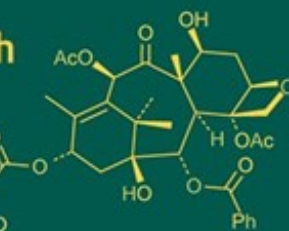
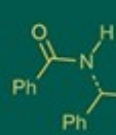


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Digital agriculture, horticulture and agriculture 4.0: Technologies, applications and opportunities for improving agricultural and horticultural productivity and farmer livelihoods: A review

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ABSTRACT

The rapid integration of digital technologies, collectively associated with Horticulture –and Agriculture 4.0, is transforming agricultural production, farm management, extension delivery and agri-food supply chains. Conventional agricultural and horticulture systems often depend on generalized recommendations and periodic field observations, which can limit the ability of farmers to respond to spatial and temporal variability in soil, crops, weather, pests, markets and resource availability. Digital agriculture provides opportunities to address these limitations through interconnected technologies such as precision agriculture, unmanned aerial vehicles (UAVs), the Internet of Things (IoT), smart sensors, artificial intelligence (AI), predictive analytics, mobile platforms, digital financial services, FinTech, blockchain, and e-commerce. These technologies enable the collection, processing, analysis, and exchange of agricultural information and can support more precise input management, early detection of crop stresses, improved decision-making, market access, financial inclusion, and supply-chain traceability. Recent reviews indicate that AI and IoT are increasingly being integrated into precision agriculture, while UAV-based remote sensing provides high-resolution information for crop monitoring, disease detection, nutrient assessment, and yield estimation. Blockchain applications are particularly relevant to traceability and transparency in agri-food supply chains. However, adoption remains constrained by high costs, limited connectivity, inadequate digital literacy, data-quality issues, interoperability, privacy concerns, and the unequal suitability of advanced technologies for smallholder farming systems. Therefore, the future of Agriculture 4.0 depends not only on technological development but also on farmer-centred design, affordable infrastructure, capacity building, appropriate institutional frameworks, and effective agricultural extension systems. (Karkikatti 2026)

Keywords: Agriculture 4.0, Digital agriculture, Precision agriculture, UAVs, Internet of Things, Artificial Intelligence, Predictive analytics, FinTech, Blockchain, E-commerce, Agricultural extension

Introduction

Agriculture and horticulture is undergoing a significant technological transformation as digital technologies become increasingly integrated into crop production, livestock management, natural-resource management, marketing and agricultural extension. This transformation is commonly described as digital agriculture or agriculture 4.0. It represents a shift from conventional, relatively uniform management practices toward data-driven systems capable of responding to spatial and temporal variability. Precision farming is initially emphasized the use of GPS, GIS, remote sensing and variable-rate technologies to manage field variability. The development of IoT, UAVs, cloud computing, AI, machine learning and big-data analytics has subsequently expanded the scope of digital agriculture. More recently, blockchain and digital platforms have extended digitalization beyond farm production into traceability, finance, marketing and supply-chain management. (Karkikatti *et al.*, 2026) [1]

Digital agriculture is particularly important because agricultural decisions are influenced by numerous interacting factors, including soil characteristics, weather, crop growth, pest and disease pressure, input availability, labour, market conditions and financial resources. Digital technologies can bring together information from these different sources and convert it into actionable information for farmers, extension personnel, agribusinesses and policymakers. However, technological availability does not automatically translate into adoption or improved livelihoods. Recent reviews highlight persistent barriers related to affordability, connectivity, digital skills, infrastructure, data governance and the suitability of technologies for smallholder production systems. (Gumbi *et al.*, 2023) [2]

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Methodology

The present study was undertaken as a systematic narrative review to examine the role of Agriculture 4.0 and digital technologies in transforming agricultural production, economics, extension services and farmer decision-making. The review focused on major digital technologies, including the Internet of Things (IoT), artificial intelligence (AI), machine learning, precision agriculture, remote sensing, unmanned aerial vehicles (UAVs), mobile applications, digital financial services, blockchain, cloud computing and digital agricultural platforms. Relevant literature was collected from major scientific databases and scholarly sources, including *Scopus*, Web of Science, ScienceDirect, SpringerLink, Google Scholar and institutional publications. Literature was identified using combinations of keywords such as “Agriculture 4.0,” “digital agriculture,” “smart farming,” “precision agriculture,” “artificial intelligence in agriculture,” “IoT in agriculture,” “UAVs in agriculture,” “digital agricultural extension,” “digital financial services,” “blockchain in agriculture,” “farmer adoption,” and “economic impact of digital agriculture.” Boolean operators such as AND and OR were used to combine keywords and improve the relevance of the search results.

Major technological components of horticulture and agriculture 4.0

The major components of digital agriculture can be conceptualized as an interconnected ecosystem:

- Precision Agriculture & UAVs
- IoT & Smart Sensors
- AI & Predictive Analytics
- Mobile Platforms & Digital Financial Services
- Blockchain & E-commerce Supply Chains
- Data-driven Farm and Market Decisions

The technologies are complementary rather than independent. For example, sensors and UAVs generate data, IoT facilitates its transmission, AI processes and interprets it, mobile platforms deliver information to users and blockchain can provide traceable records across supply chains.

Precision agriculture, horticulture and unmanned aerial vehicles

Precision agriculture (PA) is a data-driven approach to horticultural and agricultural management that considers spatial and temporal variability within agri and horti fields. It uses technologies such as GPS/GNSS, GIS, remote sensing, sensors, UAVs, satellite imagery, IoT and data analytics to support site-specific management.

The fundamental principle of precision agriculture is often expressed as applying the right input, at the right place, at the right time and in the right quantity.

The major components include:

- GPS/GNSS: Provides accurate geographical positioning.
- GIS: Supports spatial data management and mapping.
- Remote sensing: Collects information about crops and soil without direct physical contact.
- IoT and sensors: Provide real-time information on soil, crop and environmental conditions.
- Satellite imagery: Provides large-scale spatial information.
- UAVs: Provide high-resolution field-level observations.
- AI and machine learning: Analyse complex agricultural and horticultural datasets.
- Variable Rate Technology: Enables site-specific application of agricultural inputs.

Recent reviews indicate that AI and IoT are increasingly becoming integral components of precision agriculture, particularly for crop-yield prediction, disease detection and resource optimization. (Karkikatti *et al.*, 2026) [1]

Unmanned aerial vehicles

An Unmanned Aerial Vehicle (UAV) is an aircraft operated remotely or autonomously without a human pilot onboard. Agricultural and horticultural UAVs can carry RGB, multispectral, hyperspectral, thermal and LiDAR sensors. It provides high spatial and temporal resolution and are increasingly used for crop monitoring and precision management. Recent literature identifies applications in crop growth monitoring, disease detection, nutrient-status assessment and yield prediction. (Zhang *et al.*, 2025) [3]

Major agricultural and horticultural applications

Crop health monitoring: UAV imagery can identify spatial differences in crop growth and areas exhibiting stress. Its spectral information can assist in identifying spatial patterns associated with crop nutrient status. High-resolution imagery can help identify suspicious or affected areas for subsequent field verification. Thermal and multispectral observations can identify spatial patterns associated with water stress. Image-based methods can distinguish crops and weeds under suitable conditions, supporting site-specific weed management. UAV-derived spectral, structural and temporal information can be combined with machine-learning models for crop-yield estimation. A systematic review of many studies reported extensive use of UAV platforms, sensors and data-analytics approaches for yield estimation. UAVs can also strengthen agricultural extension by providing visual and location-specific information. Extension personnel can use UAV-derived maps to identify areas requiring field inspection and communicate spatially explicit information to farmers.

Internet of things and smart sensors

The Internet of Things (IoT) refers to interconnected physical devices equipped with sensors, communication capabilities and data-processing functions that collect and exchange information.

In agriculture and horticulture, IoT connects: Sensors → Communication Network → Data Processing → Decision Support → Farm Action

IoT systems can monitor soil moisture, temperature, humidity, weather conditions, irrigation systems, livestock and machinery. A smart sensor combines a sensing element with processing and communication capabilities. Compared with basic sensors, smart sensors can process and transmit information and may support automated decision-making.

Applications in agriculture and horticulture

IoT has several important applications in agriculture and horticulture, particularly in precision farming and resource management. It can be used to obtain real-time soil-moisture information and support efficient irrigation scheduling. Soil-monitoring sensors can continuously measure parameters such as moisture, temperature, pH, and electrical conductivity, helping farmers make informed decisions about crop and soil management. IoT-based weather stations provide continuous information on environmental conditions such as temperature, humidity, rainfall, and wind, which can support timely farm operations. In greenhouse automation, IoT systems can monitor environmental parameters and automatically control irrigation, ventilation and other systems. Livestock monitoring can be carried out using connected devices that provide information on animal activity and selected health indicators. IoT can also be used for farm machinery monitoring by tracking machine location, operation and performance, thereby improving machinery utilization and operational efficiency. The integration of IoT with AI can facilitate real-time agricultural monitoring and decision support. Nevertheless, interoperability, connectivity, data privacy and implementation costs remain important constraints. (Rushemi 2025) [4]

Artificial intelligence and predictive analytics

Artificial Intelligence (AI) refers to computer-based systems capable of performing tasks involving learning, pattern recognition, reasoning, prediction and decision support. In agriculture, AI can process data generated from IoT sensors, UAVs, satellites, weather stations, farm records and machinery.

Machine learning

Machine learning enables algorithms to identify patterns from data and generate predictions or classifications, making it highly useful in agriculture for crop-yield prediction, pest forecasting, disease identification, soil classification, irrigation prediction and crop classification. Deep learning, a specialized form of machine learning that uses multi-layer neural networks to analyse complex datasets, which has applications in image-based disease detection, weed identification, fruit recognition, crop counting and remote-sensing analysis. Computer vision enables computers to extract useful information from agricultural images and videos. Natural Language Processing (NLP) can facilitate farmer chatbots, voice-based agricultural advisory services, question-answer systems, analysis of farmer queries and multilingual digital extension services. Predictive analytics uses historical and current data to estimate future outcomes and can integrate weather, soil, crop, historical and remote-sensing data to develop predictive models for management decisions. Its potential applications include crop-yield forecasting, pest and disease-risk assessment, irrigation requirement prediction and market analysis. Recent systematic reviews of AI in smallholder precision agriculture have identified applications in productivity improvement and farm management while also highlighting challenges such as infrastructure costs, data privacy and limited digital literacy. (Satpati, 2026) [5]

Mobile platforms, digital financial services and fintech

Mobile platforms provide digital channels through which farmers can access information, communication, advisory services, markets and financial services.

Digital platforms are increasingly becoming important tools for strengthening agricultural extension services by providing farmers with timely weather information, crop advisories, pest and disease alerts, market information, government-scheme information, digital training and input and output market services. Thus, the conventional extension model of Extension Worker → Farmer can evolve into a digital model of Extension System → Digital Platform → Farmer, as well as an interactive model in which Farmer → Query/Photo/Voice → Digital Platform → Expert/AI → Advisory → Farmer. Such digital platforms can complement, rather than necessarily replace, conventional extension services by improving the speed, accessibility and reach of agricultural information and advisory services. Digital Financial Services (DFS) refer to the electronic delivery of financial services such as payments, savings, credit, insurance, fund transfers and government benefit transfers.

Financial Technology (FinTech) involves the use of technology to provide, improve or automate financial services. In agriculture, Agri-FinTech can support digital payments, credit assessment, insurance, savings and supply-chain finance. These technologies can contribute to greater financial inclusion among farmers; however, their effectiveness depends on factors such as internet connectivity, affordability, digital literacy, consumer protection and appropriate financial regulation. (Amos *et al.*, 2026) [6]

Blockchain and e-commerce supply chains

Blockchain is a distributed digital ledger in which validated records are stored in linked blocks across a network. Its characteristics can support traceability, auditability and information sharing.

Blockchain has received considerable attention in agri-food supply chains because of the complexity of tracing products across farmers, aggregators, processors, distributors, retailers and consumers. Reviews have documented applications focused particularly on agricultural-product traceability. (Demestichas, K. 2020.) [7]

Major applications in agriculture and horticulture

Blockchain technology has potential applications particularly in food traceability, quality management, certification and supply-chain transparency. In food traceability, blockchain can provide a shared and tamper-resistant record of product movement across different stages, including Farm → Collection → Processing → Transport → Retail → Consumer. Information related to production, harvesting, processing, storage and certification can be recorded and shared among authorized participants, supporting quality assurance and certification. Blockchain can also help in reducing information asymmetry by improving access to relevant and verifiable supply-chain information among farmers, processors, traders, retailers and consumers. Another important application is smart contracts, which are computer programs designed to automatically execute predefined actions when specified conditions are satisfied. For example, when produce is delivered and the required quality conditions are verified, the contract conditions can be fulfilled and the payment process can be initiated. However, blockchain does not automatically guarantee the accuracy of the information entered into the system; therefore, the reliability of blockchain-based agricultural systems depends on accurate data collection, proper verification, effective governance and trustworthy data sources. (Bosona *et al.*, 2023) [8]

E-commerce supply chains

Agricultural and horticultural e-commerce connects farmers to Farmer Producer Organizations (FPOs), buyers, consumers and agricultural input suppliers through digital marketplaces. In a conventional supply chain, agricultural products typically move through several intermediaries, following the pathway Farmer → Trader → Wholesaler → Distributor → Retailer → Consumer. Digital platforms can create alternative and potentially shorter pathways such as Farmer/FPO → Digital Marketplace → Buyer/Consumer, enabling direct or more efficient connections between producers and markets. Agricultural and horticultural e-commerce can potentially expand market access, improve access to price information, facilitate digital transactions and provide farmers with additional marketing opportunities.

Integrated digital agriculture and horticulture ecosystem

The greatest potential of horticulture and agriculture 4.0 lies in the integration of multiple technologies rather than their isolated use. An integrated system can combine IoT and smart sensors to collect real-time field data, while UAVs and satellites provide spatial information on crops and field conditions. Cloud and edge computing enable data storage, processing and management, whereas AI and machine learning analyse the collected data to identify patterns and support decision-making. Predictive analytics can use these insights for forecasting and risk assessment, while mobile platforms deliver timely advisories and information to farmers. FinTech can facilitate digital financial services, including payments, credit and insurance, whereas blockchain can support traceability and trusted record-keeping across agricultural supply chains. E-commerce platforms can further strengthen market connectivity by linking farmers and FPOs with buyers and consumers. Ultimately, these interconnected technologies can support farmers and FPOs in making informed decisions and taking timely actions. Recent systematic reviews indicate that the convergence of IoT, AI, and blockchain has considerable potential for transforming agricultural systems, although its implementation remains constrained by challenges such as interoperability, data privacy, real-time processing requirements, implementation costs and broader socio-technical barriers. (Gade *et al.*, 2025) [9]

Economic and livelihood implications

Digital technologies can influence agricultural economics through multiple interconnected pathways. Precision farming technologies can improve input-use efficiency by enabling more site-specific application of water, fertilizers and crop-protection inputs, thereby poten

tially reducing input wastage and production costs. Weather information, crop monitoring and predictive analytics can support early identification of production risks and help farmers make timely decisions, contributing to improved risk management. Similarly, automation and remote-monitoring technologies can enhance labour efficiency by reducing the need for certain routine field observations and operations. Mobile platforms and e-commerce can improve market access by connecting farmers with a wider range of buyers and providing timely information on prices and market opportunities. Digital financial services can promote financial inclusion by facilitating access to formal payment systems, credit, savings and insurance services. In addition, blockchain-based traceability systems can enhance value-chain transparency by improving product tracking and information availability across different stages of the supply chain. However, the adoption of digital technologies does not automatically translate into higher farmer income. The economic benefits depend on several factors, including technology costs, farm size, commodity characteristics, market access, farmers' digital skills, connectivity, physical infrastructure, institutional arrangements and the quality of implementation. Therefore, ensuring affordability, reliable connectivity, digital literacy and appropriate institutional support is essential for realizing the economic potential of digital agriculture, particularly among smallholder farmers. (Lv *et al.*, 2023) [10]

Challenges and constraints

Despite substantial technological progress, several barriers continue to influence the adoption and effective implementation of Agriculture 4.0. High initial investment is a major constraint, as advanced sensors, UAVs, software platforms and connectivity infrastructure can involve considerable costs, particularly for smallholder farmers. The digital divide further limits adoption because many smallholders have inadequate access to smartphones, reliable internet connectivity and digital infrastructure. In addition, digital literacy is essential for farmers and extension personnel to effectively use and interpret digital technologies and information. The quality of digital decision-making also depends on data quality, as artificial intelligence and predictive models require reliable, accurate and representative datasets. Interoperability remains another challenge because different digital platforms, devices and software systems may not communicate or exchange data effectively. Furthermore, data privacy and security are important concerns because agricultural, personal and financial information needs appropriate protection. The transferability of AI models can also be limited, as models developed for a particular crop, location or environmental condition may not perform equally well under different conditions. Institutional and regulatory issues, including the absence of appropriate standards, governance mechanisms, data policies and institutional support, can further slow digital transformation. Finally, the benefits of Agriculture 4.0 may not be equally distributed; without farmer-centred design, affordable technologies and inclusive delivery mechanisms, digital innovations may primarily benefit better-resourced producers. Therefore, recent systematic reviews highlight cost, infrastructure, digital literacy, privacy, data governance and institutional support as critical factors for achieving an inclusive and sustainable digital transformation of agriculture. (Satpati, 2026) [5]

Role of agricultural extension in horticulture and agriculture 4.0

The emergence of digital agriculture is transforming the role of agricultural extension from primarily disseminating generalized recommendations toward facilitating data-driven, location-specific and interactive advisory services. In the Agriculture 4.0 era, extension personnel can play a crucial role in creating awareness about digital technologies and developing farmers' digital literacy so that they can effectively access, understand and use digital information. They can assist farmers in interpreting digital advisories, facilitate access to mobile-based agricultural platforms and support demonstrations involving UAVs, sensors and other precision-agriculture technologies.

Extension personnel can also help farmers connect with digital markets and create awareness about digital financial services such as online payments, credit and insurance platforms. Furthermore, they can facilitate FPO-based adoption of digital technologies, enabling farmers to access technologies and services collectively and potentially reduce adoption costs. Extension professionals can also serve as a communication link between farmers and technology developers by conveying farmers' experiences, needs and feedback for improving digital solutions. Importantly, digital advisory systems should complement rather than replace local knowledge, farmer experience and field-level verification. Thus, the agricultural extension system can serve as an important bridge between technological innovation and farmer-level adoption, helping to ensure that digital agriculture becomes accessible, relevant and useful to farmers.

Future research directions

Future research should move beyond evaluating individual digital technologies and focus on developing integrated, farmer-centred digital ecosystems that address the technological, economic and institutional needs of agricultural communities. Key research priorities include the development of affordable digital technologies for smallholders, AI models adapted to local crops and environmental conditions and explainable and trustworthy AI that farmers and extension personnel can understand and use with confidence. Greater attention is also needed toward the integration of IoT, UAV and satellite data, interoperability among digital agricultural platforms and the development of local-language and voice-based advisory systems to improve accessibility. Research should further examine the potential of digital financial services for financial inclusion, blockchain-enabled traceability for improving value-chain transparency and FPO-based digital business models that can facilitate collective access to technologies and markets. Data governance, privacy and security also require stronger attention as the volume of agricultural data increases. Importantly, future studies should evaluate the actual farm-level economic impacts of digital technologies, including their effects on productivity, profitability, input efficiency, risk management and market access. The gender dimension and broader aspects of digital inclusion should also be incorporated to ensure that technological benefits are accessible to different categories of farmers. In parallel, greater emphasis is required on capacity building for farmers and extension personnel to strengthen digital literacy and effective technology use. Recent reviews indicate that the convergence of AI, IoT and other digital technologies is advancing rapidly; however, the extent to which these technologies translate into practical agricultural benefits will depend strongly on farmer-centred design, affordability, local adaptability, institutional support and enabling policy environments. (Purohit *et al.*, 2026) [11]

Conclusion

Agriculture 4.0 represents a transition toward connected, data-driven and increasingly intelligent agricultural systems. Precision agriculture and UAVs provide spatial information; IoT and smart sensors provide continuous field observations; AI and predictive analytics convert data into predictions and decision support; mobile platforms extend information and advisory services; FinTech expands digital financial services; and blockchain and e-commerce strengthen traceability and market connectivity. The literature indicates substantial potential for these technologies to improve resource management, agricultural decision-making, risk assessment and supply-chain transparency. Nevertheless, the benefits should not be assumed to occur automatically. Affordability, connectivity, digital literacy, data quality, interoperability, privacy, institutional support and farmer participation are critical determinants of successful adoption. (Karkikatti *et al.*, 2026) [1]. Therefore, the future direction of Agriculture 4.0 should focus not simply on introducing more advanced technologies but on developing accessible, interoperable, evidence-based and farmer-centred digital ecosystems in which technology, agricultural extension, farmer organizations, markets and financial institutions work together.

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