CHAPTER-3

EVOLUTION OF THE AGRICULTURAL SYSTEM IN THE DIGITAL ERA

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Abstract

Few developments in recent decades have altered farming as fundamentally as the arrival of digital technology. This chapter offers a wide-ranging, multidisciplinary look at how agricultural systems have evolved in the digital era beginning with pre-industrial subsistence practices and moving through mechanization and precision agriculture, all the way to today's world of artificial intelligence (AI), the Internet of Things (IoT), big data analytics, robotics, blockchain, and satellite-based remote sensing. Drawing on peer-reviewed research, policy analyses, and evidence from every inhabited continent, the chapter examines digital agriculture through technological, environmental, economic, social, governance, and ethical perspectives. The central finding is this: while these tools genuinely improve crop yields, resource efficiency, and supply chain visibility, their full potential is held back by persistent inequities in access, infrastructure, and digital skills especially among smallholder farmers in lower-income countries. The chapter also explores emerging frontiers such as AI-assisted crop breeding, 5G-connected smart farms, edge computing, and the possible future role of quantum computing in agronomic data analysis. It closes with practical, evidence-grounded recommendations aimed at policymakers, technology developers, and farming communities who want a fairer and more sustainable path forward.

Keywords: Digital Agriculture, Precision Farming, Internet of Things, Artificial Intelligence, Big Data, Food Security, Sustainable Agriculture, Smart Farming, Digital Divide, Agroinformatics

1. Introduction

1.1. Overview of Traditional Agricultural Systems

For over ten thousand years, agriculture has been a cornerstone of human civilization. From the ancient settlements in the Fertile Crescent to the lush landscapes of the Yangtze River Delta, farming communities have thrived by deeply understanding local soil properties, seasonal cycles, and communal land-management traditions passed down through generations. Techniques like crop rotation, intercropping, fallowing, and terracing were sophisticated methods developed to maintain land productivity over extended periods. However, compared to modern standards, the output per worker was low, necessitating that pre-industrial societies allocate 80 to 90 percent of their population to agriculture just to meet their basic needs (FAO et al., 2021).

1.2. Understanding the Digital Era and Its Importance in Agriculture

When experts discuss the "digital era" in agriculture, they typically refer to the time starting in the late 1990s. This period is characterized by the convergence of advanced computing power, the expansion of mobile networks, and more affordable sensors, all of which have made data-driven farm management truly feasible. Unlike the Green Revolution of the 1960s, which focused on improved seeds, chemical fertilizers, and irrigation, the current transformation is primarily centered on information. It changes the way agricultural knowledge is collected, stored, disseminated, and utilized. The essence of digital farming lies in the integration of real-time data from satellites, field sensors, weather stations, drones, and trading platforms into a unified decision-making framework. Its impact extends far beyond merely boosting yields; it influences food security, environmental conservation, rural employment, and the management of global supply chains.

1.3. Importance and Scope

The impact of digital transformation in agriculture is extensive, encompassing areas such as precision crop management, automated equipment, supply chain monitoring, rural financial services, climate forecasting, and public policy. By 2021, the global agri-food technology sector had expanded to USD 22.3 billion and is projected to exceed USD 50 billion by 2028, fueled by investments in AI, IoT, and farm management software (Mourshed et al., 2022). With the global population anticipated to reach 9.7 billion by 2050, the UN Food and Agriculture Organization estimates that food production needs to increase by approximately 70 percent from current levels a goal that many believe is unattainable without significant technological advancements (FAO et al., 2021). This chapter explores the entire spectrum while adhering to one key principle: technology is never socially neutral. Its benefits and risks are not distributed equally across different regions, genders, or income groups.

2. Historical Evolution of Agricultural Systems

2.1. Pre-Digital Agricultural Practices

Throughout most of agricultural history, farming decisions were largely shaped by keen observations of the natural world, oral traditions passed down through generations, and community-based strategies for managing land and water resources. Farmers created detailed mental calendars that tracked the timing of flowering, bird migrations, and seasonal weather patterns to identify optimal planting and harvesting periods. Despite this extensive knowledge, pre-digital agriculture faced significant challenges, including substantial post-harvest losses, limited market transparency, and restricted access to credit or insurance. For instance, in sub-Saharan Africa, post-harvest losses of staple grains frequently reached 20–30 percent due to inadequate storage facilities and a lack of market information structural issues that would later become key targets for digital solutions.

2.2. Mechanization and Early Technological Interventions

The advent of mechanization marked a pivotal moment in modern agriculture, propelled by the Industrial Revolution. Innovations in machinery for tasks such as threshing, planting, and irrigation transformed the dynamic between human labor and agricultural output in ways that manual tools could not achieve. The mid-twentieth century then saw the Green Revolution, which brought about the introduction of compact, high-yield wheat and rice strains, synthetic nitrogen fertilizers, and organized irrigation systems. These advancements led to significant yield increases across regions like South Asia, Latin America, and parts of Africa, results that previous generations could scarcely have imagined. However, these gains came with environmental drawbacks, including soil degradation, declining water levels, and reduced crop diversity. By the 1970s and 1980s, early computers began to appear on farms, utilized in management information systems and crop models such as DSSAT, while geographic information systems started mapping soils, setting the stage for precision agriculture.

2.3. Transition Phases Leading to Digital Adoption

Digital farming evolved gradually through a series of overlapping phases. The initial stage, which occurred from the 1980s to the 1990s, saw the introduction of GPS receivers on tractors and other equipment, allowing for variable-rate inputs and management on a field-by-field basis. The removal of GPS signal restrictions in 2000 significantly enhanced positioning accuracy, making precision agriculture economically viable for standard commercial operations. The second phase emerged during the 2000s and 2010s, characterized by the rapid proliferation of mobile phones in developing areas, which provided farmers with access to market prices and weather updates via simple SMS services. Despite their simplicity, these tools significantly improved decision-making. Since around 2015, a third and more transformative phase has been unfolding, characterized by the concurrent rise of AI, IoT sensors, big data platforms, robotics, blockchain, and remote sensing. These technologies have integrated into smart-farming systems capable of near-real-time analysis and, in some instances, autonomous actions at a scale and speed beyond human capability (CGIAR et al., 2022).

3. Key Digital Technologies Transforming Agriculture

3.1. Precision Agriculture: GPS, Drones, and Sensors

Precision agriculture integrates satellite positioning, sensing technologies, and equipment for variable-rate application to manage different sections of a field uniquely, acknowledging that soil, crop, and pest conditions can vary greatly even within a single farm. Drones equipped with multispectral, hyperspectral, LiDAR, or thermal cameras can swiftly produce detailed maps of crop health, canopy structure, water stress, and pest activity at a fraction of the cost of traditional aerial surveys. Studies indicate that using drones for spraying can reduce pesticide usage by up to 40 percent without compromising pest control (Sishodia et al., 2020). On the ground, networks of soil moisture probes, weather stations, leaf sensors, and nutrient analyzers continuously supply root-zone data to crop models, which can predict yield outcomes weeks before harvest allowing farmers to take corrective action when conditions begin to deteriorate.

3.2. Internet of Things in Farming

The Internet of Things (IoT) in agriculture, also referred to as the Internet of Agricultural Things (IoAT), consists of a network of physical devices equipped with sensors, actuators, and wireless communication technology. These devices autonomously gather and exchange data, eliminating the need for manual data collection. Such interconnected devices are now integrated into every phase of food production, including automated irrigation systems, climate-controlled greenhouses, cold-chain monitoring units, and biometric devices attached to livestock. In numerous applications, edge computing units perform initial data processing on-site, reducing response times and enabling immediate actions, such as opening an irrigation valve, without waiting for a cloud server's response. Livestock management is perhaps the most commercially developed sector of agricultural IoT, with ear tags and rumination collars capable of continuously monitoring each animal's movements, feed consumption, body temperature, and reproductive cycles (Verdouw et al., 2021).

3.3. Big Data Analytics and Artificial Intelligence

Modern agriculture generates a vast and diverse array of data, including satellite imagery, sensor outputs, climate data, genetic information, and market prices. Collectively, these elements create what experts refer to as an agricultural big data ecosystem, marked by its immense volume, swift pace, varied formats, uncertain quality, and significant economic potential. Machine learning and deep learning have demonstrated their effectiveness in numerous agricultural applications, such as detecting plant diseases in leaf photos, identifying weeds in field images, predicting yields using time-series satellite data, and categorizing soils through hyperspectral scans. In controlled experiments, convolutional neural networks have equalled or even outperformed experienced agronomists in diagnosing crop diseases. Recently, large language models and other generative AI tools have introduced a new era in farm advisory services, providing farmers in remote locations with personalized, scientifically grounded advice in straightforward language essentially offering the convenience of having a knowledgeable agronomist at their fingertips (Xu et al., 2024).

3.4 Robotics and Automation

Agricultural robotics encompasses devices engineered to handle physically taxing or repetitive farming activities such as sowing seeds, removing weeds, applying pesticides, harvesting fruits, and sorting agricultural products. Significant progress in computer vision, tactile grippers, motion planning, and battery advancements has brought these machines closer to being commercially viable, despite the ongoing engineering challenges posed by harsh and unpredictable outdoor environments. Notable development is occurring in the area of selective-harvest robots for high-value crops like strawberries, tomatoes, peppers, and apples, where labor expenses are substantial and shortages are frequent. Autonomous tractors and lightweight field robots equipped with centimeter-level GPS accuracy are already prevalent on large cereal farms, facilitating continuous fieldwork, minimizing soil compaction compared to heavier manned vehicles, and producing detailed records of crop conditions on a row-by-row basis (Fountas et al., 2020).

3.5. Blockchain for Supply Chain Transparency

Blockchain, a decentralized ledger that records transactions in a manner that makes them extremely hard to modify, holds significant potential for food supply chains that must be reliable from farm to shelf. Each transaction, temperature measurement, certification verification, and ownership change can be documented in a way that any authorized individual can verify, yet no single entity can alter without detection. IBM Food Trust, which Walmart uses to monitor leafy greens, notably reduced the time needed to trace produce from about seven days to just 2.2 seconds. However, expanding blockchain across multinational, multi-stakeholder supply chains is not simple: challenges include technical interoperability, governance frameworks, and the high energy consumption of older consensus mechanisms. Consequently, many recent implementations are shifting towards permissioned blockchain designs that are quicker and consume less energy (Kamble et al., 2020).

3.6. Remote Sensing and Satellite Imagery

The advent of commercial satellite constellations operating at low altitudes has revolutionized the observation of farmland from space. Planet Labs' Dove network revisits every location on Earth daily with a resolution of three meters, while the European Space Agency's Sentinel program offers free imagery at ten-meter resolution. Together, these resources facilitate a new era of crop monitoring, yield forecasting, and food security tracking systems. Vegetation indices derived from multispectral data serve as indicators of crop health and photosynthetic activity. Analysts are increasingly incorporating red-edge, shortwave infrared, and synthetic aperture radar (SAR) data to identify drought stress, map soil moisture, detect flooding, and monitor agricultural expansion in near real time (Weiss et al., 2020). The combination of free Sentinel imagery and accessible cloud computing has made advanced satellite-based monitoring available to research institutions and governments that could not have afforded it a decade ago.

4. Digital Agriculture and Sustainable Farming

4.1. Resource Optimization: Water and Fertilizers

Agriculture accounts for approximately 70 percent of the global freshwater usage, highlighting the importance of optimizing water use for both food production and environmental sustainability. Advanced irrigation systems, which integrate soil moisture sensors, evapotranspiration data, weather information, and automated valve controls, have demonstrated a reduction in water consumption by 20 to 50 percent in field tests compared to traditional fixed-schedule irrigation. Regarding nutrients, the use of variable-rate fertilizer application, informed by soil maps, canopy reflectance data, and growth models, can significantly reduce nitrogen excess one of the primary contributors to nitrate contamination in waterways and nitrous oxide emissions without compromising crop yields. Research from U.S. farms indicates that those employing precision agriculture techniques use about 7 percent less nitrogen per acre than those who do not, while maintaining comparable yields, resulting in both cost savings and environmental benefits (Balafoutis et al., 2017).

4.2. Environmental Monitoring and Climate-Smart Agriculture

Farms are increasingly adopting digital monitoring tools not only to enhance productivity but also to assess and mitigate their environmental impact. Life-cycle assessment software integrated with farm management platforms can evaluate carbon footprints, water consumption, and biodiversity scores at the field level, providing operators with concrete data to inform sustainability decisions. Satellite deforestation alerts—provided by systems like Brazil's PRODES program and Global Forest Watch, which utilize machine learning to analyze Landsat and Sentinel imagery enable near-real-time identification of illegal forest clearing for agriculture and assist regulators in enforcing land-use laws (IEA et al., 2022). Climate-smart agriculture, which aims to increase yields, enhance resilience to weather shocks, and reduce greenhouse gas emissions simultaneously, relies heavily on these digital tools as its operational foundation. Models such as DSSAT and APSIM, when supplied with local soil and weather data and run against downscaled climate projections, can identify the crop varieties, planting schedules, and irrigation strategies most likely to succeed as climates change (OECD et al., 2022).

4.3. Biodiversity and Soil Health

The advent of affordable near-infrared spectroscopy sensors has greatly eased the process of evaluating soil health. These sensors can directly assess organic carbon, nutrient levels, pH, and microbial activity from field samples, thus removing the necessity for laboratory testing. By combining this continuous data with farm management records, it becomes possible to devise specific strategies such as planting cover crops in the best locations, practicing reduced tillage, and adding compost to soils lacking nutrients to progressively increase organic matter. Furthermore, digital tools are being employed in biodiversity studies: environmental DNA metabarcoding, analyzed by AI-powered species recognition algorithms, allows both researchers and farmers to quickly and non-invasively assess soil microbial communities, pollinator populations, and aquatic organisms in farm catchments. This method aids in detecting early signs of ecosystem stress before they become irreversible (Wolfert et al., 2017).

5. Socioeconomic Impacts of Digital Agriculture

5.1. Farmer Livelihoods and Rural Economies

The economic narrative surrounding digital agriculture is characterized by significant disparities in benefits rather than widespread prosperity. Large-scale commercial farms in regions like North America, Europe, and Australia have typically been the first to reap the rewards, experiencing yield increases of 5–15 percent and reductions in input costs of 10–20 percent through precision management techniques. In stark contrast, smallholder farmers, who collectively manage over 80 percent of the world's farms and provide about 70 percent of the food consumed in lower-income nations, face a much more complex decision-making process when it comes to adopting digital tools. This involves weighing factors such as initial costs, connectivity, and the tools' relevance. While mobile-based price and market services have, in several well-documented instances, helped balance bargaining power and narrow the price gaps exploited by intermediaries, these achievements are sporadic rather than widespread (Aker, 2011).

5.2. Digital Divide and Access

The gap between those who can effectively use digital agricultural tools and those who cannot is shaped by a variety of overlapping factors, including location, household income, gender, age, and language. Despite the rapid expansion of mobile coverage in many developing regions, having coverage on a map does not always translate to practical use. Obstacles such as the cost of devices, mobile data expenses, unreliable electricity, and the absence of content in local languages prevent farmers from accessing valuable digital services. As of 2023, the International Telecommunication Union noted that around 2.7 billion people worldwide were without internet access, with most living in rural farming areas in sub-Saharan Africa, South Asia, and Southeast Asia (ITU et al., 2023). The GSMA Mobile Economy Report supports this observation, emphasizing connectivity gaps that disproportionately impact agricultural households in these areas (GSMA et al., 2023).

5.3. Gender and Inclusivity

In lower-income nations, women constitute about 43 percent of the agricultural workforce, yet they consistently fall behind their male counterparts in the use of digital tools. This disparity highlights broader issues such as unequal land ownership, restricted mobility, limited educational opportunities, and lesser influence in household decisions. Programs that fail to specifically address these barriers often exacerbate the gap, leaving women further behind. Conversely, initiatives that are designed with women in mind from the outset such as providing group-based digital training, employing female extension officers, and creating advisory content tailored to women's specific roles in farming have led to significantly more equitable results in both technology adoption and farm productivity (Quisumbing et al., 2014).

5.4. Policy Frameworks

Effective digital farming policies need to address several key areas: investment in rural broadband and electricity, regulations on data privacy and ownership, protection of intellectual property for software and algorithms, enhancement of extension services, and safety-net programs for rural workers affected by automation. The European Union's Farm to Fork Strategy views digital tools as essential to its sustainability goals and has pledged to create a unified European agricultural data space with standardized governance. Similar national strategies have been established in Australia, India, Brazil, and various African nations collaborating under the Smart Africa Alliance framework (OECD et al., 2023). Meanwhile, UNESCO's work on measuring ICT skills highlights an often-overlooked point: all the hardware and connectivity in the world are of little use if farmers cannot comprehend and utilize the information they generate (UNESCO et al., 2023).

6. Data Management and Cybersecurity in Agriculture

6.1. Data Generation and Storage Challenges

In today's interconnected agricultural landscape, farms produce data at a scale unimaginable just ten years ago. A single farm operation equipped with IoT sensors, drones, GPS-guided tractors, and satellite imagery subscriptions can gather several terabytes of raw data in one growing season. The challenge lies not only in the sheer volume but also in the diversity of data: information from various sensors, mapping platforms, weather services, and management software often comes in incompatible formats, coordinate systems, and timescales, making it truly challenging to integrate and analyze across different sources. Cloud platforms from companies like Amazon Web Services, Microsoft Azure FarmBeats, and Google Cloud for Agriculture have become the go-to solution, providing scalable storage and computing power along with machine learning tools specifically designed for geospatial tasks (Microsoft et al., 2021).

6.2. Privacy, Ownership, and Ethics

The issue of who actually owns the data produced by farms has become a particularly complex challenge in agricultural governance. In practice, most farmers end up handing over their data to platform companies by agreeing to terms-of-service agreements they rarely read, which leaves them with little control over how their data is used, shared, or monetized. Critics argue that relying on the industry's goodwill is inadequate to protect farmers from the combined market power of large agribusiness and tech companies. They assert that enforceable regulations, akin to the EU’s General Data Protection Regulation, are the only feasible solution. Initiatives like GODAN have sought to create open data standards and application programming interfaces, allowing farmers to move their data across platforms without being confined by proprietary systems an essential step toward rebalancing power dynamics (GODAN et al., 2022).

6.3. Cybersecurity Threats

As farming becomes increasingly interconnected, it becomes a more attractive target for cybercriminals. These threats can include ransomware that locks up farm management software, hackers tampering with automated irrigation or feeding systems, theft of proprietary field data, or disruptions to logistics platforms that facilitate food movement through supply chains. The 2021 ransomware attack on JBS Foods, one of the world's largest meat processing companies, highlighted the potential scale of such disruptions: processing plants in three countries were shut down, and the company paid USD 11 million to regain control (FBI et al., 2021). Vulnerabilities at the farm level are just as significant. Connected irrigation systems and automated livestock housing provide entry points that attackers could exploit, leading to costly operational failures or safety issues.

7. Digital Systems in Agricultural Value Chains

7.1. Digital Marketplaces and Finance

Digital trading platforms have swiftly expanded in both developed and developing agricultural economies, facilitating direct connections between buyers and sellers, eliminating unnecessary middlemen, and providing farmers with access to previously hidden or unavailable price information. In sub-Saharan Africa, platforms like Twiga Foods in Kenya and Hello Tractor, which operates across various African markets, have shown that digital intermediation can enhance market access for smallholders while minimizing spoilage losses that often occur along poorly connected supply chains (Reardon et al., 2021). A related issue is financial access: as of 2021, approximately 1.4 billion adults globally were unbanked, with rural farming households representing a significant portion (Demirgüç-Kunt et al., 2022). In some areas, mobile money has transformed this situation by enabling savings, loans, and payments without the need for a traditional bank. Index-based crop insurance products, which are automatically triggered by weather data or satellite vegetation indices instead of farm inspections, have also expanded through these mobile channels, reaching smallholder farmers who previously lacked protection against climate-related risks.

7.2. Supply Chain Traceability

There is a growing interest among consumers in understanding the origins and production processes of their food, a trend fueled by frequent food safety incidents and increasing concerns about sustainability and labor practices. This has led to substantial investments in digital traceability systems that utilize various technologies: IoT sensors to track temperature and humidity in cold chains, QR codes and RFID tags for product identification, satellite imagery to confirm origin claims, and blockchain ledgers to establish tamper-proof audit trails. When these elements function together seamlessly, it becomes feasible to track a product's condition almost in real time from the farm to the store shelf, minimizing spoilage risks, allowing for quicker responses to safety issues, and providing the documentation that premium and regulated markets are increasingly demanding (CGIAR et al., 2022; Kamble et al., 2020).

8. Challenges and Barriers to Digital Agriculture Adoption

8.1. Infrastructure Limitations

Many digital farming technologies depend on two essential resources that are often lacking in rural areas: reliable internet access and consistent electricity. According to the International Energy Agency, approximately 770 million individuals were without electricity in 2022, mainly in rural parts of sub-Saharan Africa and South Asia, where smallholder farming is prevalent (IEA et al., 2022). Efforts to address this issue include the creation of low-earth-orbit satellite broadband, TV white-space radio networks, community mesh systems, and solar-powered Wi-Fi hotspots. However, these initiatives have not yet provided the necessary coverage, affordability, and reliability to bridge the rural connectivity gap on the required scale (ITU et al., 2022). As a result, digital agriculture remains more of a theoretical concept than a practical reality for many smallholder farmers worldwide until these infrastructure challenges are resolved.

8.2. Cost, Affordability, and Digital Literacy

The initial expense of precision agriculture tools such as variable-rate applicators, drone fleets, sensor networks, and automated irrigation systems is excessively high for many small-scale farmers who work with narrow profit margins and have limited access to affordable financing. To make these technologies more accessible without requiring full ownership, options like equipment-sharing programs, rental agreements, and pay-per-hectare service models are being developed, although widespread implementation has been gradual. Even when the necessary hardware and connectivity are available, effectively utilizing digital tools requires more than just having a functional phone. Farmers must comprehend the data, balance digital recommendations with their own practical knowledge, and apply remotely generated instructions to the specific conditions of their land (UNESCO et al., 2023). Developing this capability requires time, ongoing support, and locally trusted channels, none of which can be achieved through a single training session.

8.3. Cultural and Institutional Factors

Farmers rarely base their decisions to adopt new technologies solely on financial considerations. Their decisions are shaped by cultural values, social trust, risk tolerance, and the compatibility of new tools with their existing practices. For families whose livelihood depends on the yield of a single season, the failure of a new technology can result in genuine hunger, leading to a cautious approach that outsiders might mistakenly see as reluctance. Social learning is vital: farmers watch their neighbors and are more inclined to embrace innovations that have been successfully tested and approved by trusted peers. Agricultural extension services, which are the main conduit for transferring knowledge from research institutions to farms, are being modernized to include digital delivery methods. However, they encounter significant resource constraints in many low-income countries, where the ratio of extension staff to farmers can reach one to three thousand.

9. Future Trends and Innovations in Digital Agriculture

9.1. AI-Driven Crop Breeding and Gene Editing

The integration of artificial intelligence with genomic science is unlocking new opportunities in plant breeding that were inconceivable a generation ago. By utilizing machine learning on extensive genomic, phenotypic, and environmental datasets, researchers can swiftly pinpoint genetic markers linked to traits such as drought resistance, disease resilience, and nitrogen efficiency, significantly reducing the time needed to develop enhanced varieties from decades to just a few years. The CRISPR-Cas9 gene-editing technology further enhances this process by enabling precise alterations at specific sites within a plant's genome, bypassing the lengthy cross-breeding cycles of traditional methods and avoiding the introduction of foreign DNA typical of older transgenic techniques. Regulatory perspectives on gene-edited crops are shifting: countries like the United States, Japan, and Argentina, along with an increasing number of others, have established frameworks that differentiate gene editing from conventional genetic modification, potentially speeding up the transition from laboratory research to agricultural application (Scheben et al., 2017).

9.2. Smart Farming Ecosystems and Integrated Platforms

In the long run, digital agriculture is moving towards more integrated systems that connect field sensors and actuators, farm management software, supply chain platforms, financial services, and regulatory reporting into unified data environments based on agreed open standards. Digital twins, which are computational models of a physical farm that replicate real conditions and conduct simulations to explore outcomes under various management scenarios or weather events, are becoming a practical tool for this type of integration (Verdouw et al., 2021). In parallel with these technical advancements, open data standards initiatives, such as GODAN, are striving to develop common data models and application interfaces that enable seamless information exchange between systems, preventing farmers from being tied to a specific commercial platform (GODAN et al., 2022).

9.3. 5G, Edge Computing, and Quantum Computing

Fifth-generation wireless networks bring three essential advantages to farm automation: minimal latency, the ability to handle a large number of connected devices simultaneously, and substantial data throughput. With 5G coverage, tasks that previously needed communication with a remote server such as coordinating drone fleets, navigating autonomous vehicles through complex terrains, or performing real-time video analysis of crop conditions can now be executed at the field's edge. Edge computing further enhances this by embedding processing power directly into field equipment, enabling crucial decisions to be made locally even when network connectivity is limited or absent. Looking ahead, quantum computing, though largely theoretical at present, holds exciting potential: quantum optimization algorithms could transform logistics scheduling and procurement decisions in supply chains too intricate for traditional computers to manage efficiently, while quantum machine learning techniques could greatly accelerate genomic analysis in breeding programs (Bornmann & Haunschild, 2021).

10. Governance, Ethics, and Agricultural Knowledge Systems

10.1. Algorithmic Decision-Making and Farmer Agency

As AI systems increasingly influence farmers' decisions on crop selection, irrigation timing, and pesticide application, a vital question emerges regarding who truly controls these farming choices. When these systems offer incorrect advice, it is the farmer who suffers the consequences, often without the ability to comprehend the model's logic or contest its results. This issue extends beyond mere inconvenience; it fundamentally challenges the farmer's autonomy in managing their farm. Experts in explainable AI (XAI) emphasize that agricultural advisory systems should be designed to make their recommendations transparent to those who must implement them clarifying not only the actions to take but also the rationale behind them and the degree of certainty involved (Klerkx et al., 2019). Beyond individual guidance, there is a larger structural concern: as numerous farm decisions are consolidated into centralized platforms, the resulting collective intelligence becomes a commercially valuable asset that can be used to predict commodity markets, influence input pricing strategies, or guide investment decisions none of which necessarily benefit the farmers whose data enabled this (Bronson & Knezevic, 2016).

10.2. Data Ownership, Platform Power, and Open Standards

The political economy related to agricultural data infrastructure is becoming a significant governance challenge for the coming decade. A small number of large agribusiness and technology companies currently control proprietary farm management platforms that collectively handle data from hundreds of millions of hectares worldwide. This concentration of control raises legitimate concerns about competition in input markets, future pricing trends of these platforms, and the potential consequences for farmers if a major provider fails or changes its terms. Achieving interoperability, which allows for the seamless exchange of data between systems without being confined to proprietary formats, is an essential technical and regulatory objective. However, voluntary industry initiatives have had limited success because dominant platforms have strong commercial incentives to maintain closed ecosystems (Carolan, 2017). Some regions are moving towards regulatory solutions: the European Commission's proposed Data Act includes provisions that would require manufacturers to give farmers real-time access to machine-generated data, marking a significant shift in the current power dynamics. Public investment in open data infrastructure, such as the CGIAR's Digital Innovation Initiative, offers an alternative by establishing neutral, shared foundations that support both commercial and public applications without the risks associated with private monopoly control.

10.3. Indigenous and Local Knowledge in the Digital Age

In the rapid growth of digital agricultural advisory systems, a significant risk that is often ignored is the marginalization of indigenous and local knowledge. This knowledge consists of practical ecological insights that farming communities have gathered over generations through direct experience with specific soils, crops, microclimates, and pests. AI models, which are mainly trained using data from large commercial farms in temperate regions, may not be effective when applied to smallholder systems in tropical areas. This is not a fault of the technology itself but rather a result of the training data not accurately reflecting those conditions. Researchers have persuasively argued that indigenous agricultural knowledge and formal scientific data should be viewed as complementary rather than competing sources of intelligence. By combining them, advisory systems become more locally accurate, gain greater trust from the farmers they serve, and are more likely to be adopted (Klerkx et al., 2019). Participatory design approaches, where farmers are involved as co-creators rather than passive users of technology, have shown promising results in promoting this kind of integration. Platforms like Digital Green, which supports farmer-generated video content and peer-to-peer learning across South Asia and East Africa, demonstrate that locally produced knowledge, when shared through appropriate channels, can spread effectively and lead to real agronomic improvements (Aker, 2011).

10.4. Labour Displacement, Equity, and the Ethics of Automation

Automation technologies, including self-operating harvesters, AI-powered spray drones, and algorithm-driven labor scheduling systems, are anticipated to greatly diminish agricultural employment, particularly in labor-intensive horticulture sectors in developing nations where farming is a primary income source for numerous rural communities. Although automation enhances efficiency, these advantages mainly benefit farm owners and tech firms, while the burdens fall on workers who often lack social safety nets, retraining opportunities, or political representation to ensure equitable outcomes. Sparrow and Howard (2021) argue that the consequences of labor displacement should be considered a matter of distributive justice rather than just an economic adjustment. Proper governance of agricultural automation requires a thorough assessment of potential employment impacts, enforceable measures to support workers during transitions, and mechanisms for income protection elements largely absent from current national digital agriculture strategies, which typically prioritize productivity and environmental objectives while treating labor impacts as secondary. Closing this gap will necessitate genuine collaboration among governments, agricultural organizations, technology developers, and worker representatives, aiming to ensure that efficiency gains do not disadvantage those least equipped to handle them.

11. Conclusion

Digital technology has fundamentally transformed the possibilities within agriculture, influencing how fields are observed, resources are distributed, crops are developed, supply chains are managed, and how farmers engage with markets and financial services. Tools such as precision sensing, artificial intelligence, autonomous equipment, satellite monitoring, and blockchain-enabled traceability have evolved from mere research interests to practical applications on farms across six continents, resulting in significant improvements in yield, resource efficiency, and environmental performance wherever conditions have allowed for their adoption. However, the same evidence discussed in this chapter also highlights that these advancements have not been equitably distributed. Large commercial farms with access to capital, connectivity, and technical support have reaped most of the benefits, while the vast number of smallholder farmers, who provide food for the majority in lower-income countries, remain excluded from the digital shift not due to irrelevance but because of lacking infrastructure, high costs, weak institutions, contested data governance, and advisory systems not tailored to their needs. Bridging this gap requires more than just better apps or cheaper sensors. It necessitates treating rural connectivity and electricity as public goods, establishing data governance frameworks that empower farmers with control over the data generated from their land, and developing breeding and advisory tools that cater to the diversity of global farming systems rather than just the wealthiest. Additionally, there must be an honest assessment of the labor displacement caused by automation in farming communities that lack a safety net. The core insight reiterated throughout this chapter is that technology does not dictate its own outcomes: the decisions made by governments, companies, researchers, and farming communities regarding access, terms, and beneficiaries will ultimately determine whether digital agriculture becomes a means for shared prosperity or a new way to exacerbate existing inequalities.

References

CGIAR. (2022). Digital transformation of food, land, and water systems. CGIAR Initiative on Digital Innovation. https://www.cgiar.org/cgiar-research-portfolio-2025-2030/digital-transformation

Aker, J. C. (2011). Dial "A" for agriculture: A review of information and communication technologies for agricultural extension in developing countries. Agricultural Economics, 42(6), 631–647.doi: 10.1111/j.1574-0862.2011.00545.x

Balafoutis, A. T., Beck, B., Fountas, S., Vangeyte, J., van der Wal, T., Soto, I., Gomes-Barbosa, M., Pedersen, S. M., & Jacobsen, B. H. (2017). Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. Sustainability, 9(8), 1339. https://doi.org/10.3390/su9081339

Bornmann, L., & Haunschild, R. (2021). Can the number of citations received by scientific papers be predicted by altmetrics? A bibliometric analysis on the field level. Quantitative Science Studies, 2(4), 1374–1396.

Bronson, K., & Knezevic, I. (2016). Big data in food and agriculture. Big Data & Society, 3(1), 2053951716648174.doi: 10.1177/2053951716648174.

Carolan, M. (2017). Publicising food: Big data, precision agriculture, and co-experimental techniques of addition. Sociologia Ruralis, 57(2), 135–154.doi: 10.1111/soru.12120.

Demirgüç-Kunt, A., Klapper, L., Singer, D., Ansar, S., & Hess, J. (2022). The Global Findex Database 2021: Financial inclusion, digital payments, and resilience in the age of COVID-19. World Bank.doi: 10.1596/978-1-4648-1897-4.

Embrapa. (2022). Strategic plan 2030: Agriculture and the challenges of society. Brazilian Agricultural Research Corporation. https://www.embrapa.br/en/visao-de-futuro-do-agro-brasileiro.

FAO. (2021). The state of food and agriculture 2021: Making agrifood systems more resilient to shocks and stresses. Food and Agriculture Organization of the United Nations.https://doi.org/10.4060/cb7351en.

FBI. (2021). FBI flash alert: Cyberattack on JBS Foods (Alert Number CP-000147-MW). Federal Bureau of Investigation Cyber Division. https://www.fbi.gov/news/press-releases/fbi-statement-on-jbs-cyberattack.

Fountas, S., Mylonas, N., Malounas, I., Rodias, E., Hellmann Santos, C., & Pekkeriet, E. (2020). Agricultural robotics for field operations. Sensors, 20(9), 2672. https://doi.org/10.3390/s20092672.

GODAN. (2022). Open data in agriculture and nutrition: A synthesis of current knowledge and recommendations for action. Global Open Data for Agriculture and Nutrition. https://www.data4sdgs.org/partner/global-open-data-agriculture-and-nutrition.

GSMA. (2023). The mobile economy 2023. GSMA Intelligence. https://event-assets.gsma.com/pdf/20231017-GSMA-Mobile-Economy-Sub-Saharan-Africa-report.pdf.

IEA. (2022). World energy outlook 2022. International Energy Agency. https://www.iea.org/reports/world-energy-outlook-2022.

ITU. (2022). Measuring digital development: ICT price trends 2021. International Telecommunication Union. https://www.itu.int/hub/publication/d-ind-ict_mdd-2022/.

ITU. (2023). Measuring digital development: Facts and figures 2023. International Telecommunication Union.https://www.itu.int/itu-d/reports/statistics/wp-content/uploads/sites/5/2023/11/Measuring-digital-development-Facts-and-figures-2023-E.pdf.

Kamble, S. S., Gunasekaran, A., & Sharma, R. (2020). Modeling the blockchain enabled traceability in agriculture supply chain. International Journal of Information Management, 52, 101967. 10.1016/j.ijinfomgt.2019.05.023.

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. NJAS Wageningen Journal of Life Sciences, 90–91, 100315. https://doi.org/10.1016/j.njas.2019.100315

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

Microsoft. (2021). Project FarmBeats: AI and IoT for agriculture. Microsoft Research. https://www.microsoft.com/en-us/research/project/farmbeats-iot-agriculture/

Ministry of Agriculture and Farmers Welfare, India. (2021). Digital agriculture mission 2021–2025. Government of India.

Mohanty, S. P., Hughes, D. P., & Salathé, M. (2016). Using deep learning for image-based plant disease detection. Frontiers in Plant Science, 7, 1419. https://doi.org/10.3389/fpls.2016.01419

Mourshed, M., Dawson, R., & Wallbaum, H. (2022). Agri-food technology market outlook 2022–2028. McKinsey Global Institute.

OECD. (2022). Agricultural policy monitoring and evaluation 2022: Reforming agricultural policies for climate change mitigation. OECD Publishing. https://www.oecd.org/en/publications/2022/06/agricultural-policy-monitoring-and-evaluation-2022_0969ef7b.html.

OECD. (2023). Agricultural outlook 2023–2032. OECD Publishing and FAO. https://www.oecd.org/en/publications/2023/07/oecd-fao-agricultural-outlook-2023-2032_859ba0c2.html.

Reardon, T., Tschirley, D., Liverpool-Tasie, L. S. O., Awokuse, T., Fanzo, J., Minten, B., & Herforth, A. (2021). The processed food revolution in African food systems and the double burden of malnutrition. Global Food Security, 28, 100466. https://doi.org/10.1016/j.gfs.2020.100466

Quisumbing, A. R., Meinzen-Dick, R., Raney, T. L., Croppenstedt, A., Behrman, J. A., & Peterman, A. (Eds.). (2014). Gender in agriculture: Closing the knowledge gap. Springer and FAO.

Scheben, A., Yuan, Y., & Edwards, D. (2017). Advances in genomics for adapting crops to climate change. Current Plant Biology, 6, 2–10. https://doi.org/10.1016/j.cpb.2016.09.001

Shepherd, M., Turner, J. A., Small, B., & Wheeler, D. (2020). Priorities for science to overcome hurdles thwarting the full promise of the 'digital agriculture' revolution. Journal of the Science of Food and Agriculture, 100(14), 5083–5092. https://doi.org/10.1002/jsfa.9346

Sparrow, R., & Howard, M. (2021). Robots in agriculture: Prospects, impacts, ethics, and policy. Precision Agriculture, 22(3), 818–833.https://doi.org/10.1007/s11119-020-09757-9

Sishodia, R. P., Ray, R. L., & Singh, S. K. (2020). Applications of remote sensing in precision agriculture: A review. Remote Sensing, 12(19), 3136. https://doi.org/10.3390/rs12193136

UNESCO. (2023). Towards an ICT skills measurement framework for education. UNESCO Institute for Statistics. https://www.unesco.org/gem-report/en/publication/technology

Verdouw, C., Tekinerdogan, B., Beulens, A., & Wolfert, S. (2021). Digital twins in smart farming. Agricultural Systems, 189, https://doi.org/103046.10.1016/j.agsy.2020.103046

Weiss, M., Jacob, F., & Duveiller, G. (2020). Remote sensing for agricultural applications: A meta-review. Remote Sensing of Environment, 236, 111402. https://www.sciencedirect.com/science/article/pii/S0034425719304213

Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming-A review. Agricultural Systems, 153, 69–80. https://doi.org/10.1016/j.agsy.2017.01.023

Xu, J., Sharma, P., Shen, J., & Sun, Y. (2024). Interactive natural language processing for agricultural advisory systems: A review of large language model applications. Computers and Electronics in Agriculture, 220, 108872.