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Application of digital technologies for ensuring agricultural productivity

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A R T I C L E I N F O

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A B S T R A C T

Over the decades, agri-food security has become one of the most critical concerns in the world. Sustainable agri-food production technologies have been reliable in mitigating poverty caused by high demands for food. Recently, the applications of agri-food system technologies have been meaningfully changing the worldwide scene due to both external strengths and internal forces. Digital agriculture (DA) is a pioneering technology helping to meet the growing global demand for sustainable food production. Integrating different sub-branches of DA technologies such as artificial intelligence, automation and robotics, sensors, Internet of Things (IoT) and data analytics into agriculture practices to reduce waste, optimize farming inputs and enhance crop production. This can help shift from tedious operations to continuously automated processes, resulting in increasing agricultural production by enabling the traceability of products and processes. The application of DA provides agri-food producers with accurate and real-time observations regarding different features influencing their productivity, such as plant health, soil quality, weather conditions, and pest and disease pressure. Analyzing the results achieved by DA can help agricultural producers and scholars make better decisions to increase yields, improve efficiency, reduce costs, and manage resources. The core focus of the current work is to clarify the benefits of some sub-branches of DA in increasing agricultural production efficiency, discuss the challenges of practical DA in the field, and highlight the future perspectives of DA. This review paper can open new directions to speed up the DA application on the farm and link traditional agriculture with modern farming technologies.

1. Introduction

Over the decades, increasing demands for supplying agri-food products have influenced agriculture patterns worldwide. Additionally, changing human lifestyles and increasing human population and urbanization have directly impacted the production and

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consumption of agri-food products [1]. The financial value of strategic plants and the scarcity of natural resources for agriculture have spurred plant producers and agriculture researchers to discover new ways to overcome the food crisis. Thus far, various modern technologies and efficient strategies have been implemented in the agri-food sectors [2]. However, reports indicate a need to find and/or improve the current agri-food tools to overcome the hunger problem and demand-supply gap by increasing production efficiency. Therefore, on a global scale, "the question of whether the scientific discoveries are able to sustainably and effectively feed everyone by 2050" is the primary concern regarding the future of the agri-food sector [1].

The implementation of digital technology can provide "versatile technology that will revolutionize food production in most critical areas around the world" [2]. Generally, Digital Agriculture (DA) is currently understood as using modern tools, data monitoring and analytics, and data-driven solutions in agriculture to improve and/or optimize farming systems, increase crop quality and yield, reduce waste, and manage pest and disease pressure [2]. By using DA, agricultural producers, and researchers are able to use information and communication technology (ICT) by collecting data, which are achieved from satellites, sensors, connected objects, smartphones, storage, and data transfer protocols (3G/4G/5G coverage, low-speed terrestrial or satellite networks, clouds) [3]. DA could be used across different agricultural ecosystems and at different levels of its production, whether on the farm (optimization of cropping operations), in support services (new agricultural advisory services based on automatically collected data), or more broadly at the territorial level (water management). It also can be used in the value chain (enhancing inputs such as seeds, improving harmony between production and the market) [3].

The general understanding of what is meant by "digital technologies in agriculture" is primarily focused on expanding data gathered "in the field," the contribution of artificial intelligence, connectivity protocols and automation [1]. Many operations, including planning farming operations, financing, reporting, monitoring numerous operations, and performances, are simplified by digital technologies. Digital technologies in agriculture have been deployed in various segments of farming, including farm equipmentation, animal handling facilities, agronomy, and communication [4]. Interestingly, DA widely covers diverse aspects of the agri-food sector from basic application, like using mobile device to get technical assistance and monitoring the farms, to a more comprehensive implementation, like using satellites and Global Positioning System (GPS) to predict the weather conditions and mapping the fields [1]. At the advanced level, specialized Farm Management Information Systems (FMIS) and Farm Management Software (FMS) help producers to control their farm or nursery from a centralized platform, including tasks such as crop rotation, planning, inventory management, and financial tracking [3]. The first history of DA dates back to the mid-20th century, when computers were used to analyze data of farms and satellites were used to monitor crop growth. Nonetheless, DA finds its own way in the 21st century, when the powerful and affordable computing systems and technologies, including GPS, smartphone, drones, and sensors, are becoming increasingly available [5]. Precision Agriculture (PA), which was developed in early 1900s, is the basis of DA. More recently, new technologies of DA, such as Internet of Things (IoT), Artificial Intelligence (AI), and blockchain were introduced [1]. IoT, AI, wireless sensors, robotics, mechanization, sensors and data analytics have the potential to boost productivity, improve the utilization of water and other farm resources. These technologies can aid in fostering resilience and long-term sustainability in crop and livestock production [5].

Based on the current understanding of DA implementation and its potential applications across various food production systems, the following research questions are relevant:

- Which digital technologies have been used in agriculture?
- How these technologies can affect the agricultural industry in regards to sustainable food production?
- What is the adoption status of these technologies?
- What are the challenges of deploying these technologies in agriculture?

The objective of this review is to elaborate the potential advantages and obstacles of using DA, and to clarify ways in which these technologies can be leveraged to support agricultural sustainability, efficiency, and productivity. To the best of the author's knowledge, this review is a comprehensive documentation of DA as a potentially reliable approach to improve agricultural outcomes and to address global agri-food issues.

1.1. Research motivation

This review was motivated by the potential benefits of digital technologies in agricultural systems, which can provide strategic solutions for improving the efficiency and effectiveness of farm production. In addition, digital transformation can enable the adoption of modern food production techniques such as hydroponics, aeroponics, and aquaponics, including vertical farming, which can help address food scarcity challenges. However, there are issues and constraints related to this transformation that must be carefully addressed in order to fully realize the potential of DA, as highlighted elsewhere [6]. Several studies have addressed the emerging trends in DA by providing some description on the significant applications, benefits, and associated research challenges of smart farming [7, 8]. These studies were limited to explaining the general aspects while focusing on one or a few digital technologies aimed at improving the performance of agricultural supply chains, promoting sustainable agronomy through precision agriculture, or suggesting a smart farming framework.

Therefore, it is crucial to examine the evolution of DA from various viewpoints to encourage discussion in the field. This study aims to elaborate the potential advantages and obstacles of using DA, and to clarify ways in which these modern technologies can be leveraged to support agricultural sustainability, efficiency, and productivity.

2. Material and method

The following sources of information was used for literature review: Scopus (https://www.scopus.com/), Springer Link (http://link.springer.com/), Science Direct (http://www.sciencedirect.com/) and the National Agricultural Library (https://www.nal.usda.gov/). Google Scholar (https://scholar.google.com/) was also used to extend the research for potentially useful publications that were not indexed in the sources mentioned above.

This study chose to use the most prominent databases of academic research, such as Scopus, due to their extensive coverage of global and local academic journals and their reliability. These databases were selected because they contain essential metadata and allow for easy data extraction compared to other databases. Scopus was searched using the following key search terms: "Digital Agriculture, Precision Technologies, Digital Farming, Precision Agriculture, Intelligent Agriculture, Digital Agriculture Technologies."

Each search was documented in a table containing the keyword used, the source, and the number of publications found. An initial review was conducted to identify potentially relevant publications for this research by evaluating the abstracts of each publication. The decision to include or exclude a publication as potentially relevant was made after each review. After the partial review of potentially relevant publications, an in-depth analysis of each publication was conducted by reading the entirety of the publication to determine whether it addressed any of the research questions. The relevant information from the publication was extracted where applicable.

2.1. *Threats to validity*

The methodology used in this study followed the standard procedures of a literature review, which involves a search strategy, record extraction, and result reporting [9]. This type of review is suitable as a research method when the aim is to provide a broad view of research in various fields on a particular subject and to analyze research advancements or compare research on the topic across disciplines. This approach can be applied to investigate themes, theoretical perspectives, or particular issues within a research field or discipline, aiming to identify new ideas or approaches as well as theoretical perspectives or issues. A good review must be independently replicable, which gives them greater scientific value [10].

The presented literature review is susceptible to threats to validity because the search was conducted using only five online repositories. It is possible that additional relevant publications may have been missed by not exploring other sources. If this literature review is replicated, it is possible that different publications may be found. This difference would result from different personal choices during the screening and eligibility steps, but it is highly unlikely that the overall findings would change.

Fig. 1. The fundamental components of DA from cell phone to blockchain technology.

3. The challenges facing agriculture

The agri-food sector is experiencing increased pressure due to worldwide shifts from traditional to modern lifestyle. Additionally, there is a growing population that has to be fed, even though their diets are shifting [7]. In order to ensure the long-term sustainability of agriculture, it is imperative that the industry expedites its adaptation process and develops innovative crop and livestock production methods that effectively minimize environmental impact, promote animal welfare, contribute to the sequestration of carbon dioxide, and preserve biodiversity [3]. Over the past seven decades, the dynamics of agriculture has consistently favoured intensification and specialization. Globalization has made the widespread phenomena of competitive pricing in the agricultural industry (farm sector) much more severe. In essence, farmers are victims of unequal power dynamics between parties with disparate, if not opposing, interests [6].

Additionally, farming is practiced in regions that, in many cases, have evolved into specializations, creating imbalances. As a result of the specialization and interdependence, there is a significant increase in complexity, which magnifies instability, increases the probability of failure, and ultimately poses a significant barrier to change [2]. Therefore, it is essential to implement strategies as soon as possible to enhance production methods and approaches to structure the agri-food system so as to strengthen its resilience [1].

4. Digital agriculture (DA)

DA is based on the following five levers for action which, when mobilized together, lead to innovation: (1) abundance of data due to the development of sensors (from nano sensors to satellites) and facilitated communication and storage, (2) increase in computing power, which makes it possible to implement artificial intelligence and new modelling methods, (3) connectivity and information exchange interfaces, (4) knowledge management and engineering for decision support in agriculture, (5) automation, control and robotics [5,11]. In the past three decades, farming practices have been revolutionized by the widespread adoption of technologies such as automation and control systems, data analysis tools, web-based and mobile applications. The primary goal of these innovations has been to maximize productivity of agricultural lands and resources. From the early 1990s until 2010, growers monitored their field and identified deficiencies using GPS, satellite maps, and local sensing equipment such as data loggers. This approach is known as Precision Agriculture (PA). Moving forward, PA and smart farming practices have evolved toward digitalization with the emergence of Unmanned Aerial Vehicles (UAVs), long-range wireless sensors, and IoT devices. This has offered new hope to increase the sustainability of food supply. The fundamental components of digital farming are depicted in Fig. 1.

To identify problems and enhance agricultural productivity by effectively utilizing available resources, PA uses the available data collected from various sources, such as satellite photos and mobile sensing platforms. Simultaneously, smart and digital agriculture utilize robotics, wireless systems, mobile applications, and IoT-based automation to detect, assess, and control the condition of the soil, water supplies, and weather fluctuations on croplands to increase field efficiency and minimize expenses [11,12]. In the field of automation, the deployment of smart irrigation, water loss control, and continuous identification of soil nutrient levels in remote places have all benefited from wireless sensors and IoT devices [12].

The adoption and use of DA technologies vary across different regions of the world, and there are several factors that influence this variation. In Europe, there is a relatively high level of adoption and use of DA technologies, particularly in countries with a high level of agricultural production, such as France, Germany, and the Netherlands. The European Union has also been promoting the adoption of PA practices through its Common Agricultural Policy [13]. In North and South America, the adoption and use of DA technologies are relatively high, and the United States, Brazil, and Canada being among the leading countries in this area. These countries have been early adopters of PA practices and have been investing in research and development of new technologies. In Asia, the adoption and use of DA technologies are growing rapidly, and China being a leading country in this area. The Chinese government has been promoting the use of PA technologies to increase crop yields and reduce environmental impact [14].

In Africa, the adoption and use of DA technologies are still relatively low, due to various factors such as limited access to technology and infrastructure, and low levels of investment in research and development. However, there are initiatives aimed at promoting the use of DA technologies in Africa, such as the African Agricultural Technology Foundation's Digital Agriculture Services project [15]. Overall, the adoption and use of DA technologies vary across different regions of the world, and are influenced by factors such as access to technology and infrastructure, government policies and initiatives, and investment in research and development [16].

5. Significant technological advancements in digital agriculture

Because of digitalization, farmers can now manage their farms and agricultural operations more efficiently from a distance. Agriculture sensors, actuators, and gadgets will all be connected in the near future by IoT, enabling automatic real-time interaction, controlling, and decision-making. This can reduce the need for human labour, which in turn, increases productivity and revenue [17]. Cloud-based farm management tools like SmartFarm and Agrivi strive to combine this information from various sources and incorporate it into their decision-making processes. The combination of these factors provides farmers with data for dynamic management planning that was previously only available to large-scale megafirms [18].

5.1. UAV-based remote sensing

UAV-based remote sensing is considered as the application of unmanned aerial vehicles (UAVs), to collect images and information of the earth's surface (in this report referring to agriculture field) from above [17]. This technology is equipped with different types of sensors such as radar, lidar, thermal, multispectral, hyperspectral sensors which facilitate the capture of high-resolution data from water bodies, vegetation, land, and man-made as well as natural features. Compared to photos obtained from satellites, the datasets collected by drones that are integrated with high-resolution imaging sensors can provide farmers with higher precision. UAV-based remote sensing is primarily used to observe soil characteristics and crop stress [19]. This generates valuable information that can be used to develop decision support systems for smart pest control, fertilization, and irrigation management. There is a wide variety of UAVs, for instance fixed wing (planes), single-rotor (helicopter), hybrid system (vertical take-off and landing), and multirotor (drone) [20]. Among these, drones (multi-rotor technology) which are lifted and propelled by four (quadrotor) or six (hex-rotor) rotors, have become increasingly popular in the agriculture sector due to their mechanical simplicity in comparison to helicopters, which rely on a much more sophisticated plate control mechanism [21].

Remote sensing is a powerful tool for digital agriculture which can be used for a variety of purposes. For example, large-scale data can be used in forecasting the impacts of undesirable weather and pathogenicity of disease on crop productivities in the field [19]. Farmers can combine remote sensing with other technology including big data analysis, IoT, and AI to improve farm management [22]. All the detailed data and forecasting can help farmers to enhance productivity by reducing crop stress through effective pest and disease as well as nutrient management. The high accuracy of remote sensing-based sensor devices has made it possible to obtain more detailed information about specific soil-based compounds, molecular interactions, crop stress and crop biophysical or biochemical characteristics [23]. Such plant growth related measurements allow for determining nutritional requirements of plants, nutrient content in soil, plant water demands and needs for weed control [24]. In addition, remote sensing not only improve productivity, but also protect the environment, since it can allow farmers to find a better match between crop growth and water/nutrient uptake. There are many discussion regarding the traditional use of remote sensing, but very little discussion about its combination with other technology [20,25]. Recently, UAV-based remote sensing has become more popular due to the advances in sensor system and availability of low-cost drones which makes it a valuable agriculture tool for plant-producers, scientists, and researchers. Table 1 shows the pros and cons of UAV based remote sensing in agriculture.

Notwithstanding the advancement in the UAV-based remote sensing application, the adoption UAV-based remote sensing into the agri-food sector is slow due to issues such as [20]:

- Cost: The cost of acquiring and maintaining remote sensing equipment can be high, which can be a barrier for many farmers.
- Complexity: The data generated by remote sensing technology can be complex, which can make it difficult for farmers to interpret and apply to their operations.
- Standardization: There is a lack of standardization for data collection and analysis, which can make it difficult to compare data across different sources or technologies.
- Data quality: The quality of remote sensing data can vary, depending on the equipment used and the conditions in which the data was collected. This can lead to uncertainty around the effectiveness of the technology.
- Access: Limited access to reliable and high-quality data and internet connection can be a challenge for many farmers, particularly in developing countries or remote areas.
- Privacy and security: There are concerns around the privacy and security of data collected through remote sensing technology, particularly as it relates to sensitive information such as crop yields and land use.

Overall, these issues have slowed the adoption of remote sensing technology in agriculture, but efforts are underway to address these challenges and increase the adoption of this technology.

5.2. *Agricultural production with the use of electronic tractors and robots*

The development of electrical systems is mainly driven by the ever-increasing demands for reducing noise and exhaust emissions.

Table 1
Advantage and disadvantages of UAV-based remote sensing.

Advantage	Disadvantage
Improved crop monitoring: It can provide detailed information on crop health, growth patterns, and stress, allowing farmers to detect issues early and take corrective action.	Battery and flight time: At the moment, lithium-ion batteries are being used because their capacity is larger than that of conventional batteries. But an increase in battery capacity increases the drone weight.
Better resource management: It can help farmers optimize the use of resources such as water and fertilizer, reducing costs and minimizing environmental impact.	Technical complexity: The data generated by remote sensing technology can be complex, which can make it difficult for farmers to interpret and apply to their operations.
Increased productivity: By providing detailed and timely information, it can help farmers make more informed decisions, leading to higher yields and improved profitability.	Data quality: The quality of remote sensing data can vary, depending on the equipment used and the conditions in which the data was collected, which can lead to uncertainty around the effectiveness of the technology.
Efficient land use: it can help farmers identify areas of their land that are underutilized or overused, allowing them to make better use of their resources and maximize productivity.	Limited access: Limited access to reliable and high-quality data can be a challenge for many farmers, particularly in developing countries or remote areas.
Accurate mapping: It can provide accurate mapping of agricultural land, allowing farmers to better understand their land and make more informed decisions about planting, harvesting, and other activities.	Privacy and security concerns: There may be concerns around the privacy and security of data collected through remote sensing technology, particularly as it relates to sensitive information

Robots and electrical tractors that run on renewable energy sources are being used in DA as modern machinery for boosting sustainability and minimizing inputs prices. By using such machinery or robots, numerous farms can produce electricity using renewable sources [26]. The European Innovation Partnership Agricultural Productivity and Sustainability's SunBot project is an illustration of this strategy in action (EIP-AGRI). The project, which started in late 2018, has focused on automating a solar-powered tractor and mower for efficient utilization of resources in berry orchards [27]. The goal of the project is to automate an emission-free electrical tractor, which eventually will lead to improved harvest quality. The proposal calls for a universal two-wheel drive orchard tractor with an all-electric drive that run on lithium iron phosphate ($LiPO_4$) batteries and has a driving output of between 20 and 30 kW. The e-tractor must be equipped with front and rear three-point linkage C1 in order to support implements, as well as an electrically driven double-blade mower (400 kg/10 kW) which is supported by an AEF electric power connector [26]. Electrical tractors and mobile robots are replacing human drivers and human operators with artificial intelligence, which is contributing to the digital transformation of agriculture. Despite this potential contribution, these technologies are still in the experimental phase of their development and are pending implementation on a commercial or large operational scale [28].

In agricultural production, a collaborative system between robots and humans can be employed to achieve common goals. This co-robotic approach has proven to be efficient in weed management, resulting in a reduction of more than 50% in human labor requirements [29]. The use of robotics can significantly enhance the effectiveness of repetitive tasks [30]. In response to the COVID-19 pandemic, certain businesses have transitioned from utilizing human cutters to utilizing robots in order to facilitate social distancing measures. This transition has the potential to not only decrease labor costs, but also improve efficiency and accuracy in agri-food operations [31].

There are significant obstacles that hinder the full utilization of robotics in the agricultural industry. The current prototypes and commercially available platforms are restricted to carrying out specific tasks, and their adaptability to different crops or environments is questionable [32]. Moreover, the agricultural robotics industry faces numerous challenges related to interoperability and standardization, including communication between different platforms and safety concerns. These obstacles pose significant barriers to progress. It is imperative to broaden the scope of robotic capabilities beyond laboratory and greenhouse environments to outdoor settings, where they can sense and operate effectively in harsh and unpredictable conditions [31]. Regardless of the technical barriers, there is considerable scepticism related to social, economic, and ethical challenges in agricultural robotics. Labor shift from repetitive tasks to high-skilled engineering jobs and the imbalanced adoption of agri-technologies by farmers is expected to create social implications. Advanced intelligence and decision-making capabilities of robots results in debates about moral aspects and, overall, who has the responsibility for these actions [27]. In addition, the high cost of advanced technologies and the need for resources and infrastructure to implement robotics in the field will present significant feasibility challenges to the widespread adoption of agricultural robotics. However, as the industry moves towards an era of intelligent systems, robotic platforms will become an essential component of agricultural operations [29].

The agricultural robotic platform has the ability to automate some practices in outdoor and indoor farms - including seeding, watering, fertilizing, spraying, plant monitoring and phenotyping [33]. The agricultural robots use a combination of emerging technologies such as computer vision, wireless sensor networks, satellite navigation systems, AI, cloud computing and IoT, thereby enhance the productivity and quality of agricultural products [34].

5.3. Automated processes using wireless sensing and IoT

An IoT-based automation system comprises sensor nodes, several repeaters, and receivers that are interconnected across the field to

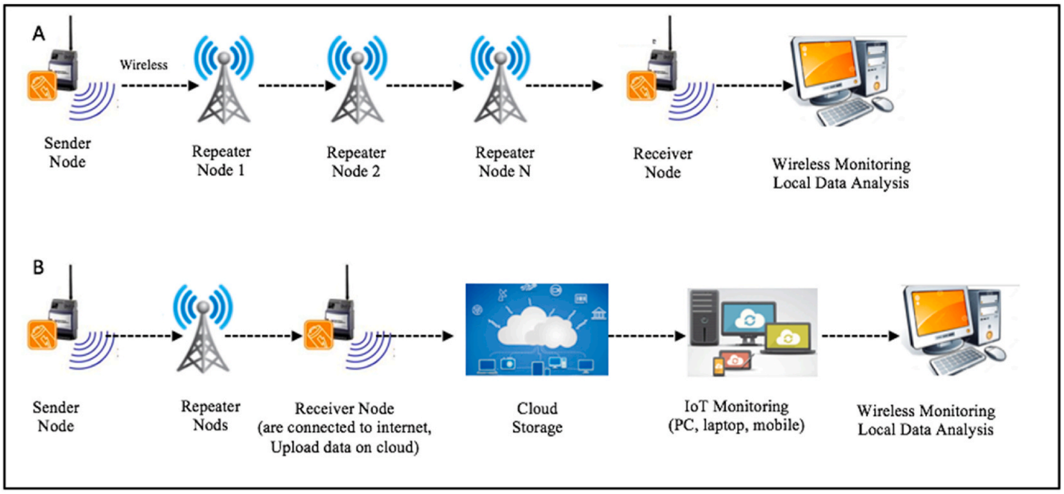

Fig. 2. A) Schematic demonstration of field measurement and data collection using a wireless sensor network and B) IoT monitoring and cloud-based data analysis.

increase the productivity and profitability of digital agriculture through a better understanding of the interactions between soil, crop, and weather [31]. Data access is limited in a wireless monitoring system because the receiver node saves data on a local host. In contrast, the receiver node in IoT-based monitoring systems uploads data to a web server so that any client device connected to the internet may access it [35]. Measurements obtained from a multitude of wireless sensors are input into a traditional Decision Support System (DSS) or crop growth model, powered by AI algorithms, through the utilization of internet connections and cloud-based streaming systems in large-scale agriculture, with the end goal of maximising both production efficiency and profitability [36]. IoT gadgets have shown to be useful for enhancing agricultural resource management and boosting output sustainability [35,36]. Fig. 2a represents field measurement and data collection using wireless sensor networks and devices, and Fig. 2b demonstrates IoT monitoring and cloud-based data analysis. The range of the distance between the sender and the monitoring device in wireless sensor networks is usually between 1-m to 100 km. However, this distance becomes unlimited when using IoT and cloud-based data analysis.

To ensure continuous data collection, large-scale farms require careful consideration of factors such as number of sensor nodes, repeater sites, power usage, operating frequencies, and distance between transmitters and receivers [37]. Developing an IoT architecture and successfully implementing its transmitters and receivers in the field can be intrinsically challenging. Most gateways utilize single-board computers equipped with ARM processors, while most software applications are intended for x86 processors. This results in compatibility concerns and unexpected behaviours [38]. WiFi, Bluetooth Low Energy (BLE), LoRaWAN, SigFox, NB-IoT, and LTE are the radio protocols that have the most widespread application for IoT [35–37].

There are different types of WSNs, which are categorized depending on the environment where they are deployed. These include Terrestrial Wireless Sensor Networks (TWSNs), Wireless Underground Sensor Networks (WUSNs), Underwater Wireless Sensor Networks (UWSNs), Wireless Multimedia Sensor Networks (WMSNs), and Mobile Wireless Sensor Networks (MWSNs) [39]. In agricultural applications, TWSN and UWSN are widely used. In TWSNs, the nodes are deployed above the ground surface, consisting of sensors for gathering the surrounding data. The second variant of WSNs is its underground counterpart, WUSNs, where sensor nodes are planted inside the soil. In this setting, lower frequencies easily penetrate through the soil, whereas higher frequencies suffer severe attenuation [37,40]. Therefore, the network requires a higher number of nodes to cover a large area because of the limited communication radius. Many research articles are available in the literature that discuss the use of WSN for different outdoor and indoor applications, such as irrigation management, water quality assessment, and environmental monitoring. These studies have focused on developing WSN architectures that are simplified, low cost, energy-efficient and scalable. Yet, various factors associated with WSNs need further attention, such as minimum maintenance, robust and fault-tolerant architecture, and interoperability [37,40].

Adoption of automated processes using wireless sensing and IoT in DA comes with several challenges. Many farmers may not be aware of the potential benefits of wireless sensing and IoT devices, making them unwilling to invest in these technologies [41]. Wireless sensing and IoT devices may be complex and require specialized knowledge to set up and use effectively, which can be a barrier for many farmers who may not have access to technical support. Additionally, some farmers may not have access to the necessary infrastructure, such as reliable internet connectivity, to support wireless sensing and IoT devices [42]. There may be concerns around the privacy and security of data collected through wireless sensing and IoT devices, particularly as it relates to sensitive information such as crop yields and land use. Furthermore, regulatory barriers may also prevent the use of wireless sensing and IoT devices in agriculture, such as restrictions on the use of certain frequencies for wireless communication [43]. Addressing these adoption issues is critical to ensure effective and widespread adoption of automated processes using wireless sensing and IoT in DA. This can be achieved through increased awareness and education, addressing cost and infrastructure challenges, ensuring data privacy and security, and establishing standard protocols and regulations to support interoperability and data compatibility [44].

5.4. Big data analysis

Rapid developments in IoT and cloud computing technologies have increased the magnitude of data immeasurably. This data, also referred to as Big Data (BD), includes textual content (i.e., structured, semi-structured, and unstructured), and multimedia content (e.g., videos, images, audio) [45]. The process of examining this data to uncover hidden patterns, unknown correlations, market trends, customer preferences, and other useful information is referred to as big data analytics (BDA). Big data is typically characterized according to five dimensions defined by five Vs, which are: (1) Value, (2) Volume, (3) Velocity (4) Variety, and (5) Veracity [46]. The paradigm of BD-driven smart agriculture is comparatively new, but the trend of this application is positive as it has the capacity to bring a revolutionary change in the food supply chain and food security through increased production. Agricultural BD is usually generated from various sectors and stages in agriculture, which can be collected either from agricultural fields through ground sensors, aerial vehicles, and ground vehicles using special cameras and sensors; from governmental bodies in the form of reports and

Table 2
Big data tools and services in agriculture.

Service category	Tools and techniques used	Big data source	Farm type	Maturity level
Water and environment management	Crop Modeling and simulation, geospatial analysis	Weather station, historical databases	Open-air	Conceptual
Crop management	Clustering, prediction, and classification. Support vector machine.	Sensor, historical, and farmer data.	Open-air	Conceptual
Irrigation management	Cloud based application. Cloud-based platform, and web services	Sensor data industry standards	Open-air Hydroponics	Conceptual, prototype

regulations; from private organizations through online web services; from farmers in the form of knowledge through surveys; or from social media [47]. The data can be environmental (weather, climate, moisture level), biological (e.g. plant pest/disease, plant nutrient), or geo-spatial depending on the agricultural domain and differs in volume, velocity, and formats. The gathered data is stored in a computer database and processed by computer algorithms to build relational assessments of seed characteristics, weather patterns, soil properties, marketing and trade operations, consumer behavior, and inventory management [45,48].

A summary of the tools and services used to decipher BD in agriculture is given in Table 2. Machine learning, cloud-based platforms, Modeling and simulation are the most commonly used techniques. Particularly, machine learning tools are used in prediction, clustering, and classification problems. Whereas cloud platforms are used for large-scale data storing, pre-processing, and visualization [45]. There are still many potential areas that are not adequately covered in the existing literature, where BDA can be applied to address various agricultural issues. For instance, these include data-intensive greenhouses and indoor vertical farming systems, quality control and health monitoring of crops in outdoor and indoor farms, genetic engineering, decision support platforms to assist farmers in the design of indoor vertical farms, and scientific models for policymakers to assist them in decision making regarding the sustainability of the physical ecosystem. Most systems are still in the prototype stage [49].

The adoption of BDA in DA has been steadily increasing in recent years. Many agricultural companies and organizations are now using advanced analytics and machine learning techniques to extract insights from large and complex datasets, such as weather data, soil samples, and satellite imagery. These insights can help farmers make more informed decisions about crop management, such as when to plant, irrigate, and harvest, as well as identify potential issues such as disease outbreaks and yield losses. They can also support a more efficient use of resources, such as water, fertilizer, and energy [50,51].

5.5. *Artificial intelligence in agriculture*

Artificial intelligence (AI) involves the development of theory and computer systems capable of performing tasks requiring human intelligence, such as sensorial perception and decision-making [50]. Combined with cloud computing, IoT, and BD, AI, particularly in the facets of Machine Learning (ML) and Deep Learning (DL), is regarded as one of the key drivers behind the digitization of agriculture. These technologies have the potential to enhance crop production and improve real-time monitoring, harvesting, processing, and marketing [51]. Several intelligent agricultural systems have been developed using ML and DL algorithms to detect weeds, predict yield, or identify plant disease. These systems are discussed in the next two sub-sections.

5.5.1. *ML in agriculture*

ML techniques are broadly classified into three categories: 1) supervised learning (linear regression, regression trees, non-linear regression, Bayesian linear regression, polynomial regression, and support vector regression), 2) unsupervised learning (k-means clustering, hierarchal clustering, anomaly detection, neural networks (NN), principal component analysis, independent component analysis, a-priori algorithm and singular value decomposition (SVD)); and 3) reinforcement learning (Markov decision process and Q learning) [52]. ML techniques and algorithms are implemented in the agriculture sector for crop yield prediction, disease and weed detection, rainfall prediction, soil physico-chemical estimation (type, moisture content, temperature, pH, nutrients), water management, fertilizer optimization and livestock production and management [53].

Crop yield prediction is a widely explored area of research. Linear regression, neural network, random forest, and support vector machine are the most used ML techniques in the domain of smart farming. Some of the use cases are still in the research phase with no reported commercial usage. AI techniques are sparsely explored in greenhouse and indoor vertical farming systems, particularly hydroponics, aquaponics, and aeroponics. Considering cyber-security and data privacy challenges, new approaches such as federated learning and privacy-preserving methods are being developed to enable DA [54]. These approaches build ML models from local parameters without sharing private data samples, thus mitigating security issues.

5.5.2. *DL in agriculture*

DL represents the extension of classical ML that can solve complex problems (classification and prediction) particularly well and fast because more "depth" (complexity) is added into the model. The primary advantage of DL is feature learning which involves automatic extraction of features (high-level information) from large datasets [55]. Different DL algorithms include Convolutional Neural Networks (CNNs), Long Short Term Memory (LSTM) networks, RecurrentNeural Networks (RNNs), Generative Adversarial Networks (GANs), Radial Basis Function Networks (RBFNs), Multi Layer Perceptrons (MLPs), Artificial Neural Network (ANN), Self Organizing Maps (SOMs), Deep Belief Networks (DBNs), Restricted Boltzmann Machines (RBMs), and autoencoders. A detailed description of these algorithms, popular architectures, and training platforms is available at various sources [56].

In the agriculture sector, DL algorithms are mostly used to solve problems associated with computer vision applications that target the prediction of key variables, such as crop yields, soil moisture content, weather conditions, and crop growth conditions including the detection of diseases, pests, and the identification of plant species [57]. Computer vision is an interdisciplinary field that has been gaining huge amounts of traction in recent years due to the surge in CNNs. Among DL algorithms, CNNs or Convet and its variants are the most used algorithms in agricultural applications. The variants of CNNs are region-based CNNs (RCNNs), FastRCNNs, Faster-RCNNs, YOLO, and Mask-RCNNs, among which the first four are mostly used to solve object detection problems. Mask-RCNN, on the other hand, is used to solve instance segmentation problems [57]. Few studies have also used other DL techniques. Most DL models are trained using image data sets while a few models are trained using sensor data gathered from fields. This shows that DL can be applied to a wide variety of datasets. Though DL has the potential to enable DA, most systems are still in the developmental phase. Additionally, the new challenges imposed by cyber-security and privacy issues require optimization of current DL and computer vision approaches [58].

5.5.3. Decision Support System (DSS) in agriculture

A DSS can be defined as a smart system that supports decision-making for specific demands and problems by providing operational answers to stakeholders and potential users based on useful information extracted from raw data, documents, personal knowledge, and/or models. DSS can be data-driven, model-driven, communication-driven, document-driven, and knowledge-driven [59].

Due to the progression of DA, the amount of farming data has increased immensely. To transfer this heterogenous data into practical knowledge, platforms like agricultural DSS are required to make precise evidence-based decisions regarding farm operation and facility layout [60]. Over the past few years, agricultural DSS has gained much attention within the agriculture sector. A number of DSSs have been developed focusing on a variety of farming components, such as farm management, water management, and environmental management. Most agricultural DSSs, however, do not consider expert knowledge, which is highly valuable as it facilitates development of systems as per user needs. Other issues with some of the agricultural DSSs are complex Graphical User Interface (GUI) and inadequate re-planning components, lack of prediction and forecast abilities, and lack of ability to adapt to uncertain and dynamic factors. It is also worth noting that the majority of agricultural DSSs are for outdoor agricultural systems. Application of agricultural DSSs for indoor soilless farming is still very much unexploited [61].

5.5.4. Agricultural Cyber Physical System (CPS)

As a key technology enabling DA, a CPS refers to an automated distributed system that integrates physical processes with communication networks and computing infrastructures [62]. There are three standard CPS reference architecture models, namely, 5C, RAMI 4.0, and IIRA, and their detailed description is available in Ref. [63]. Among these, the 5C is a well-known reference model with widespread usage. The architecture of 5C consists of five levels which are presented in Table 3.

CPS benefits from a variety of existing technologies such as agent systems, IoT, cloud computing, augmented reality, BD and ML [65]. Its implementation ensures scalability, adaptability, autonomy, reliability, resilience, safety, and security improvements. Agricultural CPSs use advanced electronic technologies and agricultural facilities to build integrated farm management systems that interact with the physical environment to maintain an optimal growth environment for crops [66]. Agricultural CPSs collect essential and appropriate data about climate, soil and crops, with high accuracy and use it to manage watering, humidity, and plant health. Most of the CPSs developed for agriculture, are still at the conceptual level. Moreover, most studies are conducted for outdoor farms, with only a few works published related to soil-based greenhouse systems. No study is found that is relevant to indoor soilless farming systems. CPSs has attracted significant research interest because of their promising applications across different domains. Deploying CPS models in real-life applications is still a challenge as it requires proper hardware and software [67].

6. Blockchain technology in agriculture

6.1. From ICT to blockchain

Blockchain is a distributed transaction ledger. It allows members of the community to exchange data with other services without the involvement of a third party and trace the transaction. Rather than keeping the information on a single server, it is distributed among multiple servers, making it extremely difficult to change or remove the records. The tamper-proof features a trademark, as well as a method that assures all data entered into the blockchain is authentic and encourages community confidence [68]. Peer-to-peer networks are used to distribute and maintain blockchains. It can exist without a centralized authority or server controlling it since it is a distributed ledger, and its data quality can be maintained using database replication and computational trust. To create a safe and valid distributed consensus, not all distributed ledgers use a chain of blocks. The blockchain's structure distinguishes it from other types of distributed ledgers. On a blockchain, data is gathered together and encrypted [69].

A distributed ledger is a database that spans several nodes or computing devices. Each node duplicates and saves a copy of the ledger. Each network member's node updates itself independently. The cost of trust is significantly reduced by distributed ledger technology. Distributed ledger designs and structures can help us reduce our reliance on banks, governments, attorneys, notaries, and regulatory compliance officials [70]. Blockchain technology can monitor food provenance and help build trustworthy food supply chains and boost customer trust. It enables using data-based technologies easier to make farming a more smart way to store data

Table 3
5C architecture for cyber-physical systems (adapted from [64]).

Implementation space	Levels of 5C	Function
Physical space	Configuration level	Self-configuration for resilience, self- configuration for variations, self-optimization for disturbance.
Cyber space	Cognitive level	Integrated simulation, decision making support system, collaborative diagnostic and visualization.
	Cyber level	Cyber-twin and big data Modeling.
	Data to information conversion level	Algorithm for smart data analytics, and performance forecast.
Physical level	Smart connection level	Sensor networks, data acquisition.

confidentially. It can also allow for prompt payment between stakeholders, which can be triggered by changes in the blockchain data in conjunction with smart contracts [71].

6.2. *Potential blockchain technology benefits for agriculture*

Through blockchain technology, peer-to-peer transactions can be completed openly and without a third party, such as a bank (in the case of cryptocurrencies) or a middleman in the agriculture sector. As a result of the elimination of the need for a central authority, trust is now provided to peer-to-peer architecture and cryptography rather than an authority. It contributes to restoring trust between producers and customers, lowering transaction costs in the agri-food sector [70].

A robust method of tracking transactions between anonymous individuals is provided by blockchain technology. Thus, fraud and errors can be found immediately. Furthermore, incorporating smart contracts also enables the real-time reporting of issues [72]. Due to the complexity of the agri-food system, this helps solve the problem of tracing goods along the extensive supply chain. Thus, blockchain technology enables the elimination food quality and safety issues, that are of great concern to consumers, and other stakeholders [73].

Blockchain technology increases transparency among all relevant parties and enables the gathering of reliable and verifiable data. From its production to its demise, the value chain of a product can be recorded using blockchain technology. The development of data-driven infrastructure and insurance solutions that make farming smarter and less susceptible, depends heavily on reliable data on the farming process [70].

6.3. *Applications of blockchain technology in the agriculture and food sector*

Four categories of blockchain applications in the agricultural and food industry are covered in this section: (1) agricultural insurance, (2) smart farming, (3) food supply chain, and (4) transactions of agricultural products [74]. These categories are discussed in the following sections.

6.3.1. *Agricultural insurance*

Index insurances are increasingly valuable as a tool for risk management, especially for farmers who have a keen interest in mitigating basic risks. The index insurance industry may benefit from blockchain technology in two ways. Firstly, a smart contract can ensure that payments are issued on schedule and without human intervention, such as when weather conditions are met [75]. Secondly, an intelligent oracle may automate the integration of meteorological data and other sources of data, such as plant growth data or data acquired by farm machinery, to better mitigate basic risks and streamline index computation and pay out. It has been shown that smart contracts that employ smart oracles to include external data can be pretty valuable in different crypto-economic contexts [76]. The initial prototypes of smart index insurance contracts have already been developed or released. For instance, the Swiss business Etherisc1, which uses blockchain technology, offers decentralized crop insurance with payments based on weather data in decentralized insurance protocol tokens as a native currency [70].

Aside from the benefits of decentralized insurance based on smart contracts that make automated pay outs, the applicability of cryptocurrency pay outs to compensate farmers must be demonstrated in the field. Furthermore, farmers in underdeveloped countries may lack access to the necessary infrastructure to participate in a decentralized blockchain-based insurance scheme. As a first option, Etherisc, for example, suggests that third-party companies provide payment channels and integrations that eliminate the end customer's need to possess cryptocurrency [77].

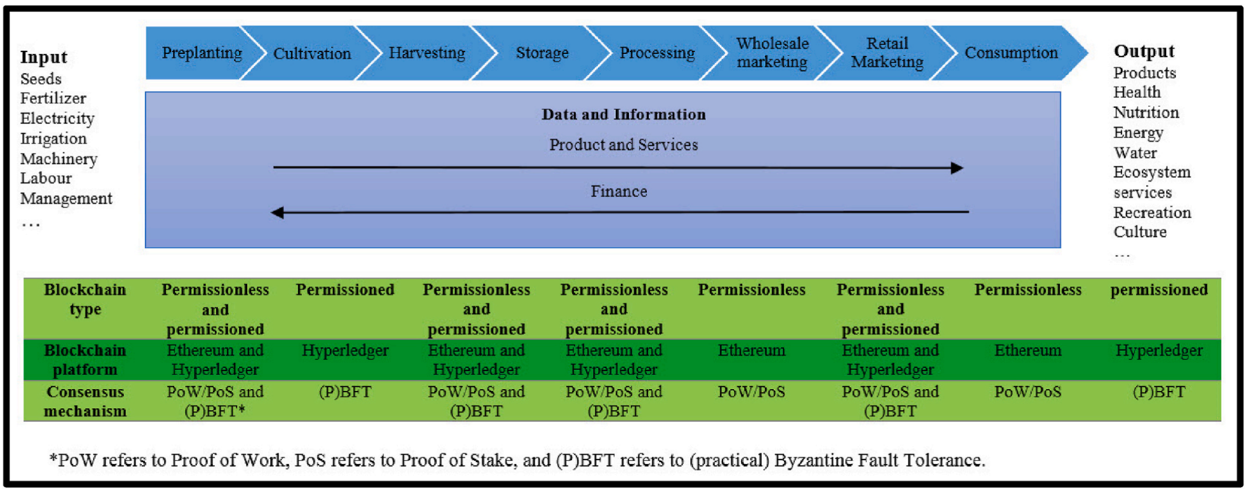

Fig. 3. Data and information flow along the food value chain.

6.3.2. Smart agriculture

Agri-food systems are supported by data and information on natural resources that sustain all types of farming. Fig. 3 illustrates the flow of data and information, the flow of products from input to output through various value-adding stages, and the flow of money from output to input. It shows how and what type of blockchain is used on different kind of platforms (Ethereum or Hyperledger) along with various consensus mechanism might be suitable to collecting data and information at different stages in crop agri-food systems [78].

Multiple actors and stakeholders produce and manage data and information depending on their capacities and needs. Utilizing ICT, IoT, and a variety of contemporary data collection and analysis tools, such as Unmanned Aerial Vehicles (UAV), sensors, and machine learning, are critical components of smart agriculture [79]. Creating a comprehensive security system that facilitates data use and management is a crucial component of smart agriculture. Traditional methods manage data in a centralized manner and are vulnerable to cyber-attacks, inaccurate data, data distortion and misuse. For instance, data from environmental monitoring is typically managed by centralized government agencies with special interests. They can influence decisions made in relation to data. Environmental monitoring data, for example, is generally collected by centralized government entities with special interests. They can influence data-driven decision-making [80]. Throughout the entire value-added process, from seed to sale, of producing an agricultural product, various actors and stakeholders generate data and information that can be stored using blockchain technology. This guarantees that all recorded data are immutable and that the data and information are transparent to all parties involved. Unlike methods, which rely on "security of obscurity," blockchain technology produces security through decentralization [79].

The combination of IoT and blockchain technology has led to the development and implementation of several smart agricultural schemes. For example, a lightweight blockchain-based architecture for smart greenhouse farms is proposed by Refs. [42,81]. IoT sensors in greenhouses function as a local, private blockchain that the owner centrally controls. A smart agricultural framework based on blockchain and IoT is proposed by Lin [78] for large scale implementation. The primary purpose of the platform is to build trust between parties utilizing blockchain. Agents involved in the selling of plantation products can access the data recorded in the blockchain using mobile devices. For application at the local and regional levels, Ref. [82] suggest a blockchain-based ICT e-agriculture model in which each actor has a piece of real-time water quality data kept in the blockchain. Additionally, farm organizations are utilizing blockchain to improve their farming practises and make it smarter. For example, Taiwan's agricultural irrigation groups use blockchain to store data collectively and improve communication with the public [81,83].

6.3.3. Food supply chain

From the producers' standpoint, using blockchain technology fosters a connection of trust with customers and enhances the reputation of their products by clearly presenting specific product information in the blockchain. Companies can boost their competitiveness by effectively achieving the value of their products. As a result, it would be challenging for sellers of low-quality products and frauds to maintain their market presence. It would be necessary for all sellers to raise the calibre of their goods across the board in the agriculture and food industries. Blockchain provides customers with accurate and trustworthy information on the production and distribution of food. It addresses customers' concerns about food safety, quality, and environmental friendliness [84,85].

The use of blockchain enables consumer-producer interactions since customers can comprehend the food production process in greater depth and with greater convenience. Lowering trade barriers helps customers feel more secure in the products they buy and the integrity of the food supply chain. From the regulatory authorities' point of view, blockchain facilitates the dissemination of credible and accurate data necessary for the implementation of well-informed and efficient rules [86].

The whole history of a product, from its point of origin to the end of the sale, can be recorded and verified using blockchain technology. A blockchain is a distributed ledger technology that can safely and permanently store information gathered at the source of a product's development, such as the genetic makeup of cattle or the levels of pesticides on grain or vegetables. Any participant in the product's supply chain can review and verify such data. The availability of such data can aid in identifying illegal activities, such as the 2013 horse meat scandal in Europe [87,88]. Having blockchain in place ensures that all manufacturing, processing, storing, and distribution data is authentic and cannot be tampered with. Using blockchain technology and IoT, Caro [71] proposed a system that can track the product's origins and destination.

In October 2016, Wal-Mart, Tsinghua University, and IBM piloted the hyper ledger blockchain system's applicability to food supply chain management by investigating the Chinese pig supply chain and the United States mango supply chain. Together with Australia Post, Alibaba investigated blockchain technology in March 2017 to prevent food tampering [70]. Wal-Mart, Nestlé, Dole, and Golden Food were among the ten top food and fast-moving consumer goods (FMCG) suppliers in the world when they partnered with IBM in August 2017 to integrate blockchain into their supply chain to detect food supplier fraud efficiently. IBM's blockchain platform is used in this partnership to aid food producers in increasing supply chain transparency and reducing food safety risks [87].

6.3.4. E-commerce of agricultural products

There are significant issues that need to be addressed in the e-commerce and trading of agricultural products. According to the research conducted by Oliveira [89], customers who have a high level of confidence in institutions, in general, are more likely to purchase online. However, consumers may have trouble verifying and trusting the basic information about agricultural products. In the meantime, the most significant difficulties for online retailers, especially those operating in developing countries, are cash on delivery and logistics service [90]. In addition, e-commerce stores have to deal with time-consuming small orders with a wide range of items, which results in significant operational costs for businesses [91].

Many of these issues may find satisfactory solutions through blockchain technology, viz. (1) information security: To fulfil authentication needs, blockchain technology offers private key encryption, a powerful technique for addressing this need [92]. As a result, it can reliably connect data from all phases of agricultural production, from planting to harvesting. (2) Supply chain management: By reducing the cost of sending and receiving signals between nodes, blockchain technology has the potential to make supply chain management more efficient than the current monitoring method [93]. Each part of the supply chain, from the manufacturer, the point of origin, the shipping company, the final destination, multimodal transport, storage facility, and the last mile, represents a "block" of information that can be tracked individually or as a whole for greater transparency, control, efficiency, and reliability [94]. (3) Payment methods: Blockchain technology enables a digital payment system with no transaction fees. Additionally, using cryptocurrencies in the trade of agricultural goods will significantly reduce transaction costs [49]. (4) Consumer confidence: Blockchain's distributed accounting system is time-stamped through a decentralized process, making all data stored therein verifiable and irreversible. Freed from the threat of counterfeit goods, consumers will once again have faith in the convenience and security of online shopping [89,90]. (5) Reduce farmers' costs: Households create a wide variety of agricultural goods. Traditional e-commerce is unable to or unwilling to serve these customers because of their low transaction volume and limited scale. Therefore, they are cut off from the market. Blockchain technology has the potential to significantly lower transaction costs and reintroduce them to the market [95].

6.4. *Challenges for blockchain implementation*

The preceding discussion indicates the increasing adoption of blockchain technology in the supply chain industry. While blockchains and distributed ledger technology hold the potential to resolve most of the challenges, it is crucial to note that they are not a cure-all [96], particularly considering the critical and often high-pressure nature of the agricultural supply chain. Additionally, the implementation of blockchain technology must consider a range of societal, technical, and financial factors [97].

Burke [98] observes the potential societal impact of blockchain implementation in the agriculture industry, noting that this sector has its own set of unwritten rules and delicate relationships that should not be disrupted. The agri-food supply chain is highly intricate and hesitant to adopt blockchain technology due to following reasons.

- The low level of technological knowledge among many stakeholders;
- The complex transformations that products undergo throughout the chain;
- The heterogeneous roles and businesses of the many stakeholders involved;
- The fact that the food supply chain is distributed over large geographical areas, sometimes spanning different continents, which creates interoperability and deployment obstacles.

Issues related to data management, particularly data ownership and data retention within the blockchain, are also important and have to be carefully considered [99]. From a technical viewpoint, while blockchains can serve as unalterable ledgers, there is no assurance of the precision of data entered by sensors or individuals. Therefore, if a sensor fails to operate correctly, the information recorded on the blockchain is not reliable [100]. Generally, there are challenges in monitoring, integrating, and evaluating specific types of data within the agricultural supply chain. For instance, obtaining and analyzing environmental data using objective methods is challenging [101].

The selection of the proper type (public, private, permissioned) of blockchain and its implementation can also be an associated issue. A large number of research works use public blockchains, and the same applies to some of the commercial products (e.g. IBM food trust). However, The performance trade-offs of using public blockchains in agri-food supply chains are not always fully discussed. This is because transactions involving multiple actors require a significant amount of time and computing power to be completed on a public blockchain [97]. Careful selection of blockchain type is crucial as it can impact the traceability performance. From a financial aspect, the adoption of blockchain technology in the food supply chain may enhance transparency and consumer trust, but it comes with significant expenses. Companies are required to invest a substantial amount of money and time to train all the relevant personnel and acquire the necessary equipment [102]. Conversely, the expenses associated with such investments in terms of time and money can be substantial and may surpass the product's cost, both in the short and long run.

Behnke [103] studied the challenges of blockchain applications in the agriculture and pointed eighteenboundary conditions for food traceability, five of which directly applied to blockchain technology. Accordingly, a significant number of the bottlenecks are related to regulatory requirements, internal supply chain and production processes, which require significant organizational changes in order to support the full benefits of traceability. In the same context, Kamilaris [104] analyzed the impact of blockchain on the agriculture supply chain. The main challenges highlighted include the accessibility to blockchain technology, governance and sustainability, policy and regulation, technical challenges and design decisions that must be taken, as well as bridging the digital gap between developed and developing countries in order to achieve successful. Kamilaris [104] also referred to the important role of governments to lead the way by digitalizing public administration.

7. Impact of DA solutions on food security

DA has been identified by scientists as one of the "ten best innovations for adaptation in agriculture" that can help achieve food security in the face of climate change while delivering co-benefits for environmental sustainability, nutrition, and livelihoods [105]. Using big data approaches to solve development problems more quickly, better, and at a larger scale, this technology can enhance the impact of agricultural development [106]. Some countries, notably Australia, are stepping up efforts to assure long-term food security through precision-based digital farming or smart farming [107].

Incorporating interactive technology and data analytics into farming can boost precision, production, and profitability for small-scale farmers and help them better prepare for climate change while reducing future adverse environmental effects [108]. Integrating additional data and digital tools into agriculture to increase productivity has various potential advantages, such as increased input efficiency and enhancement of value derived from farming a unit of land, thus reducing the motivation to convert more land for agricultural use (a major contributor to the emission of greenhouse gas). Digitalization allows for new links with markets, which helps improve value chain coordination and reduce post-harvest loss by using productivity-related data for analysis and sustainability planning at the landscape or system level [109].

As a result of various digital technologies in the food system, customers and producers are now more educated and engaged, and farms are becoming more intelligent. Blockchain technology for value chain traceability and various configurations of precision and digital agriculture are just a few examples of the cutting-edge tools available today [106].

The following are the most significant benefits of precision and digital agriculture:

- Improvement of the food system's performance, which is critical to achieving sustainable development goals,
- Improvement of food system outcomes in rural and urban locations by way of expanding digital opportunities for all, including farmers and agribusinesses,
- Farmers and growers can minimize their costs, make informed decisions, and have better access to information, knowledge, and markets [106,110,111].

8. Challenges in the development of digital technology in the agricultural industry

The advancement of digital technology in society and the changes it brings are inherently accompanied by a set of hazards intrinsic to the situation. Similar concerns are being expressed about whether DA can live up to expectations, what challenges it may pose and what weaknesses it would highlight in the agricultural industry [112].

It is believed that the advancement of digital technology in agriculture introduces some concerns, despite the numerous potential it provides [113]. These concerns include i) not meeting expectations in terms of improving the environmental friendliness of agricultural and food systems, ii) loss of autonomy and rising inequality and iii) maintaining food sovereignty. An excessively complicated food system exacerbates vulnerability, weakens governance, and reduces crop yields. Investigating these threats will allow farmers, residents, and researchers to evaluate their methods, decisions, and priorities so that digital technology can serve the stakeholders responsibly [112].

Failure to address the desire for a more ecological agriculture is the first danger. While advances in digital technologies have opened up new opportunities, some drawbacks are evident, i.e., the inability to easily switch to a different solution and the difficulty of implementing systematic changes to organizational structure which are necessary to fully realize the environmental and financial benefits [113]. In addition, the widespread adoption of digital interfaces between farmers and plants or animals, in the context of growing technologicalization of agricultural production, could also weaken connections to nature (especially the human-animal connection). Still, society today is undoubtedly looking for a type of agriculture that is more closely connected to the living world around us. The growth in equipment and processes for data collection, transport, storage, and computation might aggravate the environmental effect. Additionally, digital technology has a distinct ecological footprint that is not fully understood yet [114].

The social repercussions of using digital technology to accelerate industrialization and the concentration of production in larger and more productive farms can also pose potential complications. This trend carries the risk of excluding agricultural practices used by minority farmers with minimal productivity strength [115]. Advancement in robotics may lead to insecure employment in agriculture, especially for low-income populations of migrant workers [116]. Challenges in obtaining access to digital technology may also contribute to agricultural exclusion; this might be the case with either the individual (lack of skills) or territorial (underdeveloped digital infrastructure level. There is concern that farmers would be reduced to "data workers" as a result of digitalization, which could impact their decision-making autonomy (when using DSS) [117]. The shifting power dynamics between agricultural upstream and downstream industries is another issue that may be caused by digitalization. Due to the growing prevalence of upstream industries, digital technologies can potentially influence both the comprehension and use of production tools, resulting in a dependency on particular inputs of a specific kind [118]. With implications for sharing, governance, and the danger of subsidiary creation driven by downstream parties, new data technologies might alter the roles of some entities (such as businesses in the digital industry) across the value chain.

With the emergence of monopolistic players and tools, digitalization of the food chain may be inevitable [115]. Data control is an element of digital sovereignty, and there is a possibility that providers of digital technology or services might take possession of information related to agriculture. In order to foster innovation, the exchange of agricultural data must be organized, and the governance of this data must be made clear [118]. Linked items (e.g. sensors, robotics), the availability of geolocation systems, and the issue of avoiding piracy of agricultural data are all important factors that need consideration. Our food systems are extremely important and have mostly been unaffected up until now, making them potential targets in the future [119,120]. The digitalization of the agriculture and food system may lead to an increase in the resource dependency among the various actors within the system [80]. May expose the in a broader sense, it is important to emphasise that agriculture, together with its upstream and downstream industries, comprise a complex sociotechnical system, and within this system, the cost of energy as a whole is increasing [121]. It is crucial that this does not overshadow the expected advantages of digitalization. Digital technology advancements have the potential to magnify the dynamics of increasing complexity, thus it is important to prevent them from igniting a technological frenzy that would trap us in an uncontrollable complexity cycle [122,123].

Seizing the opportunities offered by digital technology for agroecology and rebalanced value chains while identifying and anticipating the risks also poses scientific, technical, economic, organizational, and political challenges [124]. We will focus in detail on the scientific and technological challenges and the associated human challenges to respond to four main types of issues for the sustainable food system: (i) improving collective management and incorporating the territorial level, (ii) improving farm management, (iii) rebalancing the value chain between upstream and downstream and (iv) creating and sharing data and knowledge [125,126].

8.1. Providing digital tools for collective management at a regional level

Three key areas have been identified for overcoming the obstacles linked to the use of digital technology for land management.

8.1.1. Measurement and monitoring on a large scale

The ambition to make agriculture less artificial, get the most out of local assets, and reuse natural resources, will be determined by the capacity to take advantage of material flow, the potential of biological regulation, and functions beyond the farm (e.g., ecosystem services and land ecology). Many of the different interactions can only be understood through a systemic approach [127].

(i) Some characteristics, such as the extent to which a piece of land may be traversed, can only be understood on a regional scale. In contrast, others must be considered over time, such as the capacity for resilience and speed of recovery when faced with climatic threats. Therefore, if we want to employ the principles of agroecology, we must quantify parameters that are difficult to detect such as biodiversity, soil quality water quality, greenhouse gas emissions [124]. Information theory depends on the adjustment of sampling frequency (temporal and spatial). Systems either frequently collect data at varied temporal and geographical resolutions (sensor networks) or sporadically (non-sensor networks) through crowdsourcing or mobile applications to manage heterogeneous data. This results from diversity in terms of the objects observed, sensing and collection techniques (including crowdsourcing), stakeholders, parameters measured, formats (value, images, localization), and metrological properties (precision, frequency). Data governance is also an issue that is exacerbated in multi-source data systems [128,129].

8.1.2. Data visualization

Visualization methods will need to be revolutionized for data management at a significant regional level. Given its particularities, the agricultural sector has raised research questions with no current equivalents in the field of visualization, such as [130]:

(i) Visualizing multi-scale, heterogeneous data, symbolic data, temporal data, variable data, incomplete data, quantitative data, and qualitative data depending on variations in structure such as mapping in a geographic information system (GIS) and imagery from satellites or drones.
(ii) Visualizing extreme data scales from short- or long-range, connecting them in a fluid and clear manner, and developing suitable and appropriate tools for aggregation and statistics [131].
(iii) Revealing new information semi-automatically by comparing maps or time series data, highlighting symmetries, regularities, trends and correlations.
(iv) Meeting contradictory needs such as visualizing massive data, but with mobile applications, or guiding users while respecting their autonomy.
(v) Finding innovative ways of representing complex objects, dependencies or models capable of being used by individuals from diverse backgrounds.

These questions open up new prospects for certain basic subjects, including the visualization of uncertainties and advanced visualization [125,132]. Nevertheless, there has not been much discussion on issues pertaining to privacy and usage rights for data [131].

8.1.3. Digital devices for participation, mediation, and governance

The multi-actor approach is essential at a regional level and requires support tools. The knowledge production mode is changing, with transdisciplinary research requiring significant contributions from external stakeholders, which may be easier in the digital era [124]. In sectors operating at a regional level, it is increasingly common for individual and collective interests to come into conflict with each other [133]. New digital devices from regional engineering are anticipated to facilitate dialogue within the world of agriculture and with other regional stakeholders.

8.1.3.1. Systems for monitoring animals, plants, and their environment. The common difficulty in farming is in ensuring that farmers have quick, easy-to-understand information regarding the status of their cropping or animal husbandry which can allow for early detection of problems and facilitate timely intervention. Acquisition of massive data sets has the potential to boost large-scale phenotyping on farms, which is essential for expanding the overall understanding of agroecology [133]. In the context of agroecology, one key issue is detecting malfunctions, with the compromise of "coverage" (the area covered by the detection system) versus specificity. Specific measurements (e.g., detecting a virus or bacteria) are complex due to the need to establish contact, cost, energy supply, and the issue of false alarms in livestock breeding [134].

Research on acquisition systems, sensors and IoT, data management systems, and associated digital models linked to farming could focus on [135]:

(i) Creating new sensors while respecting constraints typical of agriculture (i.e., frugality, cost, energy use). In order to improve understanding of the agroecological systems, it is becoming increasingly clear that we must take into account the physical parameters of an environment and its biological parameters (animal/soil microbiota), which would generate needs in terms of omics methodologies.
(ii) Optimize the data transfer mode, so that data can be transferred automatically to the processing center.

Research aimed at building responsible digital technology for sustainable agriculture must absolutely incorporate (i) a comprehensive perspective on agriculture and the impacts of digital technology implementation, (ii) the search for cost-effectiveness both in terms of economics and environment, (iii) the search for resilience rather than economic optimization in food systems, and protection of farmers' autonomy, and (iv) cybersecurity (i.e., attacks via the IoT, data hijacking, geolocation jamming), a topic that is all the more essential as it affects food sovereignty [136,137]. Table 4 summarizes the current challenges in the development of digital technology for agriculture.

9. Summary of findings

The goal of this review was to describe the cutting-edge digital technologies that are being integrated into the agricultural industry and to forecast the future direction of DA. Upon extensive analysis, it can be concluded that certain technologies such as big data and analytics, wireless sensor networks, and cyber-physical systems have not been extensively studied in the agri-food domain. The high cost of implementing complex and advanced technologies in the agriculture sector during the early stages of adoption could be one of

Table 4
Challenges in the development of digital technology for agriculture.

Risks	Factors	References
Compromising the ecological transition in agriculture	The agroecological transition and technological lock-in. Taking humans further away from nature. Growing environmental imprint from digital technologies.	[113,114,138]
Widening inequality and power imbalance	Risks of exclusion. A loss of autonomy for farmers. Upstream and downstream control. Accessing information and training.	[115,118,119]
Loss of sovereignty	A loss of autonomy over food supplies. Seizure of agricultural data. A loss of control over production equipment. A challenge for cybersecurity.	[115,118,119]
Accentuating vulnerabilities and negative yields.	The vulnerabilities of the agri-food system. Increasing complexity, diminishing returns, and associated risks.	[121,123]
Providing digital tools for collective management at a regional level	Monitoring and measurement at a regional level. Visualization. Digital devices for participation, mediation, and governance.	[124]
Helping farmers to manage their technical journey	Acquisition and diagnostic systems. The challenges posed by robotization and the digital transformation of agricultural labour: - Scene perception and interpretation in dynamic environments. - Advanced approaches to decision-making. - Designing new active tools - Human-machine interaction and shared autonomy. - Operational safety. - Adapting to new production systems. - Modelling to incorporate systemic effects and build practical, useable decision-support tools. - The level of integration for expert knowledge. - Building practical decision-support systems for farmers - Uncertainty and its propagation.	[124]
Transforming relationships between stakeholders within sectors	- Advisory and insurance services - Developing decision-support tools capable of integrating the specific features of individual farms (pedoclimatic, traditional agronomic techniques employed, agricultural equipment) and the preferences of farmers. - Continuing the economic analysis of decision-making employed by farmers and the dynamics for adoption of digital innovations. - Institutional analysis of the governance of the digitalization of agriculture. Traceability, complete supply chain transparency, data life-cycle - Technical challenges of blockchain technology and its governance. - Data storage and integration from agriculture and food chain, i.e. big data. - Platformization and reconfiguration of channels.	[119]
Creating and sharing data and knowledge	Participatory data (crowdsourcing). Governance and the sharing of data and knowledge. Formalization and sharing of knowledge.	[139,140]

the primary reasons for this gap. The findings of this review also demonstrate that IoT has gained significant traction in farms. This is primarily attributed to the diverse range of functions that IoT offers, including monitoring, tracking, tracing, agriculture machinery, and precision agriculture. Although, IoT is a significant area of focus in DA, very few studies have taken into account aspects such as data security and reliability, scalability, and interoperability in the development of intelligent agricultural systems. Our analysis indicate that the majority of use cases in the agricultural sector are still in the prototype stage. This is likely due to the fact that agricultural processes involve living organisms such as animals and plants, as well as perishable products, which make developing systems more challenging compared to non-living systems. Nonetheless, agriculture has been relatively slow to adopt technological advancements due to the complex and multi-disciplinary nature of the industry.

Digitalization of agricultural systems is complicated due to variation in plant or crop species and growth conditions. This emphasizes the necessity for significant research and development efforts in specific areas to guarantee successful implementation of DA in both developed and developing countries.

The potential of blockchain technology to assist the agricultural industry was also examined. The application of blockchain technology can benefit the agricultural sector by providing immutable and irreversible storage of data. Moreover, blockchain technology can enhance credibility and contribute significantly to the sustainable agri-food industry. While blockchain has the potential to ensure food traceability, there are still several limitations to be taken into account, such as regulations, stakeholder relationships, data ownership, and scalability. To enhance comprehension of the technology and enable the creation of novel applications, it would be advantageous for researchers and developers to establish a comprehensive assessment model.

The adoption of new technologies by stakeholders in the agricultural sector is only possible when they are made easy to use, enhances productivity, and delivers additional value to end users. Therefore, the implementation of new technologies in a traditional agricultural setting is a major challenge that should be approached gradually and efficiently, with the active involvement of stakeholders who are directly affected throughout the supply chain. The complexity of the agriculture ecosystem gives rise to a set of interrelated obstacles that impede the complete integration of digital technologies for DA implementation. Therefore, it is crucial to identify possible challenges to formulate strategic solutions to overcome them. This review aimed at examining these challenges.

The various advantages that can encourage farmers and stakeholders to embrace the adoption of digital technologies in the agricultural sector were identified and compiled in Table 5. These benefits possess the potential to optimize farm productivity, improve product quality, and ultimately contribute to boosting food security.

10. Future perspectives of DA

The possibility of using advanced technologies to improve plant production under normal and stress conditions can promote the development of digital farms in a scalable manner to sustain livelihood and increase food supply [106,110]. Although digital technology has enormous potential to contribute significantly to crop production and protection, the application of this modern technology also comes with risks, such as the lack of privacy, the over-concentration of service providers, exclusion and even job losses for specific occupations, and cyber security breaches [141,142]. Even though digital technologies offer numerous advantages, they should not be considered a final solution. The importance of other branches of plant science like plant biotechnology and breeding to produce new varieties or improve the defence mechanisms of available plant varieties against adverse condition should be considered. In addition to these, the role of infrastructure and the importance of investments, such as better roads, uninterrupted electricity, post-harvest storage facilities, and improved logistics for connecting farmers to markets, cannot be overstated. A more favourable investment climate and enhanced governments policies could boost the deployment of digital technologies in agriculture [106].

11. Conclusion

Modern industrial farms and enhanced agricultural production methods are becoming necessary due to the growing concern over the world's food security crisis. The Industry Revolution 4.0 agenda, which pioneered the proliferation of data-driven approaches, has equipped the agricultural sector with a wide range of creative solutions to boost agricultural yields, lower prices, reduce waste, and maintain process inputs. This review presents a comprehensive analysis of the current state of prevailing digital technologies in the

Table 5
Added value of DA.

Benefits	Explanation
Improved agility	Digital technologies enhance the flexibility and responsiveness of farm operations. By leveraging real-time monitoring and predictive systems, farmers or agricultural specialists can promptly respond to any potential changes in environmental and water conditions to protect crops from stress.
Green process	Digital platforms can enhance the efficiency of resource utilization by optimizing the quantity and quality of agricultural output while reducing the consumption of water, energy, fertilizers, and pesticides.
Time and cost savings	Digital technologies enable considerable time and cost savings by automating various operations, such as sowing, harvesting, irrigation, and regulating the application of pesticides or fertilizers.
Asset management	Digital technologies enable instantaneous monitoring of agricultural properties and equipment to prevent theft, expedite replacement of components, and carry out regular maintenance.
Product safety	The application of digital technologies ensures sufficient farm productivity and assures a safe and healthy supply of agri-food products by preventing fraudulent activities related to adulteration, counterfeiting, and artificial enhancements.

agriculture sector. Our assessment indicate that big data and analytics, wireless sensor networks, and cyber-physical systems are in still the preliminary phase. Most use cases are in the developmental stage and have not yet reached the market for commercial use. Also, incorporating blockchains can prove advantageous for farmers by enabling the irreversible and immutable storage of data. The utilization of blockchain technology for securing food traceability and data storage across the supply chain appears to hold great promise. In addition certain challenges are identified, which must be carefully examined and addressed to achieve digitalization of the agriculture industry. This review highlights and elucidates the added value of digital technologies in the agricultural industry. It is envisaged that this review will contribute a valuable resource to the ongoing research on DA. This review has two primary limitations. Firstly, the literature search was restricted to only five online repositories, (Scopus, Springer Link, Science Direct, National Agricultural Library, Google Scholar). Secondly, there is a possibility that using additional keywords and synonyms could have resulted in the identification of more relevant studies for inclusion in this review. Nevertheless, in either scenario, the likelihood of altering the overall conclusion of this study is minimal.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Rambod Abiri: Formal analysis, Resources, Visualization, Writing – original draft. **Nastaran Rizan:** Investigation, Methodology, Writing – review & editing, Supervision. **Siva K. Balasundram:** Supervision, Validation, Writing – review & editing. **Arash Bayat Shahbazi:** Formal analysis, Investigation, Writing – review & editing. **Hazandy Abdul-Hamid:** Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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