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Digital-agriculture integration of remote sensing, GIS and IoT for precision crop management: A review

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Abstract

Digital agriculture reimages traditional practices of farming to adopt more science, technology, and data driven-based production systems to improve productivity, sustainability, and resource use efficiency. The advances in digital technologies offer new possibilities to enhance agricultural practices by merging information technology, communication networks, and high-end sensing technologies. These products make it possible to more closely monitor, analyze and make decisions about agricultural activities. Technological advances, such as Remote Sensing (RS), Geographic Information Systems (GIS), and the Internet of Things (IoT) are now considered the backbone of modern farming and precision agriculture. They provide farmers, scientists, and land managers with the tools to monitor crops, quantify spatial variability at field scale, and manage agricultural inputs such as water, fertilizers, and pesticides with greater precision. These technologies contribute to efficient and site-specific crop management by delivering information that is both accurate and up-to-date. A key technology in remote sensing is remote sensing technology RST which plays a vital role in crop monitoring, vegetation growth, soil moisture and environmental conditions using satellite, unmanned aerial vehicle, airborne sensors etc. Soil properties, climatic variables, crop yield etc. can be considered as the multifaceted datasets that can be integrated and spatially analysed by using GIS for making right decisions. At the same time, IoT technologies are rapidly advancing, allowing real-time, continuous monitoring of environmental and soil parameters via networked sensors. With these technologies coming together, it is now possible to achieve precise crop management, early identification of crop stress and diseases, higher prediction of yield, better resources use, increased farm productivity and reduction in environmental impact for sustainable agriculture development globally.

Keywords: Digital agriculture, precision agriculture, remote sensing, GIS, internet of things, smart farming, crop monitoring

Introduction

Agriculture is essential for global food security and livelihoods of billions of people around the world (Basso and Antle, 2020 ^[7] agriculture sector is vital for food security and the livelihoods of billions of people worldwide). Yet the practices of food production are being imperiled as we speak by a variety of challenges in the sector of agriculture (Lowenberg and Erickson 2019) ^[34]. Among the most significant factors contributing to declining agricultural yields are climate change, population growth, land degradation, water scarcity, and soil degradation (Pathak *et al.*, 2022) ^[43]. The demand for food production will be augmented as world population is projected to attain nearly 9.7 billion by 2050 according to global estimates (FAO, 2023). However, natural resources such as water, land, and energy are becoming scarcer (Wolfert *et al.*, 2017) ^[67]. To address these issues, novel and sustainable agricultural strategies with the capability of enhancing crop productivity with minimum negative environmental consequences are needed (Liakos *et al.*, 2018) ^[32].

Conventional farming is generally based on uniform application of inputs over whole fields leading to resource inefficiency and variable yields (Mulla, 2013) ^[39]. Soil properties, moisture availability, nutrient status and the growing conditions of crops in agricultural fields are commonly highly variable in space (Sishodia *et al.*, 2020) ^[54]. Hence, enabling control of this variation is critical for increasing crop productivity and resource use efficiency (Atzberger, 2013) ^[5]. The development of digital technologies has opened new

avenues to tackle such issues by means of data-driven agricultural management system (Maes and Steppe 2019)^[35].

Digital agriculture is a new paradigm that combines information technology, sensor networks, data analytics, and geospatial technologies with agricultural activities. It is the gathering, processing and analysis of large amounts of agricultural data with the aim of better decision making and farm management (Liakos *et al.*, 2018)^[32]. Using latest technologies like remote sensing, GIS and IoT, farmers can have access to more specific information on crop, soil and environmental condition.

Spatial variability at the level of agricultural fields is managed with precision agriculture, which is also a key enabler of digital agriculture (Gebbers and Adamchuk, 2019). Precision agriculture applies geospatial technology, sensor, and automation technologies to deliver inputs such as water, fertilizer, and pesticides in a site-specific manner (Sishodia *et al.*, 2020)^[54]. This process helps farmers to enhance the efficiency of resource usage, minimize input costs, and maximize output in the form of crop yield (Khanal, 2020)^[28].

Remote sensing enables farmers to access valuable information about plant growth, vegetation status and environmental conditions at a field scale, which plays an essential part in precision agriculture (Paulauskas *et al.*, 2021). Satellite images and sensors on board drones can acquire high-resolution information to detect differences in crop vigor within fields (Zhang *et al.*, 2023). Analysis of spatial data: Integration and analysis of spatial data through GIS technology to produce maps that can be used to guide decisions in farm management (Burrough and McDonnell, 2015)^[8]. IoT Is and monitoring of environment An environment can be monitored by using the IOT technology that consists of environmental sensors for capturing data such as soil moisture, temperature, humidity and level of nutrients (Verdouw *et al.*, 2021)^[64].

The combination of remote sensing, GIS and IoT technology allows farmers to create full farm management systems with integration of macro monitoring and real-time field data. These systems make it possible to detect crop stress at early stages, accurately predict crop yield, manage irrigation, and apply fertilizers in an optimal manner (Pathak *et al.*, 2022)^[43]. With the rapid development of digital technologies, it is anticipated that the smart agriculture systems market will witness a high growth rate over the next few years. Consequently, digital agriculture is a pivotal mean through which to transition to sustainable and climate-resilient agricultural systems (Basso and Antle, 2020)^[7].

2. Concept of Digital Agriculture: Digital agriculture is the use of information and communication technologies (ICTs) in agriculture, including in particular the application of digital tools across the various agricultural production systems to increase efficiency, productivity, and environmental soundness (Wolfert *et al.*, 2017)^[67]. It is a transformation of conventional farming methods into management of agriculture based on data and supported by technology (Klerkx *et al.*, 2019)^[30]. Digital agriculture utilizes sensors, satellite imagery, artificial intelligence (AI), machine learning, big data analytics, robotics, and cloud

computing to gather, process and analyze data related to agriculture (Liakos *et al.*, 2018)^[32].

The end user of digital agriculture is the farmer and, with digital agriculture, they should be able to have the best possible information on the state of their crop and environment and what to do about it. With the help of digital resources, farmers can track the development of crops, soil quality, and climate conditions on their phones or laptops (Verdouw *et al.*, 2021)^[64]. As a result, they can immediately adjust to variations in field conditions and make optimum use of production inputs (Pathak *et al.*, 2022)^[43].

One distinguishing feature of digital agriculture is the use and integration of various technologies to develop an information management system for agriculture (Klerkx *et al.*, 2019)^[30]. Remote sensing techniques yield information on crop and vegetation conditions at a large scale (Mulla, 2023)^[39]. Detail from IoT sensors IoT sensors collect information such as soil moisture, weather, and other environmental conditions at the field level (Ray, 2017)^[48]. These data sets are brought together and made the subject of spatial analysis and visualization through the use of GIS technology (Burrough and McDonnell, 2015)^[8].

Digital agriculture is now also heavily dependent on data analytics and AI to manage the vast amount of data (Liakos *et al.*, 2018)^[32]. Machine learning algorithms may be utilized to identify trends in crop development, environmental factors, and historical yields to produce predictions and decisions for farmers (Zhang *et al.*, 2024). Cloud computing platforms allow for the storage and processing of the massive amounts of data and also allow for the dissemination of information to farmers, researchers, and policymakers.

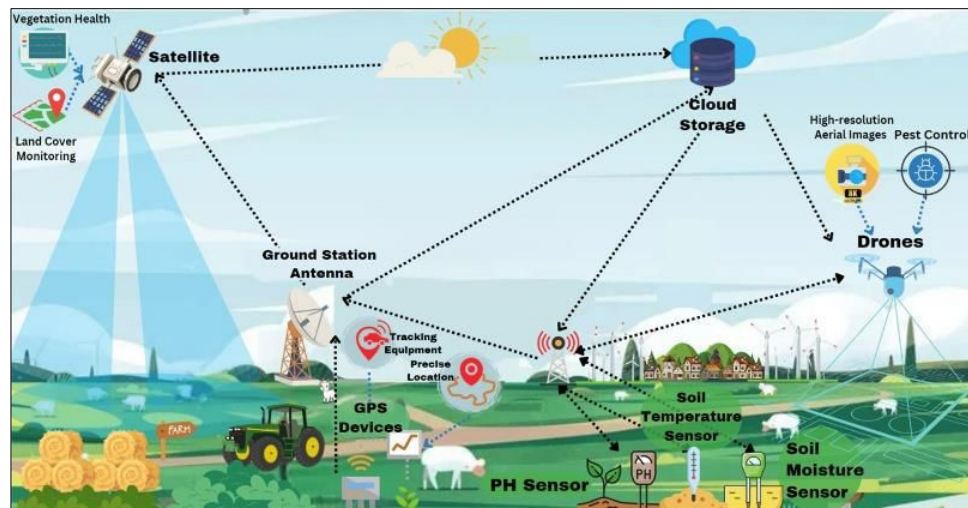
Digital agriculture is also characterized by the need for automation (Pathak *et al.*, 2022)^[43]. Smart irrigation systems, robotic harvesters and driverless tractors as automated systems can carry out agricultural tasks with little human help. These practices increase the productivity and reduce the labor input for food production (Basso and Antle, 2020)^[7].

Digital agriculture is a new form of farming that integrates the modern technology with the existing agricultural knowledge and practices to achieve higher output and sustainable food production (Klerkx *et al.*, 2019)^[30].

3. Precision Agriculture

Precision agriculture is a farming system that deals with keeping track of monitoring, measuring, and responding to intra-field variability. Precision agriculture is built on the principle that farmlands are heterogeneous and that crop production environments may change dramatically over short distances (Mulla, 2023)^[39]. Farmers can maximize production and resource use efficiency by quantifying and managing this variability (Basso and Antle, 2020)^[7].

Precision agriculture is a technology-intensive system utilizing GPS, remote sensing, GIS, IoT sensors, and decision support systems (Sishodia *et al.*, 2020)^[54]. These tools allow farmers to obtain more precise data on soil characteristics, crop development, moisture content, and weather conditions. The accumulated information can be used to create site-specific management practices (Pathak *et al.*, 2022)^[43].



(Sources: Sharpe *et al.*, 2023) ^[52]

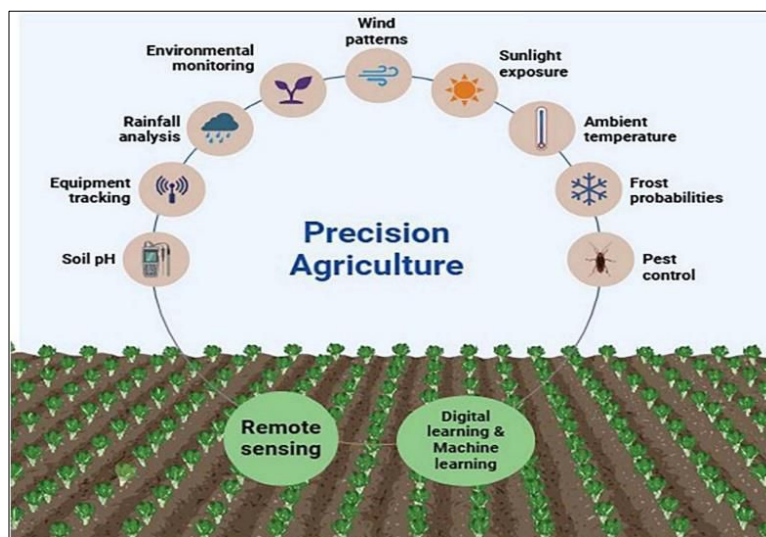
Fig 1: An Agriculture Information System Based on Integration of Remote Sensing, GIS, UAVs and IoT Sensors for Precision Crop Management

Increasing crop productivity by better management of inputs of agriculture is one of the major targets of precision agriculture. Instead of spreading fertilizers or pesticides evenly over a field, precision agriculture helps farmers to use these inputs only where they are necessary (Basso and Antle, 2020) ^[7]. This lowers the costs of inputs of production and the environmental consequences including the leaching of nutrients and the contamination of drinking water with chemicals (Klerkx *et al.*, 2019) ^[30].

Moreover, precision agriculture enhances water management through site-specific soil water monitoring and irrigation scheduling (Verdouw *et al.*, 2021) ^[64]. Soil moisture sensor and weather information can be used for

irrigation timing and amount estimation (Ray, 2017) ^[48]. In a similar vein, with nutrient application rates variable and adapting to soil nutrient concentrations and crop needs, variable rate technology can be used to modulate fertilizer application (Sishodia *et al.*, 2020) ^[54].

Yet another major advantage of precision farming is enhanced environmental sustainability (Basso and Antle, 2020) ^[7]. Precision agriculture minimizes soil erosion, water pollution and greenhouse gas emissions by precision use of agricultural inputs (Klerkx *et al.*, 2019) ^[30]. Besides, digital technologies allow farmers to observe health of crops and identify issues like pest infestations and nutrient deficiencies at an early stage.



(Sources: Mitra *et al.*, 2022) ^[38]

Fig 2: Precision Agriculture: Integration of Remote Sensing, Environmental Monitoring, and Machine Learning for Smart Farming

4. Remote Sensing in Precision Agriculture

4.1 Concept of Remote Sensing

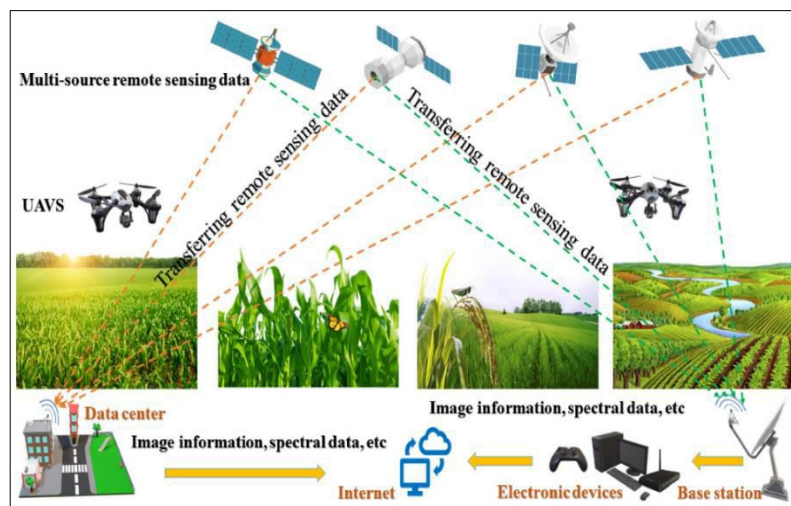
Remote sensing is the science of acquiring information about an object or phenomenon without making physical contact with the object (Sangeetha *et al.*, 2024) ^[49]. In the context of agriculture, remote sensing is the application of sensors placed on satellites, airplanes, or drones, to collect images and data from agricultural fields over a range of spatial and temporal scales (Zhang, 2025) ^[71]. These sensors

measure the electromagnetic radiation that crops, soils, and water reflect and transform that information into digital data from which agronomic information can be derived (Sangeetha *et al.*, 2024) ^[49].

Remote sensing offers a unique opportunity for monitoring agricultural fields at field scales, making it possible to monitor crop growth and stress and assess landscape variability (Zhang 2025) ^[71]. Satellite based remote sensing systems (i.e. Sentinel, Landsat) acquire multi-spectral and

thermal images of agricultural areas at regular time intervals, enabling continuous and consistent observation of crop growth and environmental factors (Sangeetha *et al.*, 2024) ^[49]. Concurrently, Unmanned Aerial Vehicles (UAVs) carrying multispectral and hyperspectral sensors, can acquire imagery at such a high spatial resolution that enables to conduct comprehensive field level examination of vegetation vigor, canopy architecture and signs of stress.

This contribution reports on an investigation of 3D reconstruction of plants with the use of multiple plant models in laser scanning and introduces a solution for detecting occlusion gaps of leaves for the 3D plant reconstruction. With the ability to utilize both satellite and UAV images, farmers and researchers are able to extract agronomic information difficult and/or very time-consuming to acquire simply through field surveys (Zhang, 2025) ^[71].



(Sources: Joaquim *et al.*, 2020)

Fig 3: Remote Sensing Data Acquisition and Transmission Network for Smart Agriculture

4.2 Vegetation Indices in Agriculture

Vegetation indices are calculations using the spectral reflectance values obtained from remote sensing data that give quantitative information about the status of vegetation in terms of its health, biomass and productivity (Sangeetha *et al.*, 2024) ^[49]. The Normalized Difference Vegetation Index (NDVI) is one of the most popular VIs utilized in agriculture as it quantifies the difference between red and near infrared reflectance to evaluate the vigor of vegetation and the activity of chlorophyll (Radočaj *et al.*, 2023) ^[45].

The higher reflectance of near infrared and absorbance of red light of healthy plants is due to chlorophyll absorption, and that is the reason why NDVI is a good indicator of crop health and biomass. Other indices, with more information on the canopy structure, soil background and water content are the Enhanced Vegetation Index (EVI), Soil Adjusted Vegetation Index (SAVI), and the Normalized Difference Water Index (NDWI), respectively.

Vegetation indices find broad applications in precision agriculture, as they are used to monitor crop health, stress conditions, nutrient deficiencies, and irrigation needs, among others; rendering them essential data based tools for crop management (Sangeetha *et al.*, 2024) ^[49].

5. Geographic Information Systems (GIS) in Agriculture

GIS (Geographic Information System) is a computer-based tool for capturing, storing, analyzing, managing and visualizing spatial data of agricultural landscapes and processes (Zhang, 2025; Burrough and McDonnell, 2015) ^[8, 71]. In precision agriculture, GIS is vital for providing the means for registration of multiple spatial layers (soil maps, satellite maps, weather maps, crop production records, and field survey data) into one common decision support system (Sangeetha *et al.*, 2024; Eastman, 2020) ^[15, 49].

GIS allows farmers and scientists to integrate these various data layers to examine spatial variation across agricultural

fields and to design site-specific strategies for managing inputs and enhancing performance. An important use of GIS in agriculture is the mapping of soil fertility, which maps the levels of nutrients in soil and its physical characteristics for variable rate application of fertilizer and soil amendment.

GIS technology is also applied in crop suitability analysis that considers soil properties, climate condition and landform attribute of a certain area for the growth of a specific crop. Moreover, GIS has also been applied in surveillance of pest outbreaks, mapping of irrigation schemes, and the planning of agricultural land use for better resource utilization (Singh *et al.*, 2022) ^[53].

6. Internet of Things (IoT) in Smart Agriculture

The IoT is a collection of devices and sensors which are connected and collect, exchange and send data through the internet to enable decisions at any time (Ray *et al.*, 2017) ^[48]. In farming, IoT solutions make it possible to monitor environmental and soil conditions continuously within field sensors scattered throughout the farm terrain.

Among these parameters are soil moisture, temperature, humidity, pH, and nutrients, measured by IoT sensors and sent to cloud based platform for raw data aggregation, processing, analysis, and visualization (Kamilaris *et al.*, 2018; Das *et al.*, 2024) ^[12]. Data driven decision making is facilitated during these events that farmers are empowered to take immediate actions to meet the needs of the field conditions (Elijah *et al.*, 2018; Rafi *et al.*, 2025) ^[17, 46].

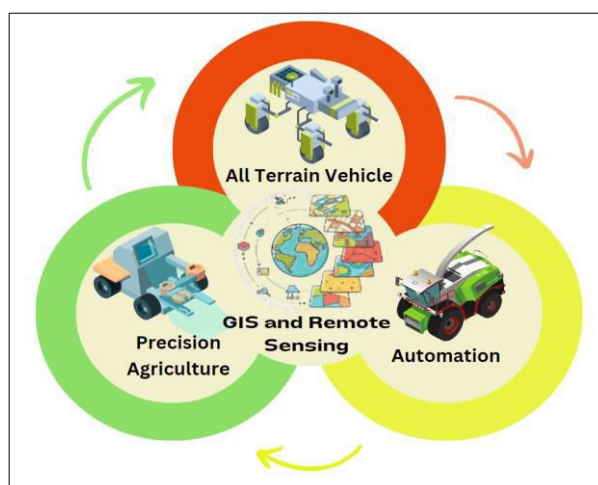
Smart irrigation systems are one of the best known examples of IoT in agriculture, since soil moisture sensors activate irrigation when water levels dip below a certain threshold, so crops get the perfect amount of water at the right time (Verdouw *et al.* (2021) ^[64]. They also provide remote monitoring of fields via mobile or web applications where farmers can obtain real time data on crop and

environmental status remotely (Jayaraman *et al.*, 2016; Ferrandez-Pastor *et al.*, 2016)^[24].

7. Integration of Remote Sensing, GIS, and IoT

The combination of remote sensing, GIS, and IoT forms the base of digital agriculture systems and these three technologies complement each other to achieve an

integrated monitoring and management (Kamilaris and Prenafeta-Boldu, 2018; Pantazi *et al.* 2016; Khaki *et al.*, 2020)^[25, 42]. Remote sensing provides extensive spatial information on crop and environmental conditions, whereas IoT sensor networks provide on-demand monitoring of soil and climate variables at the field scale (Chen *et al.* 2022; Singh *et al.* 2021; Yang *et al.* 2020)^[53].



(Sources: Rajendra *et al.*, 2020)

Fig 4: Role of GIS and Remote Sensing in Automated Precision Agriculture Systems

Subsequently, GIS combines these multiple source data to generate spatial maps and decision support tools that enable farmer to carry out site specific management practices with the potential for precision management. For example, satellite imagery can highlight regions under crop stress and IoT sensors can provide information on soil moisture levels in those regions, allowing for such targeted interventions.

8. Applications of Integrated Digital Agriculture

The uses of integrated digital agriculture systems are large in the current farming practices. Smart irrigation systems based on soil moisture sensors and weather information are developed to improve the efficiency of irrigation water use (Matese *et al.*, 2015; Tsouros *et al.*, 2019; Padua *et al.*, 2017)^[36, 59]. Remote sensing technologies provide the opportunity to monitor crop health and detect stress conditions at an early stage, enhancing proactive management decisions (Torres-Sanchez *et al.*, 2015; Nebiker *et al.*, 2018; Radoglou-Grammatikis *et al.*, 2020)^[58]. GIS derived nutrient maps allows precision fertilization management based on spatial differences of soil nutrient status.

Machine learning models are employing satellite image and sensor data to predict crop yield and identify the factors associated with rich and poor productivity (Evans and Sadler 2008; O'Shaughnessy *et al.* 2015; Vellidis *et al.* 2016; Hedley *et al.*, 2020)^[18, 61]. Drone based imaging with AI can identify pest attacks and diseases at an early stage, allowing immediate action and reducing crop losses (Lal, 2020; Pretty *et al.* 2018; Tilman *et al.*, 2011)^[44, 56].

9. Benefits of Digital Agriculture

The application of digital technologies to the agricultural sector has a number of advantages. This increases crop yields because of site specific management practices in which inputs are adjusted to local condition (Foley *et al.*, 2011; Rockstrom *et al.*, 2017)^[20]. It also eliminates need to

pay for extra fertilizers, pesticides, and water, as precision use of these inputs is ensured (Kitchen *et al.*, 2017). Digital agriculture can also improve resource use efficiency and environmental sustainability through reducing overuse of inputs and integrating management with field heterogeneity. In addition to this, digital agriculture contributes to better farm management by equipping farmers with reliable and timely information to make more informed decisions and increasing farm profitability while ensuring environmental sustainability.

10. Challenges in Digital Agriculture

Although digital agriculture has numerous advantages, it is confronted with several challenges at the technological, economic, and social levels (Klerkx *et al.*, 2019; Pathak *et al.*, 2022)^[30, 43]. One significant barrier is the costly upfront investment for digital instruments and systems such as sensors, drones, and IoT infrastructures, which can be a barrier to smallholder farmers, particularly in developing areas (Lowenberg DeBoer and Erickson, 2019; Nandeha *et al.*, 2025)^[34, 40]. In addition, limited technical expertise and digital literacy among farmers could constrain the delivery and use of high-tech agriculture (Klerkx *et al.*, 2019; Basso and Antle, 2020)^[7, 30].

A further issue is that of data integration and interoperability. This is particularly the case when dealing with diverse technologies ranging from remote sensing technologies to GIS databases and IoT sensor networks, which may lead to siloed data or at worst incompatible data sets (Zhang *et al.*, 2024; Wassay *et al.*, 2025)^[66]. In addition, complications from rural connectivity woes, such as sparse broadband availability and spotty cell phone reception, may hinder IoT systems that rely on a supplement flow of data in real time (Rafi *et al.*, 2025; Das *et al.*, 2024)^[12, 46].

Privacy and security concerns are also obstacles to adoption and farmers may be hesitant to share their valuable farm

data with the potential of it being misused or accessed without permission, especially when it involves cloud based analytics platforms (Wang *et al.*, 2022; Das *et al.*, 2024) ^[12]. Tackling these challenges will call for concerted efforts in infrastructure enhancement, capacity building, and strong data governance frameworks (Klerkx *et al.*, 2019; Nandeha *et al.*, 2025) ^[30, 40].

11. Future Trends in Digital Agriculture

It is anticipated that the next step of evolution in digital farming will be the convergence of AI, robotics, blockchain technology, satellite-based systems, and advanced communication networks, resulting in more precision management and operational efficiency (Zhang *et al.*, 2024; Aryal *et al.*, 2026) ^[4]. The models based on AI will become more and more advanced, which will allow for more precise crop yield prediction and earlier detection of diseases and stress by recognizing patterns in big data.

New trends are also the use of agri-machines and robots which could be progressively autonomous to enable the automation of field activities such as sowing, weeding, spraying, and harvesting, reducing labor reliance and enhance timeliness of farm operations (Kamilaris *et al.*, 2019; Aryal *et al.*, 2026) ^[4]. The introduction of 5G and edge computing technologies will also improve IoT system performance, by providing a higher bit rate and lower latency for data transmission and allowing for data processing at the edge of the network in real time.

Digital twin technology that offers virtual replication of the farm systems to simulate and optimize is expected to become more popular for scenario modeling and predictive management in diverse environmental conditions (Verdouw *et al.*, 2020; Wassay *et al.*, 2025) ^[66]. Blockchain technology could also be more employed to improve agricultural supply chain traceability, transparency and trust (Wolfert *et al.*, 2019; Wang *et al.*, 2022) ^[67].

12. Conclusions

Digital agriculture is transforming contemporary farming practices with the application of emerging technologies (e.g., remote sensing, GIS, and IoT) based on data. They allow continuous monitoring of crop status, analysis of spatial variability, and use of site-specific management practices. The combination of these technologies has been demonstrated to enhance crop yield, resource use efficiency, and environmental friendliness through the fine-tuning of water use, nutrient management, and pest management.

There are still challenges to be overcome, including cost barriers, connectivity limitations, and data governance issues, but it is anticipated that ongoing advances in digital technologies and infrastructure and capacity building will enable smart agricultural systems to become increasingly accessible and affordable for farmers around the world. In the future, digital agriculture is expected to play a key role in sustainable food production and in solving the intricate issues associated with global food security in the context of altering climatic and socio-economic conditions.

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