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AGTECHS FOR SMART FARM MANAGEMENT: TECHNOLOGIES SUPPORTING MONITORING, CONTROL, AND DECISION-MAKING

AGTECHS PARA A GESTÃO INTELIGENTE DE PROPRIEDADES RURAIS: TECNOLOGIAS PARA MONITORAMENTO, CONTROLE E TOMADA DE DECISÃO

AGTECHS PARA LA GESTIÓN INTELIGENTE DE EXPLOTACIONES AGROPECUARIAS: TECNOLOGÍAS PARA EL MONITOREO, EL CONTROL Y LA TOMA DE DECISIONES

Maise dos Santos Macário[1]
Isis Regina Santos de Oliveira[2]

ABSTRACT: Digital transformation has substantially expanded the use of technologies capable of monitoring agricultural systems, automating operational activities, and supporting farm decision-making. In this context, this narrative review aimed to examine how major AgTechs contribute to monitoring, operational control, and smart farm management. The review discusses technologies including smart sensors, the Internet of Things (IoT), remote sensing, unmanned aerial vehicles, Farm Management Information Systems (FMIS), artificial intelligence, decision support systems, and Digital Twins, emphasizing their integration into agricultural management processes. The findings indicate that the primary value of AgTechs lies not only in generating large volumes of data but also in transforming dispersed information into actionable knowledge that supports more efficient, predictive, and integrated decision-making. The review also addresses current barriers related to implementation costs, digital connectivity, interoperability, technical training, data security, and the adaptation of technological solutions to diverse farming realities. Future progress in smart farm management will depend on the development of accessible, interoperable, and producer-centered technologies capable of improving productivity, resilience, and sustainability across agricultural production systems.

Keywords: Digital agriculture. Precision agriculture. Decision support systems.

RESUMO: A transformação digital da agricultura tem ampliado significativamente o uso de tecnologias capazes de monitorar sistemas produtivos, automatizar operações e apoiar a tomada de decisão nas propriedades rurais. Nesse contexto, esta revisão narrativa teve como objetivo analisar como as principais AgTechs contribuem para o monitoramento, o controle operacional e a gestão inteligente das propriedades agrícolas. Foram discutidas tecnologias como sensores inteligentes, Internet das Coisas (IoT), sensoriamento remoto, veículos aéreos não tripulados, *Farm Management Information Systems* (FMIS), inteligência artificial, sistemas de apoio à decisão e *Digital Twins*, enfatizando sua integração ao processo gerencial. A revisão demonstra que o maior potencial das AgTechs não está apenas na geração de grandes volumes de dados, mas na capacidade de transformar informações dispersas em conhecimento útil para decisões mais eficientes, preditivas e integradas. Também foram discutidos desafios relacionados ao custo, conectividade, interoperabilidade, capacitação, segurança dos dados e adaptação das tecnologias às diferentes realidades produtivas. Conclui-se que o avanço da gestão inteligente dependerá do desenvolvimento de soluções acessíveis, interoperáveis e centradas nas necessidades dos produtores, promovendo uma agricultura mais eficiente, resiliente e sustentável.

Palavras-chave: Agricultura digital. Agricultura de precisão. Sistemas de apoio à decisão.

[1]Doutora em Ciências, Universidade Federal de Sergipe/UFS.
[2]Mestre em Ciências, Universidade Federal de Sergipe/UFS.

RESUMEN: La transformación digital de la agricultura ha incrementado considerablemente el uso de tecnologías capaces de monitorear los sistemas productivos, automatizar operaciones y apoyar la toma de decisiones en las explotaciones agrícolas. En este contexto, esta revisión narrativa tuvo como objetivo analizar cómo las principales AgTech contribuyen al monitoreo, al control operativo y a la gestión inteligente de las explotaciones agropecuarias. Se analizaron tecnologías como sensores inteligentes, Internet de las Cosas (IoT), teledetección, vehículos aéreos no tripulados, *Farm Management Information Systems* (FMIS), inteligencia artificial, sistemas de apoyo a la decisión y *Digital Twins*, destacando su integración en los procesos de gestión agrícola. Los resultados muestran que el principal valor de las AgTech no reside únicamente en la generación de grandes volúmenes de datos, sino en su capacidad para transformar información dispersa en conocimiento útil que facilite decisiones más eficientes, predictivas e integradas. También se discutieron desafíos relacionados con los costos de implementación, la conectividad, la interoperabilidad, la capacitación, la seguridad de los datos y la adaptación de las tecnologías a diferentes realidades productivas. Se concluye que el futuro de la gestión agrícola inteligente dependerá del desarrollo de soluciones accesibles, interoperables y centradas en las necesidades de los productores.

Palabras clave: Agricultura digital. Agricultura de precisión. Sistemas de apoyo a la decisión.

1. INTRODUCTION

Agricultural production has undergone a profound transformation over recent decades. Increasing pressure to improve productivity, optimize resource use, reduce environmental impacts, and enhance economic performance has made farm management progressively more complex. Producers are now required to monitor large volumes of technical, productive, environmental, and financial information while making rapid and accurate decisions under increasingly dynamic production conditions (FOUNTAS S, et al., 2015; WOLFERT S, et al., 2017).

Digital technologies have significantly changed the way agricultural information is collected, processed, and used. The expansion of sensors, the Internet of Things (IoT), cloud computing, artificial intelligence (AI), remote sensing, unmanned aerial vehicles (UAVs), and Farm Management Information Systems (FMIS) has enabled continuous monitoring of crops, livestock, machinery, environmental conditions, and farm operations. These technologies, commonly referred to as Agricultural Technologies (AgTechs), have shifted farm management from periodic record-keeping toward integrated, data-driven decision-making (DA SILVEIRA F, et al., 2021; JAVAID M, et al., 2022).

Although many AgTech solutions were initially developed for either crop production or livestock farming, current digital platforms increasingly integrate information from both sectors. Crop performance, animal production, machinery operation, environmental conditions, input use, production costs, and economic indicators can now be analyzed simultaneously, providing a broader understanding of farm performance and supporting more efficient management strategies (MORRONE S, et al., 2022; MENEZES GL, et al., 2025).

Scientific publications addressing AgTechs have expanded considerably during the last decade. However, most studies focus on individual technologies, specific production systems, or isolated applications, making it difficult to obtain an integrated understanding of how these tools contribute to farm management. Reviews frequently emphasize sensors, artificial intelligence, remote sensing, or precision agriculture separately, while fewer studies discuss how these technologies interact to support monitoring, operational control, and management decisions across agricultural production systems.

This review aims to synthesize the main AgTechs currently applied to smart farm management, highlighting their contributions to monitoring, operational control, data integration, and decision-making in agricultural production systems. The review also discusses the role of digital platforms in integrating crop and livestock information, the main technological challenges limiting large-scale adoption, and future perspectives for data-driven farm management.

2. METHODS

This study was conducted as a narrative literature review, aiming to synthesize and critically discuss the current scientific evidence on digital technologies supporting smart farm management, with emphasis on monitoring, operational control, and decision-making in agricultural production systems.

The literature search was conducted between May and June 2026 using the electronic databases Scopus, Web of Science, ScienceDirect, PubMed, SpringerLink, Wiley Online Library, and IEEE Xplore. Google Scholar was consulted when necessary to identify additional relevant publications not indexed in the primary databases. Official reports and technical publications from international organizations, including the Food and Agriculture Organization of the United Nations (FAO) and the World Bank, were also considered when relevant to provide institutional perspectives on digital transformation in agriculture.

The search strategy combined controlled vocabulary and free-text terms related to digital agriculture and smart farming. The principal descriptors included *digital agriculture*, *smart farming*, *Agriculture 4.0*, *precision agriculture*, *AgTech*, *Internet of Things*, *IoT*, *smart sensors*, *remote sensing*, *unmanned aerial vehicles*, *drones*, *farm management information systems*, *FMIS*, *artificial intelligence*, *machine learning*, *deep learning*, *decision support systems*, *precision livestock farming*, *digital twins*, *livestock monitoring*, automation, and agricultural management. These descriptors were combined using the Boolean operators AND and OR, according to the search syntax of each database.

Priority was given to studies published between 2015 and 2025, corresponding to the period in which digital technologies experienced the greatest expansion and consolidation within agricultural production systems. Earlier publications were included only when considered essential for presenting foundational concepts or technological developments that remain relevant to contemporary applications.

The inclusion criteria comprised peer-reviewed journal articles, review papers, and official technical reports addressing digital technologies applied to crop and livestock management, monitoring systems, operational control, artificial intelligence, precision agriculture, precision livestock farming, and decision support in agricultural production. Conference abstracts, editorials, duplicate records, studies unrelated to farm management, publications lacking sufficient methodological information, and documents unavailable in full text were excluded from the review.

Following the selection process, the retrieved publications were analyzed qualitatively through an interpretative approach. Rather than performing a quantitative synthesis, the studies were examined according to their scientific relevance, technological approaches, practical applications, reported benefits, limitations, and future perspectives. Subsequently, the selected literature was grouped according to its primary contribution to smart farm management. This thematic organization guided the structure of the review, encompassing digital transformation in agriculture, monitoring technologies, operational control systems, data-driven decision-making, integrated farm management, barriers to technology adoption, and future technological perspectives.

As a narrative review, the objective was not to exhaustively identify every publication available on the subject, but rather to provide a structured, up-to-date, and critical synthesis of scientific literature, highlighting the main technological advances and their implications for the management of contemporary agricultural production systems.

3. HOW HAS DIGITAL TRANSFORMATION CHANGED FARM MANAGEMENT?

Traditional farm management was largely based on handwritten records, field observations, producer experience, and periodic technical evaluations. Although these approaches remain valuable, they often limit the capacity to monitor production continuously, integrate information from different sectors of the farm, and respond rapidly to changes affecting productivity and resource use. As agricultural systems became more complex, management increasingly required tools capable of organizing large volumes of information and supporting evidence-based decisions (FOUNTAS S, et al., 2015; WOLFERT S, et al., 2017).

The emergence of Agriculture 4.0 accelerated the adoption of digital technologies throughout agricultural production. Similar to Industry 4.0, this approach incorporates sensors, wireless communication, cloud computing, artificial intelligence, robotics, remote sensing, and data analytics to automate data collection and improve management processes. Rather than replacing technical knowledge, these technologies provide continuous information that supports more accurate planning, monitoring, and operational control (DA SILVEIRA F, et al., 2021; JAVAID M, et al., 2022).

The concept of Smart Farming further expands this approach by integrating multiple technologies into connected production systems capable of collecting, processing, and interpreting information in real time. Within this ecosystem, AgTechs include digital tools ranging from environmental sensors and unmanned aerial vehicles to artificial intelligence models, automated machinery, cloud-based platforms, and decision-support systems. Their common objective is to transform raw data into information that improves farm management (BENOS L, et al., 2021; MILLER T, et al., 2025).

Modern farms generate information from many different sources, including crop production, livestock performance, machinery operation, weather conditions, soil properties, financial records, and input use. Digital technologies enable these datasets to be integrated into a single management environment, allowing producers to evaluate technical and economic indicators simultaneously instead of analyzing each production sector independently. This integrated perspective supports more consistent planning and facilitates the identification of factors affecting farm performance.

Among these technologies, Farm Management Information Systems have become one of the main components of digital agriculture. FMIS centralizes information generated throughout the production cycle, organizes technical and financial records, and provides dashboards, performance indicators, and historical analyses that support daily and strategic decisions. When integrated with sensors, cloud services, and analytical tools, these systems become the operational core of smart farm management, connecting monitoring technologies with decision-support processes that will be discussed in the following sections (FOUNTAS S, et al., 2015; WOLFERT S, et al., 2017).

4. HOW DO AGTECHS MONITOR AGRICULTURAL PRODUCTION SYSTEMS?

4.1 SMART SENSORS AND THE INTERNET OF THINGS

The growing availability of smart sensors has substantially expanded the capacity to monitor agricultural production systems continuously. Unlike conventional field inspections, sensor networks provide real-time measurements of environmental, productive, and operational variables, allowing producers to detect changes as they occur rather than after visible impacts on production. Continuous monitoring improves the understanding of production dynamics and creates the foundation for more precise management decisions (SOUSSI A, et al., 2024; MILLER T, et al., 2025).

Sensors are currently applied across virtually every component of agricultural production. In crop systems, they monitor soil moisture, temperature, electrical conductivity, nutrient availability, solar radiation, rainfall, and microclimatic conditions. Water management systems incorporate flow meters, pressure sensors, and irrigation controllers to optimize water application according to crop requirements. Machinery equipped with embedded sensors continuously records fuel consumption, operational efficiency, equipment performance, and field operations, generating valuable information for both technical and economic management (KHANNA A; KAUR S., 2019).

Livestock production has experienced a similar digital transformation. Wearable devices, electronic identification systems, accelerometers, rumination sensors, GPS collars, and environmental monitoring equipment allow continuous assessment of animal behavior, health status, reproductive activity, feed intake, body temperature, and movement patterns. These technologies reduce dependence on periodic visual observations while enabling earlier detection of physiological and behavioral changes that may indicate disease, stress, or reproductive events (MORRONE S, et al., 2022; MENEZES GL, et al., 2025).

The Internet of Things (IoT) has further increased the value of these monitoring systems by connecting multiple sensors through communication networks capable of transmitting information automatically to cloud-based platforms. Instead of operating as isolated devices, sensors become part of an integrated digital infrastructure in which information collected from crops, animals, machinery, weather stations, and farm facilities can be accessed simultaneously. This connectivity enables automatic alerts, remote supervision, real-time tracking, and continuous updating of production indicators, reducing the time between data collection and management decisions (VERDOUW CN, et al., 2016; MILLER T, et al., 2025).

Although sensor technologies continue to evolve rapidly, their effectiveness depends not only on measurement accuracy but also on proper installation, calibration, connectivity, and integration with management platforms capable of transforming large volumes of data into actionable information. Without adequate data processing, continuous monitoring alone provides limited value for decision-making.

4.2 REMOTE SENSING, UNMANNED AERIAL VEHICLES, AND IMAGING TECHNOLOGIES

Remote sensing technologies have become one of the most widely adopted approaches for monitoring agricultural production at different spatial scales. Satellite imagery, airborne sensors, and unmanned aerial vehicles (UAVs) enable frequent observation of crops, pastures, and natural resources without direct field intervention, providing valuable information for production planning and management (WANG J, et al., 2024).

In crop production, multispectral, hyperspectral, thermal, and RGB imaging systems support the evaluation of plant development throughout the production cycle. Vegetation indices derived from remote sensing data allow producers to identify variations in crop vigor, nutrient deficiencies, water stress, pest infestations, disease outbreaks, and planting failures before visual symptoms become evident. These technologies also contribute to estimating biomass production, predicting yields, and improving the spatial allocation of field operations (GUEBSI R, et al., 2024).

Applications for livestock production have expanded considerably in recent years. High-resolution aerial imagery combined with computer vision techniques allows monitoring of grazing distribution, pasture utilization, herd location, and animal movement across extensive production systems. Thermal cameras and automated image analysis have also been investigated for detecting behavioral alterations, heat stress, lameness, and other conditions associated with animal welfare and health, reducing the need for continuous manual observation (MENEZES GL, et al., 2025; GUO C, et al., 2025).

Beyond production monitoring, remote sensing supports environmental assessment by generating information on land use, vegetation cover, water availability, erosion risk, and landscape dynamics. Geographic Information Systems (GIS) integrate these spatial datasets with climatic, productive, and operational information, allowing producers to evaluate the spatial variability of agricultural systems and implement site-specific management practices. The combination of remote sensing, imaging technologies, and geospatial analysis has therefore become an essential component of modern farm monitoring, supplying the large volume of spatial information required by digital agricultural platforms.

4.3 FARM MANAGEMENT INFORMATION SYSTEMS

Farm Management Information Systems (FMIS) have evolved from simple record-keeping software into integrated platforms capable of organizing information generated throughout the production cycle. By consolidating technical, productive, environmental, and economic data in a single environment, these systems provide producers with a comprehensive view of farm performance and facilitate routine management activities (FOUNTAS S, et al., 2015; WOLFERT S, et al., 2017).

Modern FMIS support the registration and analysis of production indicators from both crop and livestock enterprises. Information related to planting operations, fertilizer applications, irrigation schedules, harvesting, animal identification, reproductive performance, health records, feed management, and productivity can be stored continuously and retrieved through dashboards, reports, and performance indicators. The digitalization of these records reduces information loss, minimizes transcription errors, and improves the availability of historical data for technical and economic evaluations (FOUNTAS S, et al., 2015).

Beyond productive records, FMIS also contributes to financial and operational management by integrating inventories, input consumption, machinery use, labor allocation, production costs, and commercial transactions. This integration enables producers to monitor resource utilization, evaluate operational efficiency, estimate production costs, and identify opportunities for improving profitability. Traceability has become another important function of these systems, allowing production events to be documented throughout the entire production chain and supporting quality assurance, certification programs, and regulatory compliance (VERDOUW CN, et al., 2016).

One of the greatest advantages of FMIS is their capacity to integrate information generated by different AgTechs. Data collected by sensors, weather stations, unmanned aerial vehicles, automated equipment, and remote sensing platforms can be centralized within a single management environment, creating a unified database that combines agricultural and livestock information. Rather than functioning as independent technologies, these digital tools become interconnected components of an integrated management system that supports both daily operations and long-term planning (WOLFERT S, et al., 2017; DA SILVEIRA F, et al., 2021).

The monitoring technologies discussed throughout this chapter generate a continuous flow of information describing production conditions in real time. However, collecting data alone does not improve farm performance. Their greatest value emerges when this information is converted into management actions through automated control systems and precision technologies.

5. HOW DO AGTECHS SUPPORT OPERATIONAL CONTROL?

Continuous monitoring provides the information required to understand what is happening in agricultural production systems, whereas operational control determines how management interventions are implemented. Advances in AgTechs have enabled many production activities to shift from manual execution toward automated or semi-automated operations capable of responding rapidly to variations detected in the field. As a result, monitoring and control have become complementary processes within modern farm management (JAVAID M, et al., 2022; DA SILVEIRA F, et al., 2021).

Automation technologies are widely applied to irrigation and fertigation systems, where information collected from soil moisture sensors, weather stations, and crop monitoring devices is used to regulate water and nutrient application according to field conditions. This approach reduces unnecessary resource consumption while improving water use efficiency and promoting more uniform crop development. Similar principles are applied in greenhouse production, where environmental control systems automatically regulate temperature, humidity, ventilation, and lighting to maintain suitable growing conditions throughout the production cycle (KHANNA A; KAUR S., 2019).

Precision application technologies have also transformed field operations. Variable-rate equipment adjusts the distribution of fertilizers, pesticides, seeds, and soil amendments according to spatial variability identified through remote sensing, soil analysis, and georeferenced field maps. Rather than applying uniform management practices across an entire field, producers can adapt operations to local production conditions, improving input efficiency while reducing environmental impacts (WANG J, et al., 2024).

Operational control has expanded considerably in livestock production. Automated feeding systems regulate feed delivery according to nutritional requirements, production stage, or individual animal performance. Environmental control systems continuously manage ventilation, cooling, heating, and air quality in intensive production facilities, contributing to improved animal welfare and production efficiency. Precision livestock technologies also automate functions such as milking, animal identification, weighing, reproductive monitoring, and health surveillance, reducing labor demands while increasing the consistency of management practices (MORRONE S, et al., 2022; PAPAKONSTANTINOU G, et al., 2024).

Agricultural machinery has likewise evolved toward increasing levels of automation. Autonomous tractors, robotic platforms, machine guidance systems, and computer vision technologies can perform field operations with greater precision and reduced operator intervention. These systems integrate positioning technologies, onboard sensors, imaging devices, and artificial intelligence algorithms to optimize navigation, obstacle detection, and operational efficiency under different production conditions (KAMILARIS A; PRENAFETA-BOLDÚ FX., 2018; GUEBSI R, et al., 2024).

The effectiveness of operational control depends on the continuous exchange of information between monitoring technologies and automated equipment. Sensor networks identify changes in production conditions, digital platforms process the incoming information, and control systems translate analytical outputs into management actions. This integration transforms data into practical interventions that improve productivity, optimize resource use, and increase the responsiveness of agricultural production systems.

6. HOW DO FARM DATA BECOME MANAGEMENT DECISIONS?

The continuous expansion of digital monitoring technologies has considerably increased the amount of information generated within agricultural production systems. Sensors, remote sensing platforms, automated equipment, and Farm Management Information Systems continuously collect environmental, productive, operational, and economic data. However, the availability of large datasets alone does not improve farm performance. Their practical value depends on analytical approaches capable of transforming raw information into knowledge that supports planning, resource allocation, and management decisions (WOLFERT S, et al., 2017; JAVAID M, et al., 2022).

Recent advances in data analytics have enabled agricultural information to be processed at a scale that would be impractical using conventional analytical methods. Statistical techniques, predictive models, optimization algorithms, and artificial intelligence have expanded the capacity to identify relationships among production variables, anticipate production outcomes, and support more efficient management strategies. Rather than replacing technical expertise, these analytical tools complement human decision-making by providing faster access to relevant information and reducing uncertainty during the decision-making process.

6.1 DATA ANALYTICS, ARTIFICIAL INTELLIGENCE, AND PREDICTIVE MODELING

Data analytics has become one of the principal components of digital farm management by enabling the interpretation of large and heterogeneous agricultural datasets. Information generated from crops, livestock, machinery, climate, soil, financial records, and production operations can be integrated and analyzed simultaneously, allowing producers to identify relationships that are often difficult to detect through conventional observation. This analytical capacity has substantially expanded the role of digital technologies beyond data collection, supporting more informed and evidence-based management (LIAKOS KG, et al., 2018; JAVAID M, et al., 2022).

Artificial intelligence has further enhanced this process through computational models capable of learning from historical data and continuously improving predictive performance. Machine Learning algorithms have been widely applied to estimate crop yields, predict disease outbreaks, classify production conditions, optimize irrigation scheduling, estimate feed requirements, detect reproductive events, and evaluate animal health. Deep Learning models have also demonstrated increasing potential for image recognition, behavioral analysis, disease detection, and automated interpretation of complex agricultural datasets generated by sensors and imaging technologies (KAMILARIS A; PRENAFETA-BOLDÚ FX., 2018; GUEBSI R, et al., 2024).

Predictive analytics enables producers to anticipate future production scenarios rather than simply describing current conditions. Models developed from historical and real-time information can forecast productivity, estimate resource consumption, predict economic performance, assess climatic risks, and identify factors associated with production losses. These forecasts support proactive management by allowing interventions to be implemented before adverse conditions significantly affect production efficiency (WANG J, et al., 2024; MILLER T, et al., 2025).

Another important contribution of artificial intelligence lies in its ability to identify hidden patterns within large agricultural and livestock databases. Relationships among climatic variables, management practices, production performance, animal behavior, and economic indicators can be identified through pattern recognition techniques, clustering algorithms, and predictive modeling. These analytical approaches provide valuable information for improving production efficiency, optimizing resource allocation, and supporting continuous improvement of farm management strategies.

6.2 DECISION SUPPORT SYSTEMS

Decision Support Systems (DSS) represent the interface between data analysis and practical farm management. These systems organize information generated by digital technologies into dashboards, reports, alerts, performance indicators, and recommendations that facilitate the interpretation of complex datasets by producers and technical advisors. Rather than requiring users to interpret thousands of isolated measurements, DSS present synthesized information focused on supporting management decisions (FOUNTAS S, et al., 2015; WOLFERT S, et al., 2017).

Modern dashboards integrate productive, environmental, operational, and financial indicators into interactive digital environments that allow continuous monitoring of farm performance. Visual representations of key performance indicators, historical trends, resource consumption, production efficiency, and operational status improve situational awareness and enable rapid identification of deviations requiring management intervention. Automated alerts further increase system responsiveness by notifying producers whenever predefined thresholds associated with climate, irrigation, machinery performance, animal health, or production indicators are exceeded (VERDOUW CN, et al., 2016).

The information generated by DSS supports decisions at different management levels. Operational decisions involve routine activities such as irrigation scheduling, feed adjustments, disease control, and machinery operation. Tactical decisions focus on medium-term resource allocation, crop planning, inventory management, labor organization, and production scheduling. Strategic decisions address long-term investments, technology adoption, production diversification, financial planning, and risk management. The integration of these decision levels contributes to more coordinated and efficient farm management (FOUNTAS S, et al., 2015).

Many decision-support platforms also incorporate scenario analysis tools that allow producers to compare alternative management strategies before implementing them in the field. Different combinations of climatic conditions, production practices, input prices, resource availability, and operational constraints can be simulated to estimate their potential impacts on productivity and economic performance. This capability improves planning, facilitates the prioritization of interventions, and reduces uncertainty associated with complex management decisions.

Although analytical models and decision-support systems continue to evolve rapidly, their effectiveness ultimately depends on the quality of the underlying data and the integration of digital technologies throughout the production system. Farm management increasingly relies on connected platforms capable not only of analyzing current conditions but also of representing production systems dynamically, enabling continuous evaluation of future management scenarios.

The main AgTechs supporting monitoring, operational control, and decision-making are summarized in Table 1, illustrating how digital technologies interact throughout the farm management process rather than operating as isolated solutions.

Table 1 - Main AgTechs supporting smart farm management across monitoring, operational control, and decision-making.

AgTech	Monitoring	Operational control	Decision support	Main applications
Smart sensors	✓	—	✓	Soil, water, climate, machinery, facilities, and animal monitoring
Internet of Things (IoT)	✓	✓	✓	Device connectivity, real-time data transmission, and automated alerts
Weather stations	✓	✓	✓	Local climate assessment, irrigation scheduling, and production risk management

AgTech	Monitoring	Operational control	Decision support	Main applications
Global Navigation Satellite Systems (GNSS)	✓	✓	✓	Machinery guidance, georeferencing, animal tracking, and precision operations
Unmanned aerial vehicles (UAVs)	✓	—	✓	Crop scouting, pasture assessment, spatial mapping, and livestock location
Satellite remote sensing	✓	—	✓	Vegetation, biomass, land use, water availability, and large-scale environmental monitoring
Imaging and computer vision	✓	✓	✓	Detection of crop stress, diseases, animal behavior, health conditions, and operational anomalies
Farm Management Information Systems (FMIS)	✓	✓	✓	Integration of productive, operational, economic, inventory, and traceability records
Automated control systems	✓	✓	—	Irrigation, fertigation, climate regulation, ventilation, lighting, and environmental control
Variable-rate technology (VRT)	—	✓	✓	Site-specific application of seeds, fertilizers, pesticides, and soil amendments
Precision feeding systems	✓	✓	✓	Individual or group-based feed allocation and nutritional management
Autonomous machinery and robotics	✓	✓	—	Planting, spraying, harvesting, weeding, milking, and repetitive farm operations
Artificial intelligence (AI) and data analytics	—	✓	✓	Prediction, classification, anomaly detection, optimization, and pattern recognition
Decision Support Systems (DSS)	—	—	✓	Management recommendations, scenario comparison, risk assessment, and planning
Digital Twins	✓	✓	✓	Virtual representation, process simulation, scenario testing, and system optimization

Note: ✓ indicates a direct function of the technology; indicates that the function is not its primary role, although indirect contributions may occur through system integration.
Source: Prepared by the authors based on Fountas et al. (2015), Wolfert et al. (2017), Verdouw et al. (2016), Khanna and Kaur (2019), Javaid et al. (2022), Soussi et al. (2024), Wang et al. (2024), and the reviewed literature.

6.3 DIGITAL TWINS AND INTEGRATED PLATFORMS

The increasing digitalization of agricultural production has stimulated the development of integrated platforms capable of consolidating information generated throughout the entire production system. Rather than functioning as isolated technologies, modern digital platforms connect sensors, weather stations, unmanned aerial vehicles, machinery, Farm Management Information Systems, livestock monitoring devices, financial records, and other data sources within a unified digital environment. This integration enables continuous information exchange among different production components and provides a comprehensive representation of farm operations (VERDOUW CN, et al., 2016; WOLFERT S, et al., 2017).

Integrated digital platforms improve information consistency by reducing data fragmentation and eliminating the need for multiple independent management systems. Environmental conditions, crop development, animal performance, machinery operation, resource consumption, labor activities, inventories, and financial records can be monitored simultaneously, allowing managers to evaluate farm performance from a systems perspective rather than through isolated production indicators. This holistic approach facilitates coordination among production sectors and supports more efficient management planning (DA SILVEIRA F, et al., 2021).

One of the most recent developments in digital agriculture is the application of Digital Twins. A Digital Twin is a dynamic virtual representation of a physical production system that continuously incorporates information collected from the real environment. By integrating historical records with real-time data streams, Digital Twins allow production systems to be monitored, analyzed, and updated throughout the production cycle, providing an increasingly realistic representation of farm conditions (JAVAID M, et al., 2022).

Beyond real-time monitoring, Digital Twins enable the simulation of alternative management scenarios before decisions are implemented under field conditions. Different irrigation schedules, nutritional strategies, stocking rates, machinery operations, production schedules, or environmental conditions can be evaluated virtually to estimate their potential effects on productivity, resource use, operational efficiency, and economic performance. This capacity reduces uncertainty and supports more robust planning while minimizing the risks associated with complex management decisions.

As integrated digital platforms continue to evolve, farm management increasingly shifts from reactive decision-making toward predictive and adaptive management. Instead of responding only after production problems become evident, producers are progressively able to anticipate future scenarios, evaluate alternatives, and continuously optimize management strategies through the integration of monitoring technologies, analytical models, and simulation environments.

7. WHAT CHANGES IN FARM MANAGEMENT WHEN AGTECHS ARE INTEGRATED?

The integration of AgTechs represents more than the adoption of individual digital tools. It promotes a transformation in the way agricultural production systems are planned, monitored, coordinated, and managed. As information generated from multiple sources becomes continuously available and interconnected, management evolves from fragmented decision-making toward an integrated process supported by real-time information, predictive analytics, and automated operational control (WOLFERT S, et al., 2017; JAVAID M, et al., 2022).

One of the principal changes occurs in productive management. Continuous monitoring of production indicators allows managers to evaluate crop development, animal performance, machinery operation, and resource utilization throughout the production cycle rather than relying exclusively on periodic field inspections. The availability of updated information enables faster identification of production constraints and supports timely management interventions that improve operational efficiency and production consistency.

Integrated AgTechs have also transformed both crop and livestock management. In crop production, digital technologies contribute to more precise irrigation scheduling, fertilization, pest management, harvesting, and field operations according to local production variability. In livestock systems, continuous monitoring of animal behavior, health, nutrition, reproduction, and environmental conditions enables more individualized management while improving welfare, production efficiency, and early detection of health or performance problems. The increasing integration of plant and animal information also strengthens decision-making in mixed farming systems, where multiple production components interact simultaneously.

Economic and financial management has likewise become more data driven. Digital platforms integrate production records with information related to inventories, machinery use, labor, operational costs, input consumption, and commercial activities, allowing managers to evaluate production efficiency alongside economic performance. This integration facilitates cost monitoring, profitability analysis, investment planning, and more efficient allocation of financial resources throughout the production cycle.

Environmental management has gained increasing importance within digitally integrated production systems. Continuous monitoring of soil, climate, water resources, nutrient application, and energy consumption enables producers to optimize resource use while reducing environmental impacts. Precision management practices supported by digital technologies contribute to more efficient water use, improved nutrient management, reduced chemical applications, and lower greenhouse gas emissions, supporting more sustainable agricultural production.

Traceability and risk management have also been strengthened through digital integration. The continuous recording of production events improves transparency throughout agricultural supply chains and facilitates compliance with quality standards, certification programs, and regulatory requirements. At the same time, predictive models and integrated monitoring systems support the early identification of climatic, sanitary, operational, and economic risks, allowing preventive measures to be implemented before major production losses occur.

Perhaps the most significant managerial transformation promoted by AgTech integration is the optimization of resource allocation. Information generated throughout the production system allows producers to make more efficient use of labor, water, energy, fertilizers, pesticides, feed, machinery, and financial resources according to actual production requirements rather than generalized management practices. Consequently, agricultural management becomes increasingly adaptive, evidence-based, and responsive to changing production conditions.

Rather than replacing managerial expertise, AgTechs redefine the role of farm managers. Decision-making increasingly depends on the ability to interpret integrated information, evaluate alternative scenarios, and coordinate technological resources to achieve productive, economic, environmental, and social objectives simultaneously. In this context, digital technologies function as strategic instruments that expand managerial capacity and support more resilient and sustainable agricultural production systems.

Representative applications of integrated AgTechs in crop and livestock production systems are presented in **Table 2**, illustrating how digital technologies are translated into practical management improvements across different agricultural contexts.

Table 2 - Representative applications of AgTechs in crop and livestock production systems

Production system	AgTech or digital solution	Management objective	Representative application	Expected management benefit
Field crops	Smart sensors and IoT	Soil and crop monitoring	Continuous measurement of soil moisture, temperature, and microclimatic conditions	Timely interventions and improved resource allocation
Field crops	UAVs and imaging technologies	Crop assessment	Identification of planting failures, water stress, nutritional deficiencies, pests, and diseases	Earlier detection of spatial variability and production problems
Field crops	Variable-rate technology	Input management	Site-specific application of seeds, fertilizers, and crop protection products	Reduced input waste and improved operational precision

Production system	**AgTech or digital solution**	**Management objective**	**Representative application**	**Expected management benefit**
Irrigated crops	Automated irrigation and fertigation	Water and nutrient management	Adjustment of water and nutrient delivery using sensor and climatic data	Higher water-use and nutrient-use efficiency
Protected crops	Automated climate control	Environmental management	Regulation of temperature, humidity, ventilation, lighting, and carbon dioxide levels	Greater environmental stability and crop uniformity
Pasture-based livestock	Satellite imagery, UAVs, and GNSS	Pasture and grazing management	Assessment of forage availability, herd distribution, and grazing patterns	Improved pasture use and stocking decisions
Dairy cattle	Wearable sensors and computer vision	Health and reproductive monitoring	Detection of rumination changes, estrus, lameness, and behavioral alterations	Earlier interventions and reduced dependence on periodic observation
Dairy cattle	Robotic milking systems	Milking and herd management	Automated milking with individual collection of yield and health indicators	Greater process consistency and individual animal monitoring
Beef cattle	Electronic identification and GNSS collars	Herd monitoring and traceability	Individual identification, movement tracking, and grazing behavior assessment	Improved herd control, traceability, and extensive-system management
Poultry	Sensors and automated climate control	Housing environment management	Continuous regulation of temperature, ventilation, humidity, and air quality	Improved animal welfare and reduced environmental stress
Swine	Precision feeding systems	Nutritional and cost management	Adjustment of feed supply according to production stage or individual requirements	Reduced feed waste and improved feeding efficiency
Integrated crop–livestock systems	FMIS and integrated digital platforms	Whole-farm management	Consolidation of crops, livestock, machinery, inventory, cost, and environmental records	Coordinated planning and broader assessment of farm performance
Multiple agricultural systems	AI and DSS	Prediction and planning	Forecasting yields, disease risks, resource requirements, and economic outcomes	More informed decisions and improved risk management
Multiple agricultural systems	Digital Twins	Simulation and optimization	Testing management scenarios before implementing changes in the physical system	Reduced uncertainty and improved strategic planning

Source: Prepared by the authors based on Fountas et al. (2015), Kamilaris and Prenafeta-Boldú (2018), Khanna and Kaur (2019), Morrone et al. (2022), Javaid et al. (2022), Wang et al. (2024), Menezes et al. (2025), and the reviewed literature.

8. WHY ARE AGTECHS NOT YET ACCESSIBLE TO ALL FARMS?

Despite the remarkable progress achieved in digital agriculture over the last decade, the adoption of AgTechs remains highly heterogeneous across agricultural production systems. While large commercial farms have increasingly incorporated digital technologies into routine management, many small and medium-sized producers continue to face significant barriers

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that limit the effective implementation of smart farming solutions. Consequently, the benefits associated with digital agriculture are still distributed unevenly among regions, production systems, and farm sizes (WOLFERT S, et al., 2017; LIAKOS KG, et al., 2018; JAVAID M, et al., 2022).

One of the most frequently reported barriers is the high cost associated with technological adoption. The implementation of digital agriculture often requires investments in sensors, monitoring devices, communication infrastructure, automated machinery, software licenses, cloud services, and technical support. Beyond the initial acquisition costs, producers must also consider maintenance, equipment replacement, software updates, subscription fees, and personnel training, all of which increase the long-term financial commitment required to sustain digital transformation (KHANNA A and KAUR S, 2019; JAVAID M, et al., 2022; PAPAKONSTANTINOU G, et al., 2024).

Limited digital infrastructure remains another major constraint. Many AgTech solutions depend on continuous internet connectivity to transmit sensor information, synchronize cloud-based platforms, operate decision-support systems, and enable remote monitoring. However, broadband availability remains insufficient in many rural regions worldwide, particularly in developing countries and geographically isolated production areas. Under these conditions, the performance of connected technologies may be compromised, reducing their practical value for producers who operate under limited communication infrastructure (KHANNA A and KAUR S, 2019; WANG J, et al., 2024).

Interoperability has emerged as another critical challenge for digital agriculture. Modern farms frequently employ equipment, sensors, software platforms, machinery, and analytical tools developed by different manufacturers. However, these technologies often rely on proprietary communication protocols that restrict data exchange between systems. As a result, valuable information remains fragmented across multiple independent platforms, increasing management complexity and reducing the efficiency of integrated decision-making. The adoption of open standards and interoperable digital ecosystems has therefore become one of the main priorities for the future development of smart farm management (VERDOUW CN, et al., 2016; WOLFERT S, et al., 2017; SOUSSI R, et al., 2024).

The widespread use of proprietary software platforms may further intensify these limitations. Some commercial ecosystems restrict compatibility with equipment produced by competing manufacturers, making it difficult for producers to integrate technologies acquired

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over time. Vendor lock-in may also limit data portability, increase dependence on a single technology provider, and reduce producers' flexibility when selecting new digital solutions. Such restrictions may discourage innovation while increasing the long-term costs associated with technological modernization (VERDOUW CN, et al., 2016; JAVAID M, et al., 2022).

Human factors represent equally important obstacles to digital transformation. Successful implementation depends not only on technological availability but also on producers' ability to interpret digital information and incorporate analytical outputs into everyday management. Limited digital literacy, insufficient technical training, resistance to organizational change, and shortages of qualified technical support continue to restrict the effective use of many AgTech solutions, particularly among family farms and traditional production systems. For this reason, investments in capacity building and rural extension remain essential for expanding digital agriculture beyond technologically advanced production systems (FOUNTAS S, et al., 2015; LIAKOS KG, et al., 2018; JAVAID M, et al., 2022).

As agricultural production becomes increasingly data-driven, concerns regarding data quality, ownership, privacy, and cybersecurity have also gained prominence. Predictive models and artificial intelligence algorithms depend on reliable datasets to generate accurate recommendations. Incomplete, inconsistent, or poorly standardized information may compromise analytical performance and reduce confidence in digital management tools. Furthermore, uncertainty regarding who owns agricultural data, how these data are stored, and how they may be shared or commercialized continues to raise important legal and ethical questions that remain only partially addressed by current regulatory frameworks (WOLFERT S, et al., 2017; JAVAID M, et al., 2022; PAPAKONSTANTINOU G, et al., 2024).

The digital divide between large commercial enterprises and smaller agricultural producers remains particularly relevant. Large farms generally possess greater financial capacity, specialized personnel, and easier access to technological infrastructure, facilitating the adoption of advanced digital solutions. Smaller farms, in contrast, often operate under limited financial resources while simultaneously facing greater difficulties in adapting commercially available technologies to their production realities. Consequently, innovations originally designed for large-scale production may offer limited practical benefits for producers managing smaller or more diversified farming systems (KAMILARIS A and PRENAFETA-BOLDÚ FX, 2018; JAVAID M, et al., 2022).

Another important consideration is the limited adaptation of many digital solutions to local agricultural conditions. Agricultural systems differ substantially with respect to climate, soil characteristics, production objectives, available infrastructure, labor availability, and socioeconomic context. Technologies developed under highly mechanized production environments may not adequately address the needs of producers operating under different climatic conditions or management systems. Future innovation should therefore prioritize flexible, scalable, and context-sensitive solutions capable of accommodating the diversity that characterizes global agricultural production (FOUNTAS S, et al., 2015; SOUSSI R, et al., 2024).

Ultimately, the future expansion of AgTechs will depend on overcoming these technical, economic, organizational, and social barriers simultaneously. Digital agriculture should not be understood simply as the adoption of increasingly sophisticated technologies, but rather as the construction of integrated management systems that remain economically viable, technically reliable, accessible to producers of different scales, and adaptable to the diverse realities of modern agriculture. Only under these conditions will digital transformation be capable of delivering its full potential for improving agricultural productivity, sustainability, and resilience (WOLFERT S, et al., 2017; JAVAID M, et al., 2022; WANG J, et al., 2024).

9. WHAT WILL SHAPE THE FUTURE OF SMART-FARM MANAGEMENT?

The future of smart farm management will likely be defined not by the emergence of isolated technologies, but by the increasing integration of digital tools capable of supporting continuous, adaptive, and evidence-based decision-making. The rapid expansion of sensing technologies, artificial intelligence, automation, cloud computing, and digital platforms is gradually transforming agricultural management from a reactive process into a predictive and interconnected system. Rather than simply generating larger volumes of data, future agricultural systems are expected to improve the quality, accessibility, and practical use of information throughout the production cycle (WOLFERT S, et al., 2017; JAVAID M, et al., 2022; WANG J, et al., 2024).

One concept that increasingly reflects this transformation is Agriculture 5.0. While Agriculture 4.0 emphasized digitalization, connectivity, and automation, Agriculture 5.0 expands this perspective by placing producers, sustainability, and resilience at the center of technological development. In this approach, digital technologies are expected to complement human expertise rather than replace it, promoting production systems that simultaneously improve productivity, environmental performance, animal welfare, and economic viability. Consequently, future agricultural innovation is likely to focus not only on technological efficiency but also on the social and environmental value generated by digital transformation (JAVAID M, et al., 2022; PAPAKONSTANTINOU G, et al., 2024).

Artificial intelligence will continue to evolve beyond centralized cloud computing through the growing adoption of Edge Artificial Intelligence (Edge AI). Unlike conventional approaches that require data transmission to remote servers for processing, Edge AI performs analytical tasks directly within sensors, machinery, drones, autonomous vehicles, and monitoring devices deployed on the farm. Local processing reduces communication latency, improves system reliability in regions with limited internet connectivity, decreases bandwidth requirements, and enables immediate responses to dynamic production conditions. These characteristics make Edge AI particularly attractive for livestock monitoring, autonomous machinery, precision irrigation, and real-time crop management (WANG J, et al., 2024; SOUSSI R, et al., 2024).

Another technology expected to play an increasingly important role is Digital Twin. As digital platforms become more integrated, Digital Twins are evolving from simple virtual models into continuously updated representations of entire agricultural production systems. By combining information from sensors, weather stations, machinery, crop monitoring, livestock records, economic indicators, and historical databases, Digital Twins allow producers to simulate alternative management strategies before implementing them under real production conditions. This capability supports more robust planning, continuous optimization, and proactive risk management while reducing uncertainty associated with complex production decisions (JAVAID M, et al., 2022; PAPAKONSTANTINOU G, et al., 2024).

The effectiveness of future digital agriculture will also depend heavily on advances in interoperability. As agricultural production systems become increasingly dependent on information generated by multiple technologies, seamless communication among sensors, software platforms, autonomous equipment, Farm Management Information Systems, and analytical tools will become essential. Open communication standards, standardized data formats, and interoperable digital ecosystems are expected to reduce technological fragmentation, facilitate information sharing, and improve the scalability of smart farming solutions across different production systems (VERDOUW CN, et al., 2016; WOLFERT S, et al., 2017; SOUSSI R, et al., 2024).

Automation itself is also expected to evolve toward more collaborative models. Rather than replacing producers or technical professionals, future autonomous systems will increasingly perform repetitive, labor-intensive, or highly standardized operations while leaving strategic decisions under human supervision. Collaborative robotics, intelligent machinery, automated monitoring systems, and AI-assisted decision-support platforms are therefore expected to function as complementary management tools that expand human decision-making capacity instead of substituting agricultural expertise (KAMILARIS A and PRENAFETA-BOLDÚ FX, 2018; JAVAID M, et al., 2022).

Equally important will be the development of more intuitive digital platforms. As analytical models become increasingly sophisticated, successful AgTech solutions should minimize technological complexity from the user's perspective. Future platforms are expected to provide simplified dashboards, visual performance indicators, personalized recommendations, automated alerts, and user-friendly interfaces that facilitate decision-making without requiring advanced computational knowledge. Improving usability may become as important as improving analytical performance, particularly for producers with limited digital experience (FOUNTAS S, et al., 2015; WOLFERT S, et al., 2017).

Ensuring that digital transformation reaches a broader range of agricultural producers will require the development of technologies that are both scalable and economically accessible. Small and medium-sized farms represent a substantial proportion of global agricultural production, yet many currently face financial and technical barriers to adopt advanced digital solutions. Cloud-based services, modular digital platforms, subscription models, open-source software, low-cost sensors, and mobile applications are expected to contribute to reducing implementation costs while expanding access to digital management tools. The democratization of AgTechs will therefore depend not only on technological innovation but also on business models capable of making these technologies financially viable for producers operating at different production scales (LIAKOS KG, et al., 2018; JAVAID M, et al., 2022; WANG J, et al., 2024).

Ultimately, the future of smart farm management will depend on the successful integration of three complementary sources of knowledge: scientific and technical evidence, producers' practical experience, and data-driven analytical models. Although artificial intelligence, automation, and predictive analytics will continue to increase their contribution to agricultural management, effective decision-making will remain strongly dependent on human interpretation, contextual knowledge, and local production experience. The most successful agricultural systems will therefore be those capable of integrating computational intelligence with practical expertise, creating adaptive management strategies that respond to the biological, environmental, and socioeconomic complexity of modern agriculture (WOLFERT S, et al., 2017; KAMILARIS A and PRENAFETA-BOLDÚ FX, 2018; PAPAKONSTANTINOU G, et al., 2024).

10. FINAL CONSIDERATIONS

The digital transformation of agriculture has considerably expanded the capacity to monitor production systems, automate operational activities, and support farm management through increasingly integrated technological solutions. Although sensors, connected devices, artificial intelligence, and digital platforms have become essential components of modern agriculture, their greatest contribution lies not in the technologies themselves but in their ability to transform dispersed information into meaningful knowledge that supports decision-making across the farm as an integrated production system.

Future advances in smart farm management will depend not only on technological innovation but also on the development of reliable, interoperable, accessible, and producer-centered solutions capable of responding to the diversity of agricultural realities. Expanding the adoption of AgTechs will require technologies that integrate technical knowledge, practical farming experience, and data-driven analysis while remaining adaptable to farms of different sizes, production systems, and socioeconomic contexts. Under these conditions, digital agriculture can evolve toward more efficient, resilient, and sustainable management models that generate value for producers, society, and the agricultural sector.

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