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REVIEW ARTICLE

Digital technologies for precision agriculture: Current approaches, advances and future perspectives

Ali Sabir[1*] & Zehra Ozkececi[2]

[1]Horticulture Department, Agriculture Faculty, Selcuk University, Konya 42075, Turkey
[2]Radio, Television and Cinema Department, Fine Arts and Architecture Faculty, Necmettin Erbakan University, Konya 42075, Turkey

*Correspondence email - asabir@selcuk.edu.tr

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Abstract

The frequent occurrence of climatic extremes has been exerting significant pressure on the agricultural sector worldwide. This pressure forced the agriculturists to implement intensified agricultural practices such as digital technologies to cope with ever-increasing environmental stress factors. Given these challenges, this review aims to scrutinize current developments in digital technologies and the constraints hindering the adoption of digital agriculture. Digital technologies, such as Global Positioning System (GPS), Internet of Things (IoT), spectral sensors, unmanned aerial vehicles (UAVs), robotics, thermal infrared cameras (TIR), Artificial Intelligence (AI), virtual reality, Big Data, Metaverse, cloud computing, blockchain and digital mapping have been offering new pathways for companies to achieve economic, social and environmental purposes. Combined use of multiple technologies would be more beneficial for precision agriculture and economic efficiency. Advanced digital technologies are extensively adopted in many regions of the world, although there are significant differences among the countries in terms of the digital transformation. A bibliometric evaluation revealed that factors such as cost, ease of use of technical devices, technological infrastructure, farmers' willingness, technology reliability and concerns about data security and privacy are key challenges in the adoption of digital agriculture. Therefore, policymakers should focus on particular challenges to promote the widespread adoption of digital technologies for sustainable agriculture. Sustainable agricultural production can be achieved through improved, precise use of affordable digital technologies and effective, site- and crop-specific data-driven decision support. Present developments demonstrate that AI and new autonomous approaches will become increasingly important for the detection and management of spatial variability. This review article focused on the bibliometric assessment of current approaches, feasibility, benefits, restrictions and future perspectives of digital technologies in increasing agricultural production. Overall investigations revealed that digitalization enables farmers to optimize resource use, enhance crop yields and address pressing challenges such as climate change and food security by integrating advanced technologies such as remote sensors, drones, robotics and data-driven decision-making tools. Data presented in this article is anticipated to guide agriculturists to speed up and employ the digital technology applications on the modern farming technologies.

Keywords: artificial intelligence; climate change; food security; precision agriculture; sensors and robotics; smart farming

Introduction

Intensifying climate crisis and escalating resource depletion become a critical issue on the global agenda. Exacerbated by climate extremes and a volatile macroeconomic environment, the agriculture sector is facing multiple challenges varying from soil degradation and increasing water scarcity to labour shortages and soaring input costs. The deteriorations of environmental and economic pillars of sustainability threatens the natural resources and global economies, indicating the urgency of sustainable development actions. On the other hand, the global population is projected to reach 9.7 billion by 2050 (1). In order to meet the food requirements of this population, agricultural production should be increased by 70 % (2). Traditional agricultural practices, once aimed at boosting yields, have proven neither economically viable nor environmentally sustainable. The rapid expansion of industrial production methods has led to severe caused environmental challenges, such as resource shortage and pollution, which in turn increase plant stress (3). Moreover, addressing these stress factors using conventional methods increase production costs and reduces both the quality and quantity of agricultural output (4). In response to these challenges, the early detection of plant stress using advanced technologies, particularly the Internet of Things (IoT), has become crucial for timely intervention (5). Modern computing methods can simulate virtual digital twins, predict the techno-economic aspects of complex technologies and optimize Big Data-driven industrial production and business administration, autonomous machine perception and multiple manufacturing process management (6). Breakthrough innovations in digital era show that enterprise process automation could be improved by digital twin technologies, multi-agent reinforcement learning, Big Data fusion simulation algorithms and multi granularity cognitive computing systems (7). Upon these developments, innovative concepts such as, digital agriculture, digital farming, Agriculture

4.0, smart farming or smart agriculture, all of which comprise the use of information and communication technologies in collecting, generating, transmitting, storing and analysing data to enhance decision-making at all stages of the agricultural production and postharvest chain, poised to have a transformative impact on the world (8). Digital agriculture employs tools like IoT devices, remote sensing, artificial intelligence (AI), Big Data analytics, cloud computing and sensors to provide farmers with actionable insights, enabling optimized production processes and resource use (9). The advent of digital tools empowered the companies to carry our breakthrough innovations. By integrating digital technologies with business and administration processes, firms can effectively expand knowledge channels, enhance the efficiency of technological information flow and ultimately improve the likelihood of achieving breakthrough innovations. Hence, exploring how enterprises leverage digital technologies to enhance breakthrough innovations is of great practical importance in digital era (10).

Plant response to environmental stress factors can be expressed with numerical information in various ways (11). These responses can be recorded, transmitted and analysed using digital technologies such as electronic sensors and mechanical tools. In recent years the rapid technological development in various sensors and the IoT provided to collect significant data on crops. Digital technology tools have been used for many purposes such as height control, leaf area index (LAI), biomass detection, pest and disease management, including other essential physiological features. Pathogens alone contribute to global yield losses of approximately 20-40 %, but sensor-based technologies offer promising solutions for early detection and control (12). Multispectral sensors receive radiation in the visible and non-visible spectrum, which can be used to obtain a crop's phenotype (13). The development of digital technology offers the possibility to a large number of devices to incorporate and work together exchanging information for example detecting soil and water conditions for efficient use of limited water sources in irrigation management of farms and vineyards (14). Accurate analyses of the data achieved by digital technology can support agricultural producers and scholars make better decisions to increase crop yields, improve energy use efficiency, manage resources, recycle waste and reduce costs (15). In spatial planning processes, digital twin-based Internet of Robotic Things, robotic swarm and virtual and augmented reality simulation technologies can undertake pivotal roles (16). Furthermore, crop loss reduction during the production and marketing processes could be achieved by effective use of digitalized programs such as industrial Metaverse technologies, multi-modal machine learning algorithms, enterprise digital twin system modelling (17). Therefore, it has been hypothesized that digital technologies offer the potential to boast productivity, sustainability and income when accurately employed. This review study followed a systematic approach to collect, scrutinize and synthesize relevant literature knowledge on the digitalization in sustainable agriculture.

Digital tools and technologies in sustainable agriculture

Unpredictable ecological changes, worsened by global climate change, have increased the urgency to understand how plants physiologically respond to environmental stress for achieving sustainable food production. Accurate understanding the physiological and molecular mechanisms of interactions between plants and its surrounding environment can provide more economical and sustainable crop production (18). However, differential and complex responses of different plants to stressors prevent researchers from reaching definitive conclusions under multiple environmental factors (19). Recent developments on plant sensor devices provided significant benefits on accurate, non-destructive and prompt definition of the plant response to environmental variables and stressors. Digital technologies in agriculture means primarily focus on expanding data collected from the production area, the contribution of AI, connectivity protocols and automation in farm management (20). Recent advances in AI allow agriculturists to estimate the impacts of new concepts and innovations in the conditions of specific economies (21). The continuous innovations, driven by AI integration, will contribute to a deeper understanding of broader social issues and corporate performance while providing a more comprehensive view of how different sectors adjust to evolving sustainability requirements (22). Studies verify that AI innovations significantly boost economic output, particularly in countries with robust AI strategies and advanced infrastructure (23).

Digital technologies streamline numerous agricultural operations by collecting real-time data through sensors, satellites, smartphones and other interconnected devices (24). Digital technologies simplify the farm management operations such as planning, financing, monitoring and reporting efficiency analyses (25) as well as combining mobile devices like smartphones and drones to get technical assistance and monitoring the farms like using satellites and Global Positioning System (GPS) (26). By this technology, Farm Management Information Systems (FMIS) and Farm Management Software (FMS) can be established at more advanced level to control the farm from a centralized platform (27). The use of these technologies can help in fostering resilience and sustainability in agriculture, oenology and other agricultural sectors. By the help of proper digitalization, producers can manage the agricultural operations more efficiently from a distance through connecting the remote or proximate sensors and actuators equipped with IoT. This can provide dynamic management of production stages and reduce the need for human labour, which in turn, improves productivity and revenue. The collected information can be combined in cloud-based farm management tools like SmartFarm and Agrivi strive for proper decision-making processes (24).

Various digital technologies are being employed in agriculture and oenology, including spectral sensors, soil tensiometers, thermal infrared (TIR) cameras, unmanned aerial vehicles (UAVs), leaf porometers, LiDAR systems, drones, robotics and localized sensing equipment such as data loggers (28). The combined use of sensor data (such as humidity and temperature for both air and soil, soil conductivity, soil pH) and satellite images to monitor in real time environmental factors would be more effective for precision agriculture, plant protection, resource protection and food processing like oenology (29). For instance, the remote sensing to assess phenolic and colour attributes in Cabernet Sauvignon grapes, enabling optimized harvest timing (30). Moving forward, precision agriculture and smart farming practices have evolved toward digitalization with the emergence of UAVs like drones, IoT devices, smartphones and long-range wireless sensors. Drones have become increasingly widespread in agriculture due to their ability to create high-resolution images, reveal crop stress and display crop growth (31). Drone-assisted real time precision monitoring to decipher plant physiological response to environmental factors for sustainable farm managements and efficient resource protection is illustrated in Fig. 1.

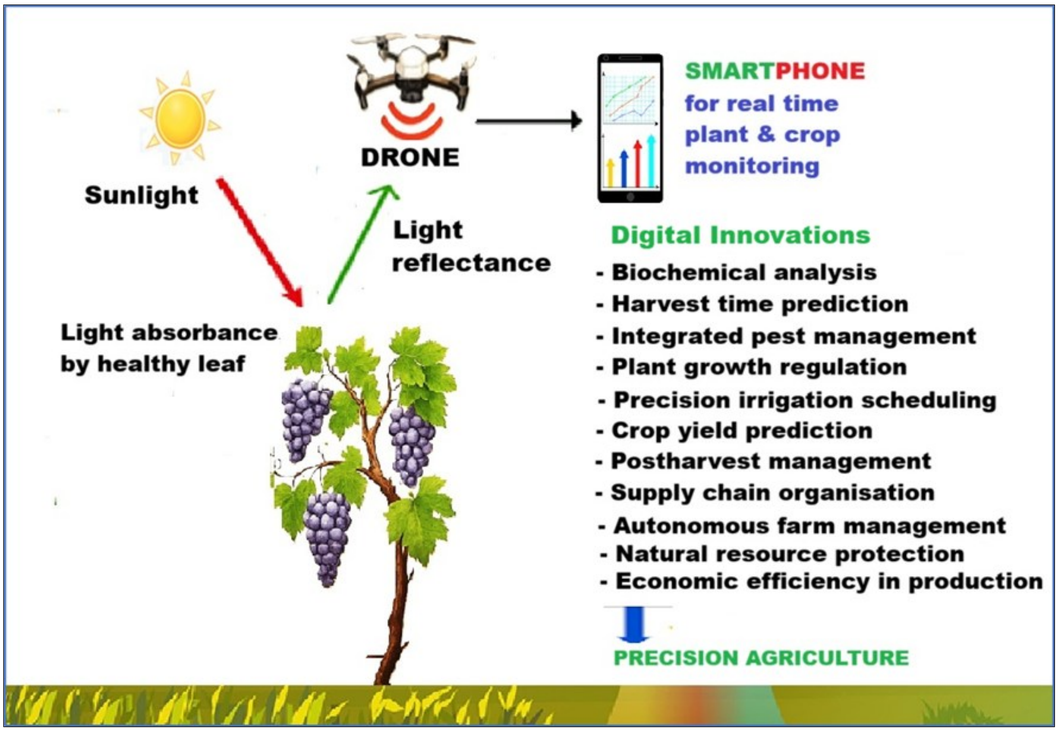

Fig. 1. Drone-based real time precision monitoring the plant response to environmental factors for sustainable farm and resource managements.

The data received from sensors and imagery, enables agriculturists and winegrowers for the application of AI in mechanization (29). AI-powered software provides valuable insights into measurable attributes such as berry size, color and yield, as well as overall crop and environmental conditions in vineyards and farms (30). However, AI technologies are still in the experimental improvement phase and are pending implementation on a commercial or large operational scale although new potential developments (32).

The IoT describes the network of physical objects of plans that incorporate sensors, software and other technologies to link and exchange data with other devices and systems over the internet (33). These tools vary from common household objects to sophisticated industrial devices. In vineyard managements and wineries, digital devices can be implemented directly in the soil, placed into vine canopy or embedded into trunk depending on the data to measure, to improve productivity and climate prediction under the effects of environmental stressors (34).

In addition to main digital technologies, many others have also been increasingly used in precision agriculture. For example, the practical use of 3D printed objects in agriculture engineering projects can open up new avenues for improving the enormous potential of machine learning (35). On the other hand, the implementation of the Big Data analytics could efficiently mitigate agricultural carbon emissions (36). Recent improvement of technology in the analytics of Big Data sparked a transformative revolution in precision agriculture, enabling producers to make informed decisions, optimize resources and empower sustainable productivity (6). Big Data analysis could also help agriculturists effectively control processes from production to marketing, optimize resource use, improve industrial production efficiency, sustain economic analyses and autonomise mechanisation (7). Producers can showcase and sell their produces online by creation of virtual stands in the Metaverse (37). Common digital technologies and tools used in agriculture with their application area have been summarized in Table 1.

Digital transformation for advancing agricultural sustainability

Digital transformation has become a cornerstone of modern agriculture strategy, offering new pathways for companies to achieve economic, social and environmental purposes (50). Many governments in developed or developing countries have initiated their journey to digital transformation over the past two decades. The recent studies reveals that advanced digital technologies are extensively adopted across the Central Europe to improving business agility, labor productivity and maintain business continuity in a crisis (51). Global crises, like the COVID-19, significantly accelerated environmental innovation across EU countries, with digital technologies undertaking a pivotal role in enabling organizations to respond efficiently to the challenges (52). The crises highlighted the importance of adaptability, collaboration and technology in driving social innovation, setting the stage for a more resilient and digitally enabled future. In this region, UK efficiently improved the digital infrastructure, with Cloud Computing being the most widely used technology (with up to 80 % adoption in all sectors and regions), although AI adoption seems moderate. More specialised technologies such as Robotics and 3D Printing are adopted less frequently, mainly in the manufacturing and extractive sectors. Companies are increasingly employing multiple technologies cooperated with Cloud Computing most frequently paired with AI and Big Data, underscoring a trend towards data-driven business processes (53). As Europe seeks to evolve its agriculture in line with the European Green Deal, understanding stakeholder perspectives is crucial to address barriers to adoption and foster collaborative strategies (54).

Recent improvements in information technology and governmental support promoted the remarkable development of digital agriculture in several Asian countries. In China, digital technologies are highly transmissible and adaptable in agriculture, enabling innovations in cultivation practices and improvements in

Table 1. Key digital tools and technologies and their functions/applications in agriculture

Digital technology	Applications and references
Global Positioning System (GPS)	Combining mobile devices like smartphones and drones to get technical assistance and monitoring the farms (24)
Farm Management Information Systems (FMIS) and Farm Management Software (FMS)	Controlling the farm from a centralized platform (27). Current implementations of FMIS and FMS in farm management is limited due to digital illiteracy and poor he information and communications technology infrastructures in rural areas (38)
Internet of Things (IoT)	The network of objects of plans that incorporate sensors, software and other technologies to connect and exchange information with other devices over the internet (39)
Agriculture 4.0	Information and communications in collecting, generating, transmitting, storing and analysing data from production to postharvest chain (8)
Spectral sensors, soil tensiometers, leaf porometers, data loggers	Monitoring real time environmental factors and plant response (40)
Drones and unmanned aerial vehicles (UAVs)	Technical assistance and real time displaying the farms, plants, diseases or agricultural structures to promote farming practices by reducing resource wastage and minimizing environmental impact (41)
Cameras	Yield estimation, plant canopy management (42)
LiDAR systems, robotics	Cultural practices during production, plant protection, harvesting, food processing like oenology, capture of high-resolution images (28)
Thermal infrared (TIR) cameras	Environmental imaging, instantaneous and seasonal variability of plant health status (6)
Artificial intelligence (AI)	Measuring plant/crop attributes, soil condition, crop processing procedures, automation in farm management, economic analyses, automation in farm administration, resource management (32)
Meteorological systems	Weather forecasting, irrigation scheduling, resource preservation, historical data settings (43)
Big Data	Enabling optimized production processes and resource use, industrial production efficiency, economic analyses, autonomous machine perception, multiple manufacturing process management, breakthrough innovations multi-agent reinforcement learning, Big Data fusion simulation algorithms and multi granularity cognitive computing systems (7)
3D immersive virtual reality (virtual reality, augmented reality) and digital twin Metaverse technologies	Internet-based robotic manufacturing and process management, knowledge accumulation in synthetic simulated environments (7). Obtaining simulated multi-level crop data in real time. Quick access to structured data to enable timely action, for optimizing growing conditions (44)
6G sensing and holographic simulation technologies	Error elimination in production processes, machine vision-based defect prediction, detection, diagnosis and management (17)
3D object rendering and machine intelligence algorithms	Production and workflow management operations to enable industrial process automation, sustainable business growth and economic value co-creation (35)
Metaverse technologies	Crop loss reduction during the production and marketing, autonomous robotics, business intelligence algorithms, economic value co-creation, supply chain and operations management (45)
Cloud computing	Data-driven business processes, increasing productivity, cost reduction, improved efficiency, reducing infrastructure needs and software costs (46)
Blockchain	Tracking the information on plants, such as growth, seed quality and improving supply chain transparency and eliminate concerns associated with illegal processes (47)
Digital mapping and photogrammetry	Detailed and up-to-date understanding of soil distribution, crucial for agricultural planning and natural resource management (48), three-dimensional (3D) reconstructions of landscapes to capture high throughput phenotyping, monitoring growth patterns, nutrient deficiencies, diseases and pest attacks (49)

efficiency to be quickly adopted across different regions. The level of digitalization in agriculture in China steadily improved during the last decade. The agricultural digitalization levels in the three main regions (eastern, central and western) showed a decreasing pattern from east to west (55). In general, the bibliometrics studies revealed that digitalisation in Asian agriculture policies is still inadequate in areas such as risk control and prevention, standardization and cooperation. Therefore, policy makers should focus on improving standardization and data security to enhance the development and popularization of digital agriculture. Nonetheless, the available literature data on smart agriculture in Asia have increased significantly over the recent years, indicating a promising development soon for digital agriculture in Asia (56). A bibliometric study analysis of the state of digitalization in Southeast Asia showed that remarkable strides in digitalization, marked by improved scholarly attention and publication output, especially from countries such as Indonesia, Malaysia, Singapore and Thailand (57). The mentioned study further highlights a stark digital divide within the region, with countries like Laos, Cambodia and Myanmar significant lagging in digital literacy and infrastructure.

In a comprehensive study, a panel data collected from 25 African countries over the period 2005-2021 revealed that digital transformation has not significantly enhanced total factor productivity across the Africa. The study further demonstrated that the absence of a significant moderating effect of human capital indicates an ongoing skill deficit. The study underlined the importance of a holistic policy approach that integrates digital infrastructure development with improvements in education, healthcare systems and institutions to fully capitalize on the productivity gains from digital transformation in Africa. Widespread lack of technical skills remains a major constraint on the productivity of digital technologies. Besides, inadequate structural conditions hinder the effective use of digital technology. It was recommended that African governments perform a comprehensive policy strategy combining developments in digital infrastructure, education reforms and health systems for converting digital potential into sustainable and inclusive economic growth (58).

In Antarctica, the emergence of super powered social media platforms, specialised online sales and the power of influencers has greatly played a key role in increase in tourism. Therefore, digital infrastructure has been documented as resulting in profound shifts in how tourism destinations are mediated, shared, portrayed and recollected (59). On the other hand, recent improvements in both fishing technology and new product markets resulted in a steady increase in Antarctic fishery, causing excessive krill catches and threatening the marine ecosystem. Recent studies underlined that development and implementation of software programs and monitoring data programs for automatic processing and data transfer will be beneficial to reduce ecosystem risks with a sustain management strategy (60).

States in Australia have generally developed the digital transformation in agriculture, while several of them, including Victoria still consider digitalisation as less priority (61). On the other hand, labour shortages cause limitation in digitalisation in general (62).

In North America, particularly in the United States of America, agriculture has become increasingly data driven. Field-level data measurements in smart agriculture technologies to capture temperature, precipitation, soil quality, input applications, yields and other indicators of crop and livestock health have been effectively implemented in many parts of the country. Reliance on remote sensing practices and geospatial tools to operate agricultural lands at large scales has rapidly expanded. For example, smart tractors equipped with GPS are extensively employed for efficient use of cultivated soil (63).

Bibliometric studies in Latin America show that the central barriers include insufficient digital literacy, economic constraints, labor deficiency, inadequate service provider accessibility and infrastructure constraints. The studies highlight the requirements for strategic policy interventions to overcome these barriers, improving digital literacy, infrastructure and connectivity (8).

Overall literature on the agricultural digitalization over the world indicated that the lack of reliable infrastructure, mistrust in technology providers and the burden of legal compliance were main recurring constraints that obstruct the adoption of digital technologies. To cope with these challenges, rapid investments in infrastructure, adequate financial support and efficient communication between stakeholders are essential. In addition, improving data security, fostering inclusivity and constructing collaborative platforms for resource-sharing can help ensure that the usefulness of digitalization is accessible to all agriculturists. A brief definition on digitalisation levels of the world on the basis of continental comparison was summarized in Table 2.

Objectives of digital technologies in agriculture

One of the main objectives for using digital technologies in agriculture is to forecast and reduce climatic risks during production and harvesting (9). Most of the digital sensors and satellites used in the fields focus on plant physiology, crop quality control (40) or meteorological aspects such as monitoring soil and water conditions for efficient water use, irrigation management and weather forecasting (68). Digital sensor technology also allows monitoring essential parameters such as ambient temperature, wind speed, relative humidity, leaf wetness, soil moisture and rainfall. The potential of using remote sensing method as a cost-effective strategy for monitoring soil water content and predicting areas at risk of salinization in vineyards, considering the predicted increase in droughts (69).

Accurate crop yield estimation can be achieved using remote sensing technologies, such as UAVs equipped with RGB cameras. These technologies enable growers to better manage fields and vineyards and gain insights into expected harvest outcomes. In a vineyard in Slovakia, UAVs captured high-resolution orthophotos of individual grapevine rows, which were used to generate three-dimensional (3D) model of the area. This allowed researchers to measure various vine canopy characteristics, including thickness, side-section dimensions, volume and surface area. The study concluded that the combination of side-section area and canopy thickness yielded the most accurate grape yield predictions (70). The use of multiple morphological parameters is recommended for more reliable estimations. Furthermore, imaging should be conducted close to harvest, following vine canopy management, for optimal accuracy (71). When applied correctly, imaging technologies also assist in pre-harvest planning and can enhance postharvest storage outcomes for perishable crops.

Table 2. Comparative adoption levels to digital technologies across the continents

Continent	Digitalisation level
European	Most of the European member states are increasingly using remote sensing technologies such as satellite images, geotagged pictures and combine this with advanced algorithms and machine learning, although differences have existed between the members in terms of digitalisation level (64). Digital technologies are extensively adopted across the Central Europe to enhance business agility and labor productivity. Cloud Computing is proven as the most widely used digital technology (46)
Asia	Recent bibliometrics studies on smart agriculture indicated that digitalisation in Asia is still inadequate in risk prevention, standardization and cooperation areas, while number of publications on agricultural digitalisation indicate a promising development in the near future (56)
Africa	Africa has not yet yielded the substantial improvements in economic productivity, primarily due to lack of technical skills and insufficient digital infrastructure development. Yet adoption rates vary greatly among African countries, reflecting deeper structural differences in digital capacity. Internet usage, for example, averages at 15.33 % with significant disparities between countries. Insufficient internet access, lack of policies and regulations is potentially impeding the realization of full digitalization potential (65)
Antarctica	Digitalisation has been significantly rising in Antarctic tourism management over the past decade to manage tourist destinations, operate wildlife safaris, trekking or cruise tours and capturing objects such as AI-transformed 3D digital map of penguin colonies (59)
Australia	Many states in Australia have already extensively developed the digital transformation, while several of them, including Victoria still consider digitalisation as less priority (61). Labour shortages cause limitation in digitalisation in general (62)
North America	Reliance on geospatial tools and remote sensing operations to operate agricultural practices at large scales has expanded. A survey study on Canadian farmers revealed that digital agricultural technologies are put into practices for many farmers. The most common affective technologies are GPS, computers, auto-steer and IoT (33). Many farmers found digital technologies as expensive, confusing and difficult to implement (66)
South America	In Latin America, digitalisation at agricultural sector has showed slight improvements in spite of a wide range barriers some of which are insufficient digital literacy, economic constraints, labor deficiency, inadequate service provider accessibility and infrastructure constraints. Interview data collected from 220 farmers in Argentina, 477 in Brazil and 214 in Venezuela showed that the countries greatly differ in terms of agricultural digitalisation. Latin American data workers do not experience the same conditions as their counterparts in richer countries. Argentina, Brazil and Venezuela are three major Latin American countries using AI in several agricultural sectors (67)

The integrated use of digital tools such as infrared sensors, drones and multispectral imaging has significantly improved pest and disease control in agricultural systems (72). Several wineries have already combined sensor data (humidity and temperature of both air and soil, soil conductivity, solar radiation, grape and vine quality) and satellite imagery to monitor key environmental factors for the harvest in the correct time. Digital technology allows mitigate the adverse effects that environmental conditions have on plants. Sensors as digital technologies can help to control fruit or grape quality parameters for a correct winemaking process and to guarantee a quality product (73). Because of changing climate conditions, each year the product, even though it is produced in the same processes, has certain differences. This fact can create difficulties in universalisation of digital technologies.

Sensorial devices enable concretely monitoring and controlling the harvesting and processing such as winemaking in real time. By this technology, certain modifications can also be performed to achieve a special product that is as close as possible to what is desired. Machine learning based models help producers to make accurate and techno-economic decisions during production processed (74). Machine vision systems, as sensorial devices, have been used in the bottling, capping and labelling processes to match the desired quality standards. In wine cellars, these devices can monitor the key factors of temperature, light and humidity for the proper ageing of wine, because even the slightest fluctuations in cellar atmosphere may alter the oxidation of the wine and therefore significantly affect the quality (75). The effective use of a bienzymatic biosensor for real-time monitoring of glucose and ethanol during fermentation, providing results that were consistent with conventional methods and highlighting its potential in enhancing the winemaking process (76).

Data collected through digital tools at large scale can help to assess the impact of adverse weather events and pests or disease outbreaks on crops (77). By integrating remote sensing with IoT and Big Data analytics, farmers can manage their fields or vineyards more efficiently, control pathogen infection, reduce plant stress and minimize yield losses from environmental stressors, including those caused by climate change (78). Big Data is the complements of techniques that necessitate integration forms to distinguish unrecognized values from large scale, various and complex data sets (79). Big Data enables farmers to view all production parameters of real-time operations and enhance decision-making processes (80). The use of Big Data enables early anomaly detection to analyse abundant amounts of data to foresee potential risks and optimize management practices, ensuring that the food reaching our tables is safe and of high quality (81).

Digital technologies play a crucial role in enhancing traceability within the food supply chain. Providing accurate and verifiable information on product labels can improve consumer trust and increase the competitiveness of agricultural companies. Digital technologies play a crucial role in enhancing traceability within the food supply chain. Providing accurate and verifiable information on product labels can improve consumer trust and increase the competitiveness of agricultural companies. The entire history of a produce, from its point of origin to the end of the sale, can be recorded and verified by employing blockchain technology. The availability of these data can aid in identifying illegal applications (24).

Practical and site-adapted applications of digital technologies are transforming urban spaces into productive agricultural zones. Vertical farming, emerged as a critical solution for addressing food sustainability challenges in urban areas, is an innovative food production strategy to agriculture, offering numerous advantages such as traceability in food production, over common rural agriculture, as evidenced by its alignment with the three pillars of sustainability: economic, social and environmental. The integration of soilless culture techniques such as hydroponics, aquaponics, aeroponics and solid volume contains culture has revolutionized the agricultural landscape, challenging the needs for soil-based farming for a wide range of crops. This innovation is further enhanced by the integration of modern greenhouse technologies-using glass or plastic structures-and supporting systems including multi-tier mechanized setups, renewable energy sources (solar, wind), LED lighting, recycling systems, drones, storage batteries, software applications and IoT networks. To fully harness these technologies, interdisciplinary collaboration is essential to develop advanced vertical farming models and ensure sustainable food production for future urban populations (81).

Digital technologies can play a pivotal role in attracting young farmers and encouraging new participants in agriculture. Innovations in digitalization empower producers with timely access to market data, financial tools and customized solutions, thereby promoting more inclusive and resilient livelihoods. To ensure wider adoption, policy makers should implement support programs that connect farmers through teleconferencing, video platforms and digital advisory services. Such initiatives can enhance awareness and motivation for adopting cost-effective digital tools in agricultural production (54).

Restrictions and difficulties to overcome

Despite the opportunities created by advances in digital technologies, several limitations remain. One major gap is the lack of fully automated systems that can manage the entire agricultural cycle-from vineyard establishment to harvesting and post-processing stages such as winemaking. Currently, smart farms and vineyards are equipped with advanced measurement tools, primarily wireless sensors integrated with satellite or drone imagery and powered by AI. The uncontrolled fast development in equipment and processes for data collection, transport, storage and computation might aggravate the adverse environmental effect.

The adoption and accurate use of digital technologies in agriculture vary across different countries due to differences in environments, policies and cultural traditions. For example, France, Germany, the Netherland, the United States, Brazil and Canada are among the countries with high level of adopting the digitalization in agriculture due to funding from the European Union (41). In China, the government has also been supporting the use of digital technologies to increase agricultural produces and reduce environmental damages (82). Conversely, agricultural digitalization remains limited in many parts of Africa, primarily due to restricted access to technology and infrastructure-despite efforts like the African Agricultural Technology Foundation's Digital Agriculture Services Project (83).

The high cost of establishing and maintaining the equipment of digital technologies can be a barrier for many farmers (84). The costs of both sensor devices and networks to collect high spatiotemporal data should be as logical as pollable to widen their employments in sustainable agriculture. The collected data can be fused in a data platform, providing standardized exchange interfaces for stakeholders to improve and reduce costs (54). On the other hand, small-scale farmers should be supported for proper use of digital technologies to prevent them from disappearing, as they are important for biodiversity, climate, food security and resilience, food sovereignty and livelihoods in rural areas. Policymakers and development agencies should prioritize inclusive digital strategies that empower smallholders to thrive in a rapidly evolving agricultural landscape.

Usefulness of technology and growers' willingness to innovate are also factors determining the extension of the digital technologies in agriculture. Resistance of the older generation of farmers who have more difficulty to adapt to the use of new digital technologies, new sources of information can be an important barrier to overcome (85). Therefore, devices and programs used in digital technology should be easy to understand and operate.

The vast amounts of rich data generated by sensing equipment-including multi-sensor inputs, meteorological records, land observation data, map services and historical datasets-are often highly complex and vary significantly in format (43). Therefore, there is a need to develop a concept that enables combining and using variable data sources to demonstrate the utility of upscaled data for more economically resilient and sustainable agriculture.

Lack of standardization in data collection and analysis hampers the ability to compare outputs across different sources and technologies. Complex or unclear data further complicates governance and discourages farmers from adopting digital agricultural tools (86). Data governance is known as a set of processes, standards and guidelines that express how the data assets are managed (87). Data governance refers to establishing rules for data collection, processing, recording, usage, sharing and security to ensure that data is accurate, consistent and trustworthy (85).

Data privacy and security remain critical concerns in digital agriculture, especially regarding sensitive information such as crop yields, land use patterns and farm management practices. Many producers are reluctant to share such data due to its business-sensitive nature. In this context, edge computing offers a viable solution by enabling producers to process data locally-on-site or on-device-without the need to transmit sensitive information to external servers. This approach allows for real-time analytics while preserving data ownership and confidentiality (88).

Adoption to digital farming is also affected by social factors, education and training. Trust, education and awareness are important issues that affect farmers' decision-making processes in adoption. Recent studies demonstrated that farmers frequently put off implementing SFTs because they are resistant to change and worry on data security. Adoption rates are also impacted by gender-related inequities, generational variances and peer pressure. The effect of these elements on the adoption of smart farming technology should be modulated by governmental regulations and institutional supports, underscoring the necessity of focused interventions. Collaborative research, interdisciplinary approaches and policy frameworks would also beneficial to increase adoption (89).

To overcome the difficulties in digitalisation, researchers emphasized the significance of using integrated digital tools for monitoring the performance of cultivation practices and farm management rather than standalone tools that are currently widely available. Integrated tools that incorporate different applications and approaches can simplify data collection and encourage precise record-keeping, prevent or reduce human error and save time and cost. Combined use of various tools can also help producers to adjust their agricultural plans with accurate weather forecasts in regions susceptible to climate change effects (90). Common barriers in agricultural digitalisation and proposed solutions are listed in Table 3.

Future perspectives and Conclusions

The growing global population and shifting lifestyles have placed immense pressure on the agri-food sector to increase food production under increasingly severe environmental stressors intensified by climate change. To meet this demand, it is imperative that the agricultural industry rapidly adapts by developing innovative and sustainable strategies that reduce environmental impacts, preserve biodiversity and contribute to carbon sequestration. Studies indicated that interest in remote and proximal sensing technologies, variable rate technology machines and robotics will increase for precision agriculture technologies to challenge with ever-increasing environmental stress factors, including global climate change. The capture of high-resolution images and obtaining accurate digital data from the cultivation area or natural sources can provide higher precision for sustainable modernization in agriculture. The easy-

Table 3. Major challenges/barriers and proposed solutions for digital agriculture

Challenges/barriers	Proposed solutions
Insufficiency for fully automated systems to manage the entire processes	Precision modelling of production and handling stages in agricultural cycle from plant cultivation to marketing and properly combining the multiple data sources could improve the combined use of digital technologies
Difficulties in adoption digital technologies for different countries, environments, policies and cultural traditions	Providing governmental supports to producers for learning and implementing new technologies could provide easier adoptions for digitalization in agriculture
High cost of establishing and maintaining the digital technologies	Policymakers and development agencies should prioritize inclusive digital technologies that support smallholders to thrive in a rapidly evolving agricultural landscape
Lack of agriculturists' willingness	Devices and programs in digital technology should be easy to understand and operate. National and international projects on courses and demonstrations could help agriculturists to acquire the use of digital technologies
Complexity and variations in format	Combining different data sources in an easy program to improve the usefulness of upscaled data for more economically resilient agriculture could encourage the agriculturists to implement
Lack of standardization in data collection and analysis	Development of high throughput standardisation of data collection and evaluation programs would allow agriculturists to utilize digital technologies
Data privacy and security	Edge computing would offer a viable solution without the need to transmit sensitive information
Limitation in accessing the modern computing methods and new technologies	Governmental support to strengthen the accessibility of digital technologies would help producers and marketers for implementing and empowering breakthrough innovations in precision agriculture

to-handle proximate and remote sensor devices with high accuracy level will lead to record more detailed data on crops and cultivation area. Establishing clear methodologies combined with molecular interactions and plant biophysical or biochemical characteristics will provide new innovations to sustain food production. This innovation will not only enhance productivity but also provide cost-effective protection of environment and plant genetic resources. Further research is needed to fill gaps and guide policies for sustainable adoption of digital technologies in agriculture under the effects of climatic extremes. Scientific, public and political efforts should focus on integration of digital monitoring tools in improving data accuracy, collecting the Big Data, preventing the human mistake, decreasing the cost, streamlining certification processes and promoting eco-friendly practices, all of which are crucial for the evolving carbon market under the effects of ever-worsening climate change.

Authors' contributions

AS carried out the conceptualization of the study and applied the required methodology for the study and written the article and drafted the manuscript. ZO carried out the literature investigations and writing the draft format. All authors read and approved the final manuscript.

Compliance with ethical standards

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