based systems to store vast amounts of sensitive data, farmers face concerns about unauthorized access and data misuse. These risks are further complicated by the collaborative nature of precision agriculture, which involves multiple stakeholders such as agronomists and technology companies, raising questions of data ownership and sharing protocols (Kavitha *et al*., 2022; GIS Applications in Agriculture, 2022).

Emerging technologies are advancing at an unprecedented pace, driving automation, creating new industries, and unlocking possibilities across all sectors. Organizations are turning to these innovations to enhance productivity, optimize processes, and address complex issues, making them central to future competitiveness. Their widespread impact will continue shaping society, presenting both opportunities and challenges for individuals, businesses, and governments (Daniel Schlepps, 2024). In agriculture, automation and robotics are enhancing activities such as planting,

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harvesting, and pest control with greater precision and efficiency (Simelton and McCampbell, 2021; Fleming *et al*., 2021). These advances contribute to a more resilient farming system, better equipped to respond to climate change and resource limitations. As geographic information systems (GIS) integrate further with farm machinery, issues of data privacy and security in agricultural practices become increasingly important.

Agricultural technology (AgTech) encompasses tools, machinery, and scientific methods that modify farms, inputs, outputs, and systems (Wang *et al*., 2023). Biotechnology, genetic improvement, hydroponics, and blockchain are vital components of AgTech (Prazeres *et al*., 2017; Xiong *et al*., 2020). Heavy-duty mechanization, such as tractors, harvesters, and threshers, has revolutionized farming, while irrigation technology remains a cornerstone of productivity (Onomu and Aliber, 2024). More recently, technologies such as drones, AI, blockchain, robotics, and automation are reshaping how crops are grown, harvested, and processed (Dileep *et al*., 2020; Javaid *et al*., 2022; Alobid *et al*., 2022). Innovations such as driverless tractors, operating with GPS and sensors, illustrate the trajectory of agriculture in developed nations (Rehman *et al*., 2016).

Collaboration between technology providers and agricultural stakeholders is essential for creating solutions tailored to regional needs (Delgado *et al*., 2019; Ukhurebor *et al*., 2022). Precision farming, remote sensing, and data analytics can optimize resources, increase yields, and reduce environmental impacts, supporting sustainability. Continuous farmer training in these technologies is also vital, enabling informed decision-making and strengthening resilience against climate and market challenges (Masud Cheema and Khan, 2019). This cooperative model fosters innovation, economic growth, and long-term sustainability, ultimately strengthening food security and helping communities adapt to environmental change. Investment in research and development, alongside education, will be key to identifying new techniques and equipping farmers with the necessary skills (Sarkar *et al*., 2023; Saber, 2022; Raturi, 2022).

Future perspective in agriculture refers to how farming and food production are expected to evolve in the coming years, based on current trends, challenges, and technological advancements. It is about looking ahead and identifying opportunities, risks, and innovations that will shape the agricultural sector. In simple terms, future perspective in agriculture means envisioning how farming will adapt to feed the world in sustainable, efficient, and innovative ways (Usman *et al*., 2025). Looking ahead, the "future perspective" of agriculture highlights opportunities, risks, and innovations that will shape food production (Usman *et al*., 2025). Six key aspects define this outlook:

a. Technological innovations – AI, drones, robotics, sensors, smart irrigation, and biotechnology;
b. Sustainability and climate adaptation – eco-friendly practices, climate-resilient crops, and soil and water management;
c. Food security and nutrition – nutrient-rich crops, robust supply chains, and feeding a growing population;
d. Digital agriculture – big data, satellite monitoring, blockchain, and farm management platforms;
e. Alternative farming systems – urban agriculture, hydroponics, aquaponics, and lab-grown protein;
f. Policy, economics, and trade – government support, global cooperation, rural development, and farmer equity.

Previous research confirms that agricultural transformation is impossible without technological adoption. Modern tools such as GPS, GIS, and sensors support precision farming, livestock monitoring, yield documentation, and farm management by providing real-time data on crops and soil health (Benu, 2015; Helwatkar *et al*., 2014). GPS, for example, reduces waste in seed, fertilizer, and fuel usage, while biotechnology enables pest-resistant hybrids, lowering pesticide reliance and promoting sustainability (Rehman *et al*., 2016).

Technological transformation in Ukraine has advanced its agricultural sector toward global standards (Kyrylov *et al*., 2022). Developed countries have long benefited from modern agriculture, but smallholders in developing regions lag behind (Rehman *et al*., 2016). Studies show developed nations lead in technological adoption,

while developing countries often stagnate (Onomu and Aliber, 2024). In Nigeria, many farmers still lack access to modern technologies, partly due to gaps in research on implementation strategies (Okoye and Adamade, 2016). Expanding the use of mobile, IoT, blockchain, and AI tools could boost productivity, improve quality, and meet both local and international standards. These tools also have potential to generate employment, reduce rural-urban migration, and attract younger generations to farming (NITDA, 2020).

Digital agriculture provides real-time data on weather, soil, processing, storage, and markets, helping farmers maximize yields, minimize waste, cut costs, and ensure environmental sustainability (NITDA, 2020). However, monitoring still consumes a majority of farmers' time, making advanced tools such as IoT crucial for efficiency. Wireless sensors now enable accurate, continuous monitoring of soil and crops, detecting problems early and optimizing decisions (Sisinni, 2018). Coupled with drones, UAVs, robot weeders, and automated harvesters, these innovations enhance every stage of crop growth and management.

Institutions and industries are actively developing IoT-based solutions for better farm management, helping minimize inefficiencies and improve yields (Ayaz *et al*., 2017; 2019; Lin *et al*., 2017; Shi *et al*., 2019; Khan *et al*., 2020). While IoT remains an emerging technology, its adaptability and efficiency make it a promising driver of sustainable agriculture.

Emerging technologies are redefining agriculture by providing innovative solutions to age-old challenges. They hold the potential to boost productivity, strengthen food security, and promote sustainable practices. However, challenges such as data privacy, affordability, skill gaps, and weak policies must be addressed, especially in Nigeria, where smallholder farmers form the majority of producers. For Nigeria to fully harness the opportunities, deliberate investment in research, farmer training, and policy reforms will be crucial. If well integrated, these technologies will not only secure the nation's food future but also drive broader economic transformation. This review, therefore, evaluates the role of emerging technologies in advancing agricultural sustainability, examining their potential, challenges, and future prospects.

## EMERGING TECHNOLOGIES IN AGRICULTURE

The development of technology has progressed dramatically, moving from simple hand tools to highly sophisticated, advanced systems. Early inventions such as the plow and reaper transformed agriculture by improving efficiency and productivity (GZ Industrial Supply, 2025). Today, cutting-edge innovations have brought forth machinery capable of operating autonomously, relying on data-driven insights, and reducing farming's environmental footprint. This transformation is vital as agriculture faces the dual challenge of producing more food with fewer resources. With the global population steadily increasing, food demand is rising, intensifying pressure on the agricultural sector. Modern agricultural machinery is critical to meeting this need, enhancing efficiency, lowering labor costs, and reducing environmental impact. As farmers confront issues like labor shortages, climate change, and resource scarcity, emerging technologies provide solutions that support both productivity and sustainability. According to GZ Industrial Supply (2025) and Croptracker (2025), the following emerging agricultural technologies demonstrate significant potential to enhance precision and productivity:

### Autonomous Machinery

Innovations such as self-operating tractors, harvesters, and drones represent a major milestone in agricultural technology. These machines, equipped with algorithms, GPS, and sensors, can perform tasks such as planting, tilling, and harvesting with little human oversight. Autonomous equipment increases efficiency, cuts labor costs, and enables continuous operation to maximize productivity.

### Drones and Aerial Imaging

Drones outfitted with sensors and high-resolution cameras allow farmers to survey fields quickly and accurately. They provide critical insights into crop health, pest infestations, and treatment effectiveness. Drones also enable precision pesticide and fertilizer application, reducing manual work while minimizing environmental harm.

**Precision Agriculture**

Also called precision farming, this method uses technology and data to fine-tune agricultural practices (Saikanth *et al*., 2024). GPS enables exact mapping and navigation, while sensors capture soil, crop, and weather data. AI systems analyze this information to optimize resource use, ensuring accurate application of seeds, fertilizers, and water. The result is reduced waste, higher yields, and better farm management.

**Robotics in Agriculture**

Robots designed for planting, weeding, and harvesting are addressing labor shortages while improving efficiency. Robotic harvesters handle produce gently to prevent damage, while weeding robots remove unwanted plants without chemicals, supporting sustainable farming.

**Electric and Hybrid Machinery**

The adoption of electric and hybrid-powered equipment is increasing. Electric tractors reduce emissions, lower costs, and operate quietly, while hybrids balance performance with environmental benefits. This trend aligns with global sustainability goals.

**Laser Scarecrows**

Birds can destroy large portions of crops in a short time, costing farmers significant revenue. Traditional scare tactics have often failed, but laser scarecrows – developed at the University of Rhode Island – project green laser beams a color that birds are highly sensitive to. These devices effectively deter pests, are environmentally friendly, and require less labor compared to alternatives like netting. Some models are solar-powered and feature auto-targeting, offering up to 90% crop protection (Croptracker, 2025).

**Bee Vectoring**

This innovative pest and disease management method, developed in Canada, uses bees to distribute a natural fungus called Vectorite (BVT-CR7). As bees leave their hives, they spread the solution across crops, improving disease resistance, enhancing growth, and extending shelf life—all without chemical pesticides (Croptracker, 2025).

**Harvest Quality Vision (HQV)**

Developed by Croptracker, HQV uses scanners to evaluate the quality and quantity of harvested produce, reducing reliance on manual inspections. The system identifies defects, diseases, and shortages early, enabling corrective action. At present applied to apple grading, HQV is expected to expand to other crops in the near future (Croptracker, 2025).

**Crop and Soil Monitoring**

Data collection is essential but time-consuming in precision farming. Tools like FarmBeats integrate drones, sensors, and satellites to create real-time, cloud-based farm performance models. Similarly, Agrocares and SGS offer soil fertility and nutrient analysis using cloud and GPS technologies, enabling more effective nutrient management and decision-making (Croptracker, 2025).

**Radio-Frequency Identification (RFID)**

RFID tags, unlike barcodes, can store more data and be read without direct contact. Croptracker applies RFID in crop harvesting, storage, and packaging to automate tracking, reduce errors, and improve traceability. This enhances consumer trust by providing detailed product origin information.

**Minichromosome Technology**

Genetic engineering advances allow for the use of minichromosomes – small DNA structures carrying limited genetic material – to enhance crop traits. This technology enables biofortification, drought resistance, and other improvements without interfering with a plant's natural growth, making it more acceptable to consumers than conventional genetically modified organisms (GMOs).

### Big Data and Analytics

Agricultural machinery now generates massive amounts of data, which can be analyzed to optimize resource use, predict equipment needs, and improve crop management. For instance, soil data informs fertilizer application, while equipment performance data helps prevent costly breakdowns.

### IoT Integration

IoT connects farming equipment to the internet, allowing for real-time monitoring of fuel levels, engine performance, and operational efficiency. Farmers can oversee machinery remotely, saving energy and streamlining operations.

### Artificial Intelligence (AI) and Machine Learning (ML)

AI systems analyze inputs from sensors and satellite imagery to forecast crop yields, detect pests, and suggest optimal planting conditions. ML algorithms enhance accuracy over time, supporting smarter, data-driven farming practices.

## CHALLENGES OF ADOPTION OF EMERGING TECHNOLOGIES

The integration and influence of emerging technologies in sustainable agriculture and rural development encounter multiple challenges and obstacles. These barriers often limit the full realization of the advantages offered by technology-driven farming practices (Saikanth *et al*., 2024).

### Financial Barriers

Advanced agricultural equipment usually requires substantial initial investment. The high purchase and implementation costs pose difficulties, particularly for small and medium-scale farmers. Although these technologies can deliver long-term benefits – such as improved efficiency and lower operating costs – the upfront financial burden can discourage adoption. Providing subsidies, financial support, and accessible credit mechanisms is critical to promote wider use of these innovations.

### Infrastructure and Connectivity

Many rural regions lack the infrastructure and reliable connectivity necessary to take full advantage of modern agricultural technologies. Since IoT systems and data-driven solutions depend heavily on consistent internet access, farmers in remote areas often face limitations. Bridging infrastructure gaps and enhancing connectivity are vital steps to ensure equitable access to technological benefits. Collaborative initiatives involving governments, technology providers, and local communities are essential to address these issues.

### Training and Workforce Readiness

With machinery and systems becoming increasingly sophisticated, farmers and agricultural workers need proper training to operate them effectively. Skills development programs and capacity-building initiatives are crucial to reduce the knowledge gap and prepare the workforce to adapt to technological changes. Continuous training and support will enable farmers to make full use of emerging tools and maximize their potential benefits.

### Resistance to Change

Some farmers remain reluctant to adopt new technologies due to uncertainty about their advantages or a strong preference for traditional farming methods.

### Regulatory Misalignment

Existing policies and regulatory frameworks are often ill-suited to accommodate new technologies in agriculture, creating uncertainty and restricting innovation.

### Weak Market Linkages

Limited access to markets and incomplete value chains reduce the economic incentives for adopting technology. Without strong market connections, the profitability of technological investments for farmers remains uncertain.

### Restricted Access to Credit

The lack of affordable credit options, combined with high upfront costs and uncertainty about returns, limits farmers' ability to invest in new equipment and technologies, slowing down adoption rates.

### Insufficient Continuous Support

Sustained adoption of technology requires ongoing learning and technical assistance. Without mechanisms for continuous education and support, farmers may struggle to keep up with evolving technologies. Overcoming these barriers requires a comprehensive strategy involving governments, NGOs, the private sector, and rural communities. Policymakers, in particular, have a central role in shaping an enabling environment that fosters technology adoption and ensures that the benefits of emerging innovations reach rural areas.

## OPPORTUNITIES OF EMERGING TECHNOLOGIES FOR FUTURE PERSPECTIVE IN NIGERIA

Emerging technologies are reshaping industries, economies, and societies on a global scale. Innovations such as AI, blockchain, quantum computing, 5G, and biotechnology are not only enhancing existing systems but also creating new ways of conducting business, communicating, and solving challenges (Daniel Schlepps, 2024). The potential applications of these technologies are vast.

### AI and ML

AI and ML are transformative tools with wide-ranging applications, including in agriculture. They support decision-making, optimize resource allocation, and increase farm efficiency. ML algorithms analyze diverse data sources – such as satellite images and drone data – to assess crop health and detect diseases early, enabling timely interventions (Jin X *et al*., 2020; Saikanth *et al*., 2024). Precision agriculture applies ML models to soil sensors, GPS, and weather station data for real-time recommendations on planting, fertilization, and irrigation, ultimately improving yields while conserving resources (Saikanth *et al*., 2024).

### Blockchain in Supply Chain Management

Blockchain has become valuable in agriculture for improving transparency, efficiency, and traceability within supply chains. By recording every stage of production and distribution on an immutable ledger, it ensures food safety and reduces fraud. Consumers can verify product origins, production methods, and certifications (Mou, 2020; Campos *et al*., 2019). Blockchain also supports rapid recalls of unsafe products, lowering risks of foodborne illnesses (Lebedev *et al.*, 2019). Its cryptographic safeguards protect data integrity, minimizing fraud and counterfeiting (Zhong *et al*., 2019).

### Climate-Resilient Farming Practices

Climate-smart agriculture involves adopting strategies that help farming systems withstand and adapt to climate change (Saikanth *et al*., 2024). This includes diversifying crops to reduce vulnerability, implementing efficient water management such as rainwater harvesting and precision irrigation (Pandey *et al*., 2017), and improving soil health through crop rotation, cover crops, and reduced tillage (Basso B *et al*., 2016). Accurate forecasts and early warning systems guide timely decisions (Kogan, 2019), while breeding climate-resilient crop varieties supports long-term food security (Dwivedi *et al*., 2019).

### E-commerce Platforms for Agribusiness

Digital marketplaces such as AgriMart and Farmers Business Network have modernized agriculture by linking farmers, agribusinesses, and consumers. They facilitate input purchases, produce sales, and provide real-time information on market prices and expert advice. By streamlining supply chains and enabling data-driven insights, these platforms foster growth, efficiency, and sustainability in agribusiness (Saikanth *et al*., 2024).

### Digital Financial Services (DFS)

DFS use mobile and digital technologies to provide farmers and other stakeholders with access to financial products. Mobile banking and payment

platforms enable digital transactions, reducing reliance on cash (Mas and Ng'weno, 2016). Digital lending platforms use data analytics to provide accessible credit (Morduch, 2019), while digital insurance services offer weather- and crop-based coverage (Karlan and Osei, 2018). Savings tools and financial planning apps empower farmers to better manage resources and plan investments (Gine *et al*., 2018).

### 5G Technology

The rollout of 5G provides faster speeds, low latency, and improved connectivity, opening new opportunities for IoT, autonomous vehicles, and smart cities (Daniel Schlepps, 2024). It supports real-time interactions across industries, such as enabling remote medical procedures, enhancing self-driving car communication, and improving urban systems like energy management and traffic flow.

### Biotechnology and Genomic Advances

Biotechnology – spanning genetic engineering, CRISPR, and synthetic biology – continues to revolutionize healthcare, agriculture, and environmental sustainability (Daniel Schlepps, 2024). In medicine, it enables treatments for genetic diseases and advances personalized medicine (Parveen and Akter, 2021). In agriculture, genetically modified crops boost food security by improving pest and disease resistance. Biotechnology also offers environmental benefits, including biofuel development and bioremediation.

### Quantum Computing

Quantum computing leverages qubits to process information in ways impossible for classical computers, enabling faster and more complex computations. This breakthrough holds major potential in industries requiring heavy data analysis. In pharmaceuticals, it can speed up drug discovery through molecular simulations (Bogren, Banu and Parvin, 2020). In finance, it offers new solutions for portfolio optimization, risk management, and cryptography. It also promises significant advancements in AI, ML, and cybersecurity.

## ETHICAL AND SOCIAL IMPLICATIONS ASSOCIATED WITH EMERGING TECHNOLOGIES

Although biotechnology holds promise for addressing some of the world's most urgent challenges, it also introduces serious ethical and societal dilemmas. Gene editing, for example, raises concerns about "designer babies" and the risk of unintended changes to the gene pool. The environmental effects of GMOs are also debated, along with questions of accessibility – advanced treatments may not be equally available to all populations (Zaman and Khaled, 2020). Emerging technologies may deepen the digital divide, especially in rural regions with limited access. Promoting fair access to both technology and knowledge is vital to prevent exclusion (Gupta *et al*., 2021). In agriculture, the collection and exchange of data bring issues of privacy and security, highlighting the need to protect farmers' personal and agricultural data while clearly defining ownership rights (Bilali *et al*., 2019). The adoption of new tools should support sustainable farming practices and avoid negative side effects such as greater energy consumption or pollution (Hobbs and Kerr, 2020).

Automation and AI introduce further ethical challenges by potentially displacing traditional agricultural jobs. This requires solutions that provide alternative livelihoods and address the social impacts of job losses (Lowder *et al*., 2019). Food safety and quality also remain critical; failure to uphold safety standards can put consumers' health at risk (Kumar *et al*., 2023). Beyond economics, new technologies can disrupt cultural traditions and farming practices, raising ethical questions about preserving cultural heritage and social cohesion (Hobbs and Kerr, 2020).

Intellectual property rights in agricultural technologies add another layer of complexity. Striking a balance between incentivizing innovation and serving the public good is a significant challenge (Stone, 2018). Furthermore, AI systems and algorithms can perpetuate bias, making transparency and accountability in their development essential (Friedler *et al*., 2019). Adequate training and education are equally important to ensure rural communities can benefit from these tools (Gupta *et al*., 2021).

Unequal distribution of technological benefits could create economic disparities, requiring policies that foster inclusive growth and shared benefits (Lowder *et al*., 2019). Strong regulatory frameworks are therefore crucial to address ethical concerns. Both governments and international organizations must establish clear standards and guidelines (Bilali *et al*., 2019). Ultimately, balancing the potential of biotechnology and emerging technologies with social and ethical responsibilities is key to promoting sustainable, equitable agricultural and rural development.

## CONCLUSION

Emerging technologies have the potential to revolutionize agriculture by addressing long-standing challenges of productivity, climate change, and food insecurity. From precision agriculture to biotechnology and blockchain-enabled supply chains, these innovations present transformative opportunities for efficiency, sustainability, and resilience. Nevertheless, their widespread adoption in Nigeria is hindered by financial, infrastructural, educational, and regulatory constraints. Overcoming these barriers requires collaborative efforts between governments, private stakeholders, researchers, and farming communities. Strategic investments in digital infrastructure, affordable financing, farmer capacity-building, and enabling policies will be critical to bridging the technological gap between developed and developing economies. If integrated effectively, these technologies will not only secure Nigeria's agricultural future but also catalyze broader economic growth and rural development, positioning the sector as a driver of national transformation.

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