DIGITAL TRANSFORMATION IN AGRICULTURE: USE OF SMART AGRICULTURAL TECHNOLOGIES AND ARTIFICIAL INTELLIGENCE

TARIMDA DİJİTAL DÖNÜŞÜM: AKILLI TARIM TEKNOLOJİLERİ VE YAPAY ZEKÂNIN KULLANIMI

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Abstract

This research examines smart agricultural technologies, which are a reflection of digital transformation in the agricultural sector, with a multidimensional approach. Components such as sensors, artificial intelligence, robots, image processing systems, drone and satellite technologies developed in line with the goal of increasing the efficiency of agricultural production, optimizing resource use and ensuring sustainability form the basis of the study. The capacity of smart sensors to collect data such as soil moisture, temperature, and pH; the role of artificial intelligence in forecasting and decision support systems; the effectiveness of robot technologies in automation processes; Topics such as the contribution of image processing techniques in disease detection and product classification are discussed. In addition, the difficulties encountered in the implementation process and solution suggestions were evaluated; Elements such as legislative deficiencies, costs, technical competence and digital literacy of farmers were discussed. As a result, smart agricultural technologies create a revolutionary transformation in agricultural production; It is becoming a strategic tool in terms of food security, environmental sustainability and combating climate change. In this context, accelerating technological adaptation, increasing educational activities and providing policy support stand out as an important necessity.

Keywords: Smart Agricultural Technologies, Artificial Intelligence, Digital Transformation in Agriculture, Agriculture.

Öz

Bu araştırma, tarım sektöründeki dijital dönüşümün bir yansıması olan akıllı tarım teknolojilerini çok boyutlu bir yaklaşımla incelemektedir. Tarım üretiminin verimliliğini artırmak, kaynak kullanımını optimize etmek ve sürdürülebilirliği sağlamak amacıyla geliştirilen sensörler, yapay zekâ, robotlar, görüntü işleme sistemleri, drone ve uydu teknolojileri gibi bileşenler çalışmanın temelini oluşturmaktadır. Akıllı sensörlerin toprak nemi, sıcaklık ve pH gibi verileri toplama kapasitesi; yapay zekânın tahmin ve karar destek sistemlerindeki rolü; robot teknolojilerinin otomasyon süreçlerindeki etkinliği; görüntü işleme tekniklerinin hastalık tespiti ve ürün sınıflandırmasında katkısı gibi konular ele alınmaktadır. Ayrıca, uygulama sürecinde karşılaşılan zorluklar ve çözüm önerileri değerlendirilmiş; mevzuat eksiklikleri, maliyetler, teknik yeterlilik ve çiftçilerin dijital okuryazarlığı gibi unsurlar ele alınmıştır. Sonuç olarak, akıllı tarım teknolojileri tarımsal üretimde devrim niteliğinde bir dönüşüm yaratmaktadır; gıda güvenliği, çevresel sürdürülebilirlik ve iklim değişikliğiyle mücadele açısından stratejik bir araç haline gelmektedir. Bu bağlamda, teknolojik adaptasyonun hızlandırılması, eğitim faaliyetlerinin artırılması ve politika desteğinin sağlanması önemli bir gereklilik olarak öne çıkmaktadır.

Anahtar Kelimeler: Akıllı tarım teknolojileri, yapay zekâ, tarımda dijital dönüşüm, tarım.

1. Introduction

The agricultural sector, as one of the most deep-rooted production activities in human history, is not only food production; It is also the cornerstone of social welfare, economic growth and environmental sustainability. The rapid increase in the global population, the limited nature of natural resources and the increasing effects of climate change necessitate a rethink of agricultural production not only in terms of quantity but also quality. The fact that traditional agricultural practices have reached the limits of productivity in many regions has made the need for digital solutions in the sector more visible day by day (Bhuyan, Beg, Farooq, & Haq, 2024; Karam et al., 2024).

At the center of this transformation are smart agricultural technologies. Integration of digitalization into agricultural production, especially in developed countries; It offers significant advantages in areas such as data-based decision-making, efficiency in resource use, early warning systems and automation. For developing countries, these technologies have the potential to support rural development as well as increase in productivity (Papazoglou et al., 2025; Chen, Zhang, Chen, & Zhong, 2021). In this context, the historical development of the concept of smart agriculture and the effects of digitalization on agriculture are at the center of today's agricultural policies and research.

1.1. The Global Importance of Agriculture and the Concept of Smart Agriculture

Today, it is predicted that the world population will reach 9.7 billion by 2050. This situation necessitates increasing agricultural production by at least 60% (Feng, 2022). However, current agricultural practices are based on intensive use of natural resources such as water, land, and energy. Unsustainable consumption of these resources both threatens the environmental balance and puts food security at risk (Cheng et al., 2023). Agriculture is both the cause and the victim of climate change at the same time. Agricultural activities account for about 24% of global greenhouse gas emissions, while climate change directly affects agricultural productivity through droughts, floods, and seasonal irregularities (Botero-Valencia, Mejia-Herrera, & Pearce, 2022). In this context, it is necessary to restructure agriculture to adapt to climate change (Rehman et al., 2021).

Increasing urbanization on a global scale and the decrease in rural population bring with it the problem of finding labor force in agriculture. In particular, the decrease in the interest of the young population in agriculture limits the transfer of knowledge and skills in rural areas and reduces the production potential (Fizza et al., 2022). This situation further

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increases the need for technological solutions for the continuity of agricultural production. The global importance of agriculture is not limited to its economic dimension. It also has a cultural, social and political function. Especially in developing countries, agriculture constitutes a large part of employment and is decisive in shaping the social structure (Roman et al., 2025). Therefore, the crises faced by agriculture affect not only the production processes but also the social balances. The issue of food security is another factor that further reinforces the global importance of agriculture. The pandemic process has exposed the fragility of international food supply chains and made it clear that every country needs to develop self-sufficient agricultural policies (Kumari & Praveen, 2024).

In recent years, the integration of technological developments into the agricultural sector has greatly transformed traditional production models. The most prominent role in this transformation belongs to digital solutions such as sensor technologies, remote sensing, big data analytics, and artificial intelligence (Chen et al., 2021). Thanks to digitalization, producers can instantly monitor crop development and plan irrigation, fertilization and harvest timing based on data (Tang et al., 2025). Data collection systems are of great importance in this process. Many parameters such as soil moisture, air temperature, sunshine duration can be monitored through sensors; these data are transferred to cloud-based platforms and analyzed with artificial intelligence algorithms (Gan et al., 2023; Mowla et al., 2023). Thus, agricultural decisions are not based on hunch or past experience, but on hard data.

Digitalization not only increases production efficiency, but also contributes to the creation of sustainable agricultural policies. For example, goals such as efficient use of water resources, reduction of chemical inputs, and reduction of carbon footprint can be achieved more easily with smart systems (Cheng et al., 2023; Papazoglou et al., 2025). In addition, digital farming systems enable farmers to become more resilient to climate change. Practices such as early warning systems, disease and pest prediction, and planning of crop patterns according to seasonal changes help producers manage risks more effectively (Bhuyan et al., 2024; Amirinezhadfard, Niazi Tabar, Bashir, & Yang, 2025). However, this transformation process brings with it some structural problems. Elements such as internet infrastructure, technological equipment, training, and financing, which are necessary for the dissemination of digital agricultural practices, still pose a serious problem, especially in developing countries (Fizza et al., 2022; Roman et al., 2025).

Smart agriculture is an innovative approach that refers to the integration of information and communication technologies (ICT) into agricultural production processes. In this model, production processes are carried out in an optimized and sustainable manner that is sensitive to environmental conditions (Amirinezhadfard et al., 2025). This approach, which was initially limited to automation systems, has now become multi-layered with sensor networks, remote sensing, robot technologies, artificial intelligence and image processing systems. The development of smart agriculture is directly linked to the digitalization phase called agriculture 4.0. Agriculture 4.0; It offers a structure in which production processes are managed through machine-to-machine communication, data analytics and autonomous systems. Thanks to this structure, continuous monitoring of production areas, early detection of risks, and more effective use of resources become possible (Chen et al., 2021; Gan et al., 2023).

Smart agricultural technologies are being tried to be made suitable for use not only in large-scale enterprises but also in small farmers. In this context, low-cost sensor solutions, mobile applications and open-source software are being developed (Kumari & Praveen, 2024). Thus, it is aimed to prevent technological inequalities and reduce the digital divide. On the other hand, the success of smart agriculture practices is not only due to technology; It also depends on users' digital proficiency levels and adaptation processes. Farmers' adoption of these systems, cost-benefit analyses, and dissemination of technical support services are critical for the effective implementation of smart agriculture (Rehman et al., 2021; Mowla et al., 2023).

1.2. Smart Agricultural Technologies and Their Benefits

Smart agriculture is an approach based on the systematic integration of information and communication technologies into agricultural production processes. This approach includes the development of data-driven decision-making mechanisms in agriculture, the dissemination of automation systems, and the use of digital technologies at all stages of production (Maddikunta et al., 2021). Smart agriculture is not only limited to the use of technology, but also aims to manage the agricultural ecosystem with a holistic approach. The basic principles of this technology-based approach include continuous data collection through sensors, analysis of the obtained data with artificial intelligence algorithms, automatic interventions in line with these analyzes, and remote monitoring of all processes

(Ullo & Sinha, 2021). In this way, measurable and optimizeable digital systems take the place of error-prone manual practices in agricultural production.

Smart agriculture applications are mainly based on five main components: (1) data collection (sensors and satellite systems), (2) data transfer (wireless communication infrastructures), (3) data processing (cloud computing and artificial intelligence), (4) decision making (automated algorithms), and (5) application (robotic machines and control systems) (Alex, Sobin, & Ali, 2023; Luo, 2025). This structural integrity increases the functionality and sustainability of smart agriculture. In addition, smart agriculture offers adaptable systems not only for high-tech farms, but also for small and medium-sized enterprises. For example, thanks to applications compatible with mobile devices, farmers can instantly monitor the data of their fields and benefit from digital decision support systems (Li, Li, & Zhang, 2024). This contributes to the democratization of technology. One of the basic principles of smart agriculture is to observe environmental balance. While this understanding aims to achieve maximum efficiency with minimum use of resources in the production process, it also encourages the adoption of environmentally friendly practices (Miles et al., 2020; Wang et al., 2022).

The main purpose of smart agriculture is to make agricultural production more efficient, sustainable, traceable and predictable. Thanks to these systems, farmers can make more strategic decisions by evaluating historical and instant data on production processes together (Amarasingam, Musthafa, Mohamed Najim, & Baig, 2024). At the same time, minimizing environmental impacts and adapting to climate change are among the main goals of these technologies. However, smart agricultural technologies offer significant economic gains to farmers. For example, automating irrigation systems reduces not only water consumption, but also energy and fertilizer use; this creates a direct cost advantage (Marković et al., 2024). Likewise, thanks to early warning systems, disease and pest interventions can be made in a timely manner and product loss can be minimized.

Traceability is one of the most critical benefits of smart agriculture. The ability to trace agricultural products throughout their entire journey from field to table both increases consumer confidence and facilitates quality control processes (Yu et al., 2024). This traceability also plays an important role in shaping agricultural policies and establishing food safety standards. Smart agriculture also increases labor productivity and offers alternative solutions to qualified labor problems in rural areas. In particular, robotic

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systems and autonomous machines can perform operations such as planting, irrigation and harvesting without the need for human intervention; This reduces human error. In this respect, smart agriculture is also a part of the technological workforce transformation (Li et al., 2022; Mahlous, 2024). In addition, digital agricultural systems make agricultural risk management more effective. Developing preventive strategies against possible negativities such as climate change, natural disasters, drought or excessive rainfall has become possible with big data analysis and AI-supported scenario generation (Lu et al., 2024; Mandrone et al., 2021). Thus, agricultural activities can gain more durable and flexible structures.

1.3. The Importance of Smart Agriculture for Agricultural Productivity and Sustainability

Agricultural productivity is not only increasing the amount of production; It should also be evaluated in terms of the efficiency of the resources used in production. In this context, smart agricultural practices both increase yield and prevent waste by optimizing resource use (Wang et al., 2022). From a sustainability point of view, smart agriculture offers structural advantages for the protection of natural resources. For example, irrigation systems supported by sensors ensure that water is supplied only to the areas where it is needed, while reducing the risk of erosion by preventing excessive irrigation of the soil. This, in turn, both contributes to ecological balance and maintains long-term soil fertility (Maddikunta et al., 2021; Luo, 2025).

Another important contribution of smart agriculture is the reduction of the carbon footprint in agricultural production. While traditional production models consume large amounts of energy, digital systems reduce environmental impact by optimizing energy use (Amarasingam et al., 2024). For example, solar-powered sensors and energy-efficient machines are paving the way for green farming practices. Sustainability in agriculture includes not only environmental but also economic and social dimensions. Smart systems support rural development by increasing the competitiveness of small farmers; Thus, it also contributes to the increase of social welfare. This situation necessitates that agriculture should be considered not only as a production area but also as an element of social stability (Alex et al., 2023; Li, Li, & Zhang, 2024). In this context, smart agricultural technologies not only meet the current needs of agricultural production, but also offer an inclusive model that takes into account the production and food safety needs of future generations. In this context, the digital transformation process of agriculture is not only a matter of

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technology; it should also be treated as an ethical, environmental, and socioeconomic imperative (Marković et al., 2024).

1.3.1. Sensor Technologies

Sensor technologies form the basis of data collection mechanisms at the heart of smart agriculture. Sensors used in agriculture provide continuous data on soil, plants, weather, and environmental conditions, allowing monitoring and control of every stage of the production process (Chen et al., 2021). In this way, farmers can increase production efficiency and quality by making data-based interventions. Sensor systems; It can instantly measure many parameters such as temperature, humidity, pH, EC, light intensity and transmit this data to management systems via wireless communication networks. In particular, combining this data with AI-powered analytics enables the development of advanced decision support systems (Bhuyan, Beg, Farooq, & Haq, 2024; Kumari & Praveen, 2024).

In addition, sensors facilitate the implementation of automated processes by minimizing human error in production. Measurements that are too frequent or detailed to be done manually can be carried out in seconds by means of sensors (Marković et al., 2024). This saves time and resources, especially in agriculture in large areas. Sensors used in agriculture can be classified into two groups as ground-based (in-situ) and air-based (integrated into aircraft). Ground-based sensors generally provide detailed data at the soil and plant level, while air-based sensors are preferred for analysis covering larger areas (Alex, Sobin, & Ali, 2023; Wang et al., 2022). However, the success of sensor technologies is not limited to hardware quality alone. Correct interpretation of the collected data and transforming it into meaningful decision support models is one of the main factors determining the effectiveness of these systems (Gan et al., 2023; Mahlous, 2024).

1.3.1.1. Soil Moisture and Temperature Sensors

Soil moisture and temperature are among the most important environmental factors that have a direct impact on plant growth. For this reason, sensors that can instantly measure soil moisture and temperature play a decisive role in many agricultural decisions, especially irrigation management (Lu et al., 2024). These sensors ensure that water is used only when and in the amount it is needed, especially in precision agriculture applications. Soil moisture sensors can be placed at different depths, allowing precise monitoring of the water level in the root zone. Thus, environmental damages such as erosion and nutrient

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loss that can be caused by excessive irrigation are prevented, while rapid intervention is possible in drought situations (Papazoglou et al., 2025; Li et al., 2022).

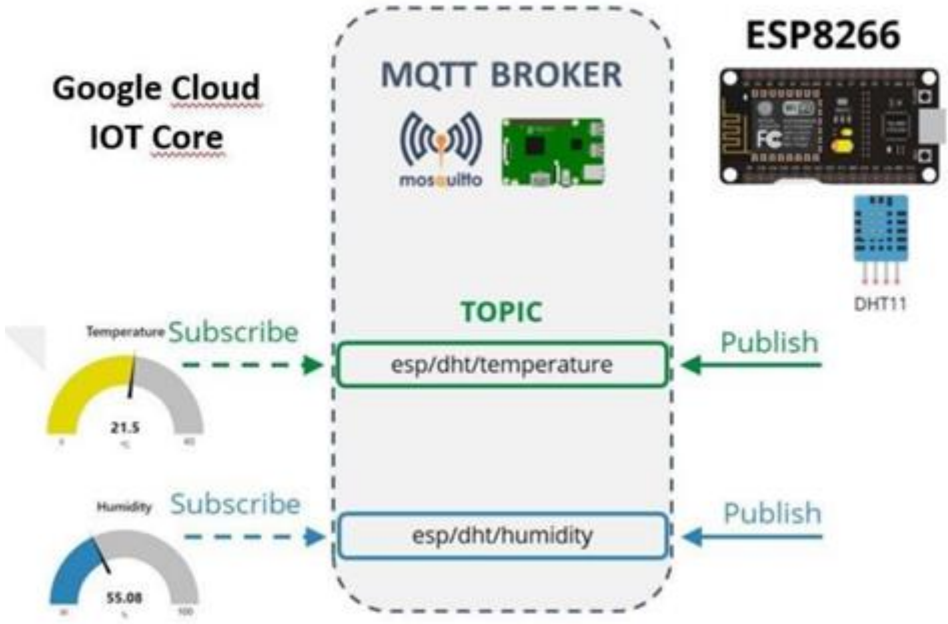

Figure 1. Sensor Technologies (Siropyan, 2022)

Temperature sensors, on the other hand, are used to measure both soil and environmental temperature values. In particular, early detection of frost events or high temperature stress makes it possible to take timely measures to prevent damage to production (Chen, Zhang, Chen, & Zhong, 2021; Feng, 2022). These sensors form the basis of automatic irrigation mechanisms by working integrated with irrigation systems. For example, irrigation systems automatically kick in when a certain humidity threshold is reached, and stop the system when the specified value is achieved (Rehman et al., 2021). This structure both optimizes the use of resources and reduces the need for labor. In addition, connecting these sensors to IoT systems ensures that data is collected in cloud systems and managed with central control. This makes for an ideal digital infrastructure, especially for large-scale agribusinesses (Amirinezhadfard, Niazi Tabar, Bashir, & Yang, 2025).

1.3.1.2. Phytosanitary and Nutrient Analysis Sensors

Protecting plant health is the basis for efficient production. For this reason, sensor systems used for the early diagnosis of plant nutrient status, chlorophyll level, stress level and disease symptoms are of great importance (Tang et al., 2025). These sensors provide instant information about the state of health by measuring various physical and chemical parameters in the plant leaves or root zone.

Chlorophyll sensors produce data on the plant's photosynthetic capacity by measuring the green color intensity of the leaves. In this way, nitrogen deficiency or stress situations can be detected early (Botero-Valencia, Mejia-Herrera, & Pearce, 2022). Thus, fertilization strategies can be planned more effectively and on time. In addition, microscopic changes on the plant can be detected thanks to leaf moisture and pH sensors. These data enable preventive interventions against the possibility of developing potential diseases (Yü et al., 2024). This provides both economic and environmental benefits by reducing the use of pesticides.

Nutrient analysis sensors detect the levels of macro and micronutrients in soil or plant tissue. For example, a deficiency of elements such as nitrogen, phosphorus, and potassium can be identified through sensors and targeted fertilization can be carried out (Mowla et al., 2023; Cheng et al., 2023). Plant health sensor applications enable early diagnosis of both diseases and nutrient deficiencies, ensuring the protection of product quality and yield. At the same time, these practices make a significant contribution to the understanding of sustainable and environmentally friendly agriculture (Kumari & Praveen, 2024).

1.3.2. Remote Sensing Systems

Remote sensing technologies collect data with high accuracy in agricultural areas, providing decision-makers with information on important issues such as plant growth, disease occurrence and yield predictions. Thanks to these systems, producers can adopt more sustainable and efficient agricultural practices, saving time and cost on large areas of land (Chen et al., 2021; Luo, 2025). Remote sensing methods, especially integrated with image processing and geographic information systems (GIS), play a strategic role in the planning and monitoring of agricultural activities (Rehman et al., 2021).

Remote sensing systems can be evaluated under two main headings: satellite technologies and drone-based agricultural observation. While satellite imagery allows to observe large areas at low cost; drones, on the other hand, provide more detailed and high-resolution data (Tang et al., 2025; Marković et al., 2024). By integrating these systems with advanced data analysis software, outputs such as soil moisture maps, chlorophyll levels, and early warnings of disease can be produced (Roman et al., 2025).

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1.3.2.1. Satellite Technologies

Satellite technologies allow spatial and temporal analysis of agricultural production processes, offering farmers the advantage of wide-area and continuous observation. With high-resolution satellite data, factors such as the development status of cultivated areas, water stress, and nutrient deficiencies can be detected remotely (Feng, 2022; Botero-Valencia, Mejia-Herrera, & Pearce, 2022). In this way, the regions that require intervention are determined in advance and yield losses are prevented. In particular, by using spectral analysis methods such as NDVI (Normalized Difference Vegetation Index), plant health can be monitored and digital decision support systems can be developed about production areas (Wang et al., 2022). Thanks to these practices, seasonal planning is made in agriculture and production risks are reduced (Kumari & Praveen, 2024).

Thanks to the developing artificial intelligence algorithms, satellite data is analyzed more quickly and accurately, for example, it is becoming widespread in applications such as early disease detection and pest-related damage determination (Amarasingam, Musthafa, Mohamed Najim, & Baig, 2024). In addition, satellite-based modeling is integrated into the agricultural sector for the management of risks arising from climate change (Mahlous, 2024). Satellite imagery also plays an important role in shaping agricultural policies. Information such as the distribution of agricultural production areas and crop patterns enable government policies to be regulated in a more data-driven manner (Gan et al., 2023). In this respect, satellite technologies are strategic decision support tools not only for individual manufacturers but also for public institutions.

The use of satellite technologies in agricultural production has become one of the main components of modern agriculture. These technologies, which provide great advantages in terms of efficiency, sustainability, and risk management, are expected to become more widespread (Alex, Sobin, & Ali, 2023; Li, Li, & Zhang, 2024).

1.3.2.2. Agricultural Observation by Drone

Drones are increasingly being used in agriculture in manufacturing processes thanks to their ability to collect fast, local, and high-resolution data. These tools, which are more accessible in terms of cost, especially for small and medium-sized enterprises, make it possible to quickly identify situations that require early intervention (Cheng et al., 2023; Maddikunta et al., 2021). Thanks to the observations made with drones, irregularities in

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plant growth, symptoms and harmful effects due to water stress can be detected with high accuracy.

Equipped with multispectral and hyperspectral cameras, drones provide multi-layered data on soil and plant health. Through these technologies, farmers are able to develop informed intervention strategies by identifying not only visible but also invisible problems (Bhuyan, Beg, Farooq, & Haq, 2024; Li et al., 2022). Thus, applications such as spraying, irrigation and fertilization can be done more efficiently and in a targeted manner. When drone systems are integrated with artificial intelligence, operations such as automatic analysis of images and mapping of risky areas take place much faster (Fizza et al., 2022). In this way, human error is minimized, while production decisions are based on objective data. In addition, early warning systems are established in the fight against diseases and pests by regular observation with drones, and yield losses are prevented (Yu et al., 2024).

Drone technologies are also actively used in direct applications such as seeding, spraying and harvesting. This offers a great advantage, especially in areas where there is a shortage of labor (Papazoglou et al., 2025). In addition, it contributes to more efficient use of production areas by facilitating access in difficult terrain conditions (Miles et al., 2020). Overall, the use of drones in agricultural production offers significant opportunities in terms of efficiency, environmental sustainability, and resource optimization. With the proliferation of these technologies, the effects of digital agriculture are becoming more visible, giving producers a competitive advantage (Amirinezhadfard, Niazi Tabar, Bashir, & Yang, 2025; Ullo & Sinha, 2021).

1.3.3. Artificial Intelligence Applications

Artificial intelligence (AI), one of the most remarkable components of smart agriculture, plays a critical role in automating agricultural processes, analyzing large data sets, and making the right decisions. Thanks to AI-based systems, farmers can increase their productivity by making use of algorithms that learn from historical data and make predictions for the future with this data (Amirinezhadfard et al., 2025). In particular, analyses on variable weather conditions, soil structure and plant health data support strategic decisions. In addition, artificial intelligence evaluates data from sensors, drones and satellite systems in a holistic manner, allowing agricultural activities to be planned more intelligently. In this way, the use of agricultural inputs is minimized, while

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sustainable production targets can be achieved more easily (Papazoglou et al., 2025). At the same time, thanks to artificial intelligence algorithms, early warning systems for diseases, pests and plant stress are being developed.

A key advantage of AI-powered applications is that they can provide more reliable and consistent outputs by minimizing human error (Chen, Zhang, Chen, & Zhong, 2021). This situation allows the acceleration of managerial processes, time and cost savings, especially in large-scale enterprises. In addition, AI goes beyond traditional methods of analysis through deep learning models that can detect complex relationships. With the widespread use of artificial intelligence in agriculture, intelligent decision support systems are becoming increasingly sophisticated. These systems can advise farmers on many issues, from planting time to irrigation timing, from spraying strategies to harvest schedule (Lu et al., 2024). Thus, decisions become both more scientific and personalized for the farmer. Today, it is seen that public and private sector investments have increased for the more effective use of artificial intelligence in the field of agriculture. The developed artificial intelligence platforms can also manage real-time data flows by working in integration with cloud systems (Mowla et al., 2023). All these developments make it clear that artificial intelligence has become an essential component in the digital transformation of agriculture.

1.3.3.1. Agricultural Data Analytics and Forecasting Models

Since the agricultural production process is under the influence of many variables, artificial intelligence-supported data analytics and forecasting models are being developed in order to make these processes more predictable. These models can create scenarios for the future using various data sources such as climate data, soil parameters, crop yield, and environmental impacts (Gan et al., 2023). Thus, farmers have the opportunity to make their production plans more consciously. Thanks to data analytics, the long-term course of soil fertility can be monitored and appropriate planting patterns can be determined. In addition, these systems make significant contributions to sustainability by providing detailed analysis on when and how much inputs should be used. Optimizing input costs also has a direct impact on the economic well-being of farmers (Bhuyan, Beg, Farooq, & Haq, 2024).

Forecasting models play an effective role in managing climate-related risks such as drought and excessive rainfall. Given the negative effects of climate change on agricultural production, the development of such models is of great importance (Wang et al., 2022).

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Techniques such as artificial neural networks and support vector machines are among the models with a high capacity to learn from data. In addition, AI-powered forecasting models enable more efficient execution of workforce and equipment planning by accurately determining the harvest date (Marković et al., 2024). Especially in production activities carried out on large lands, such systems offer serious operational advantages. At the same time, product supply can be provided with timing in accordance with market needs.

The success of applications in this field depends on accurate data collection and quality processing of this data. For this reason, issues such as data security, ethical rules and algorithmic transparency are also raised. The future of AI in agricultural data analytics is shaped not only by technological but also by governance approaches (Roman et al., 2025).

1.3.3.2. Disease and Pest Identification Systems

Plant diseases and pests are among the main threats to agricultural production worldwide. AI-based disease and pest identification systems significantly reduce crop losses by enabling early intervention in these problems (Cheng et al., 2023). Thanks to image processing and deep learning methods, abnormalities on leaves, stems and fruits can be detected with high accuracy. The algorithms used in these systems are trained on thousands of visual data and can classify disease types. For example, models are being developed that can distinguish whether the cause of spotting on a tomato leaf is a fungus, bacteria or pests. As this classification accuracy increases, spraying strategies become more targeted (Fizza et al., 2022).

Early detection not only preserves crop yields; it also supports environmental sustainability by reducing the use of pesticides (Miles et al., 2020). Preventing unnecessary chemical interventions prevents pollution of soil and water resources and protects biodiversity. The use of artificial intelligence in this field also coincides with environmentally sensitive agricultural policies. Thanks to mobile applications and cloud-based platforms, farmers can access instant information about diseases and pests. Some systems can diagnose and make recommendations by analyzing the plant through photos taken with a mobile phone. These advances ensure technological equity, especially for small and medium-sized producers (Alex, Sobin, & Ali, 2023).

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It is expected that these systems will become even smarter in the future. Thanks to the models that work integrated with location data, regional disease spread maps can be created and these maps can be integrated into early warning systems. In this way, proactive struggle mechanisms can be developed not only at the individual level but also at the community level (Luo, 2025).

1.3.4. Robot Technologies

1.3.4.1. Autonomous Tractors and Agricultural Machinery

Autonomous tractors and agricultural machinery represent a revolutionary development within smart agricultural technologies. These machines are integrated with GPS, sensors, artificial intelligence, and image processing technologies to perform agricultural operations without the need for human intervention (Bhuyan, Beg, Farooq, & Haq, 2024). Especially in large-scale agricultural enterprises, it reduces labor costs and increases the sensitivity of agricultural activities. The applicability of these technologies is especially evident in repetitive tasks such as tillage, fertilization and spraying. Autonomous machines are able to adapt to different types of terrain and adjust themselves depending on weather conditions (Li, Li, & Zhang, 2024). Thus, while efficiency in production processes increases, losses caused by human error are minimized.

Research shows that autonomous tractors perform more precise navigation across the field surface, especially when equipped with advanced sensors (Amarasingam, Musthafa, Mohamed Najim, & Baig, 2024). This contributes to the reduction of fuel consumption and the minimization of environmental impacts. In addition, these tools provide integrated data flow to agricultural management software with their data collection function. However, the widespread use of these technologies brings with it some challenges such as infrastructure requirements and high cost. Especially in developing countries, farmers' access to these systems may be limited (Marković et al., 2024). In addition, the need for technical knowledge for the maintenance and software updates of these machines affects the utilization rate. However, in line with sustainable agriculture goals, the role of autonomous systems continues to increase. Going forward, it is expected that these technologies will be adopted on a global scale, with the development of more cost-effective and user-friendly solutions (Roman et al., 2025).

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1.3.4.1. Planting, Irrigation and Harvesting Robots

Planting, irrigation, and harvesting processes are the most basic and labor-intensive stages of agriculture. Therefore, the robot technologies used in these processes directly affect production efficiency (Chen et al., 2021). Sowing processes carried out with robotic systems encourage homogeneous growth by ensuring that the seeds are placed in a certain order and depth.

Irrigation robots, on the other hand, analyze soil moisture in real time, making it possible to deliver water only to the areas where it is needed. This is critical for the sustainable use of water resources (Miles et al., 2020). At the same time, it stands out as an application that supports plant health. Harvesting robots, on the other hand, offer an alternative to manpower, especially in the collection of sensitive products such as fruits and vegetables. Thanks to image processing and artificial intelligence technologies, it determines the maturity level and collects only products suitable for harvest, thus raising the quality standard. In addition, these robots have the ability to work day and night (Fizza et al., 2022).

One of the most important benefits of using these robots in agriculture is that they offer a solution to the labor shortage. The decline in seasonal workers and the decline in interest in agricultural labor increase the importance of such automation systems (Ullo & Sinha, 2021). Especially in countries with aging rural populations, these robots play a strategic role in terms of continuity of production. However, research is ongoing to increase the sensitivity of harvesting robots in the fruit recognition and picking process. With the development of artificial intelligence algorithms, the accuracy rate of these systems is increasing and they are finding wider use in agriculture (Tang et al., 2025).

1.3.5. Image Processing Technologies

1.3.5.1. Plant Development and Disease Monitoring

Image processing technologies are among the innovative methods frequently used in agriculture to monitor plant growth and health status. These technologies enable the analysis of plant leaves, stems, and general field status through high-resolution cameras, drones, and satellite systems (Lu et al., 2024). Thus, it is possible to detect the disease in the early period. Early diagnosis of plant diseases reduces the need for chemical spraying and contributes to the natural production process. Image processing systems can provide information about the type of disease by analyzing symptoms such as color changes in

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leaves, drying, and fungal formation (Karam et al., 2024). These systems offer higher accuracy when supported by artificial intelligence-supported algorithms.

Monitoring plant development stages is also beneficial in terms of optimizing the timing of interventions such as fertilization and irrigation. This both reduces costs and increases agricultural productivity (Luo, 2025). In addition, thanks to remote monitoring, it eliminates the need for manual control on large plots of land. Image processing technologies can also present visual analysis results to farmers through mobile applications or desktop software, thus facilitating decision support processes (Papazoglou et al., 2025). The integration of these technologies with cloud systems provides time- and location-independent monitoring. Still, the effectiveness of these technologies depends on the quality of the equipment used, the image resolution, and the power of the analysis software. Therefore, the level of access to technology and user training directly affect the success of the application (Gan et al., 2023).

1.3.5.2. Yield Mapping and Digital Field Analysis

Yield mapping is an important technology that visualizes the spatial distribution of crop productivity across the field and guides future production planning. This is done using data analysis tools combined with drone and satellite-assisted imaging, providing farmers with detailed information about the field (Botero-Valencia, Mejia-Herrera, & Pearce, 2022). Digital field analysis helps to predict which types of plants will grow more efficiently in which regions by analyzing parameters such as soil organic matter status, moisture content, pH level. These analyses are important in terms of reducing the use of inputs in agriculture and increasing sustainability (Alex, Sobin, & Ali, 2023).

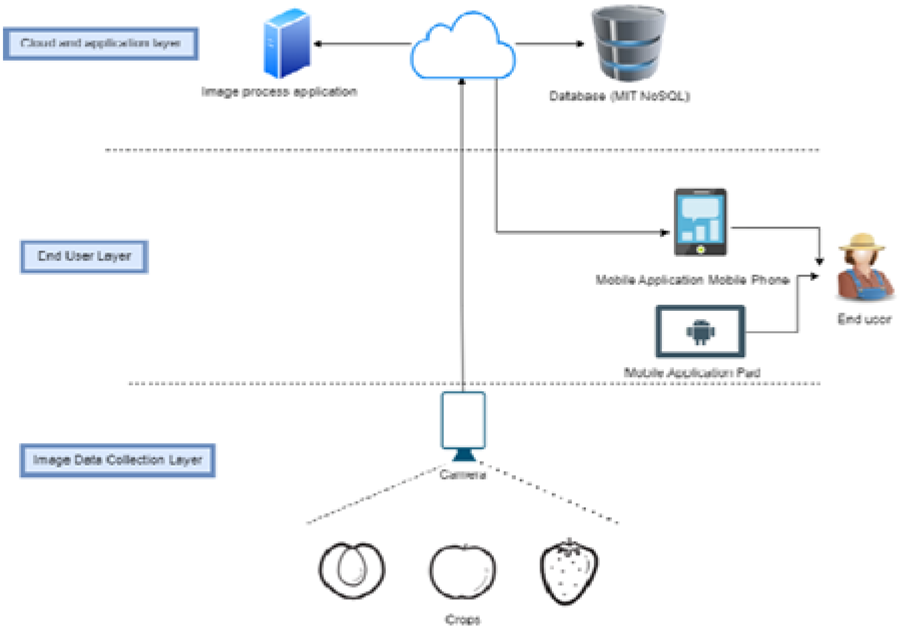

Figure 2. Smart Agriculture Application With Image Processing (Ömerciklioğlu, 2023)

Yield maps also make it possible to perform variability analysis by comparing them with data from previous years. In this way, farmers can develop targeted interventions to improve low-yield areas (Wang et al., 2022). At the same time, regional fertilization and irrigation strategies can be applied according to in-field variability. Thanks to AI-powered analytics, imaging data can be processed faster and automatic reports can be generated. This saves time and labor for farmers by digitizing agricultural management (Rehman et al., 2021). Especially for large-scale agricultural enterprises, these applications are becoming an indispensable part of decision support systems. However, the installation and sustainable operation of these systems may require high investment costs. For this reason, it is recommended to facilitate farmers' access to these systems through publicly funded projects, cooperative models, or technology-based government incentives (Chen, Zhang, Chen, & Zhong, 2021).

1.3.6. Field Crops and Smart Applications

Smart agricultural technologies are widely used to increase efficiency in field crop production, ensure environmental sustainability and reduce production costs. The most striking applications among these technologies are; soil moisture sensors, variable rate fertilization systems and data analytics based on remote sensing. In particular, sensor-assisted irrigation systems both save water and optimize plant growth. (Chen et al., 2021).

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AI-powered decision support systems make the production process more predictable by providing suggestions on when farmers should plant, irrigate, or spray (Rehman et al., 2021). At the same time, these systems can be used in future production planning by analyzing historical data. This situation provides stability in agricultural production for both the producer and the consumer. Satellite imaging systems and drone technologies create productivity maps by making detailed analysis of the field surface and support regional management approaches (Gan et al., 2023). In this way, different interventions can be made in different areas of the same field, and resource use is optimized. These techniques produce very effective results, especially in large-scale agricultural areas.

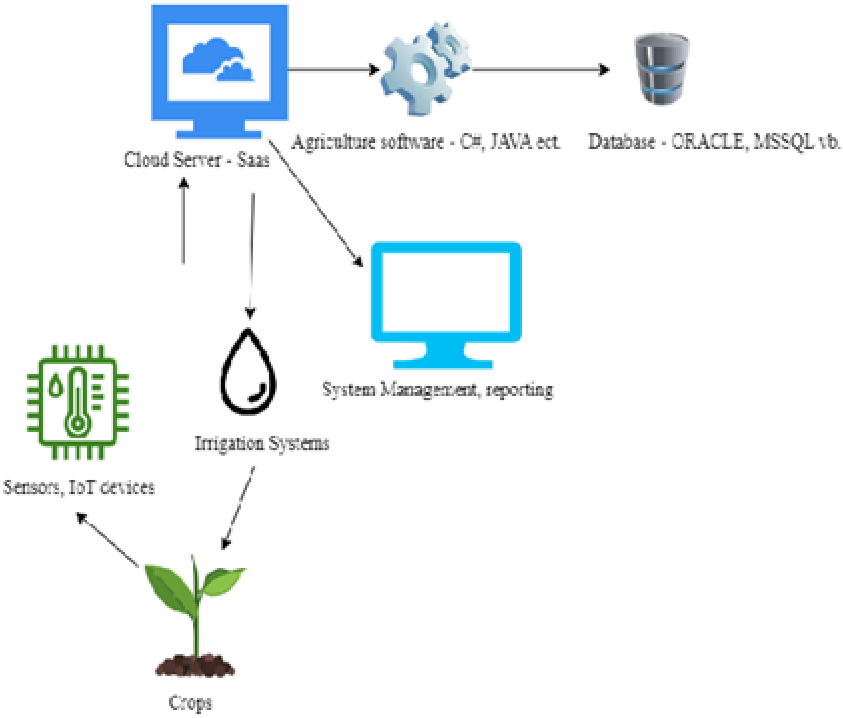

Figure 3. Crop irrigation system with IoT (Ömerciklioğlu, 2023)

For example, the "Precision Wheat Farming System" implemented in India and integrated with artificial intelligence has increased yield by 20% in wheat fields and reduced water consumption by 30% (Amarasingam et al., 2024). Similarly, in a system piloted in China, fertilizer consumption was reduced by 25% and product quality was significantly increased with drone-assisted fertilization (Lu et al., 2024). In order to disseminate such practices, it is important to increase the level of digital literacy,

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strengthen extension activities for farmers and facilitate access to technologies. In addition, issues such as data security, system integration, and infrastructure deficiencies should also be on the agenda of policymakers (Botero-Valencia et al., 2022).

1.3.6.1. Digitalization in Horticulture and Greenhouse

Horticulture and greenhouse cultivation are among the agricultural production areas that benefit the most from smart agricultural technologies. Especially in greenhouses with controlled environment farming, it is possible to automatically manage temperature, humidity, light and carbon dioxide levels (Cheng et al., 2023). These environmental controls optimise plant growth, allowing for continuous production throughout the year. Disease and pest detection systems supported by image processing technologies prevent product loss by providing early warning. These systems can quickly identify individuals with signs of disease by analyzing the leaf colors, shape changes, or surface deterioration of plants (Fizza et al., 2022). Thus, the use of pesticides is reduced and healthier products are obtained.

Smart irrigation systems can be programmed to respond to variable humidity needs according to the plant type in greenhouses. Thanks to the soil and environmental sensors used in these systems, it is ensured that water is given only in the required amount and waste is prevented (Miles et al., 2020). It is critical to disseminate these systems, especially in regions where water resources are limited. The "Smart Greenhouse" projects implemented in Europe aim to increase product quality and reduce the need for labor with artificial intelligence supported systems. In an application in the Netherlands, the entire production process was automated with artificial intelligence, increasing the amount of product taken from the unit area by 40% (Papazoglou et al., 2025). This achievement clearly demonstrates the potential that digitalization can create in horticulture. However, the spread of these technologies may be limited, especially for small-scale businesses, due to high investment costs. At this point, technological transformation should be supported with structures such as government-supported incentive programs, low-interest loans, and joint producer cooperatives (Alex, Sobin, & Ali, 2023).

1.3.7. Smart Systems in Animal Husbandry

Smart systems in animal husbandry increase efficiency in production and improve animal welfare by monitoring the health, nutrition and behavior of animals. Sensor-assisted collars can continuously monitor the location, mobility, and body temperature of animals

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and provide an alert when there is an abnormal situation (Ullo & Sinha, 2021). Thanks to these systems, early diagnosis of infectious diseases becomes possible.

Artificial intelligence and IoT (internet of things) based systems are used to optimize feed consumption and milk yield. Algorithms developed based on historical data of animals are able to create nutrition plans based on individual needs and reduce feed waste (Kumari & Praveen, 2024). While this reduces production costs, it also provides a sustainable animal husbandry practice. In addition, with farm management software, information such as the date of birth, vaccination schedule, and production performance of animals are transferred to the digital environment and management processes are facilitated by creating reports from these data (Wang et al., 2022). These software also contribute to the timely and effective execution of veterinary services.

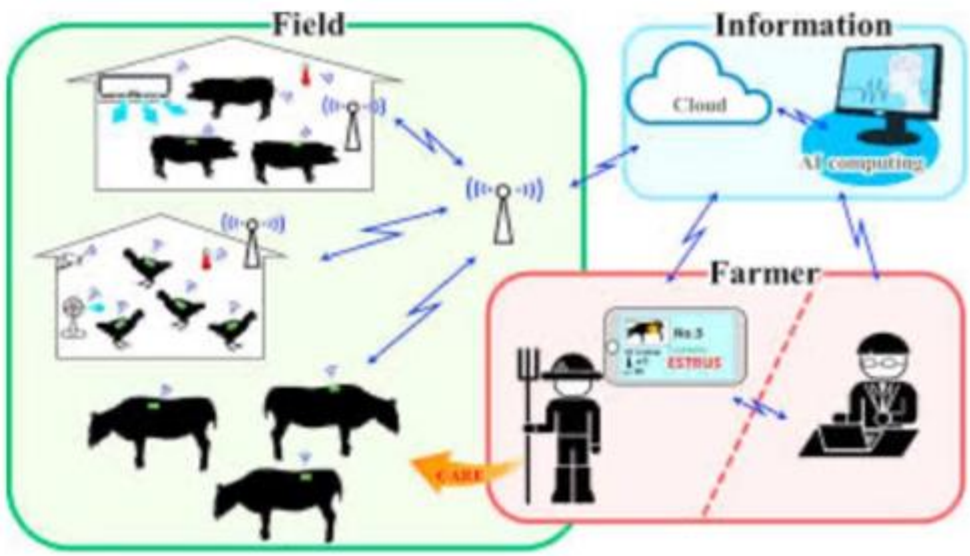

Figure 4. IoT for livestock management (Agritechdigest, 2025).

Within the scope of the "Smart Dairy Farming" project implemented in Canada, a system was established in which all animals were tracked with RFID chips, resulting in an 18% increase in milk yield (Marković et al., 2024). In addition, there has been a significant decrease in disease rates, with the annual cost per animal reduced by 12%. The success of smart technologies in animal husbandry depends on the success of big data analytics, the sophistication of biosensors, and on-farm integration. Therefore, it is of great importance that the systems are user-friendly, training programs for farmers are disseminated, and technical support services are accessible (Amirinezhadfard et al., 2025).

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2. Opportunities and Challenges of Smart Agriculture

Smart agricultural technologies increase efficiency in agricultural production and reduce environmental impacts. Thanks to precision agriculture practices, the use of fertilizers and pesticides is carried out only in the necessary areas, thus reducing the risk of chemical use harming nature (Lu et al., 2024). This stands out as an important advantage, especially in preventing the pollution of groundwater resources.

From an economic point of view, the decrease in production costs and the increase in product quality provide a significant increase in the income level of farmers. For example, sensor-assisted irrigation systems contribute to more efficient use of water, which both reduces water costs and provides sustainability benefits (Alex, Sobin, & Ali, 2023). The increase in yield achieved with these technologies makes it possible for agricultural products to be more competitive in the market. With decision support systems and artificial intelligence applications, manufacturers can make more informed decisions in line with climatic conditions and market data. These systems allow production processes to be optimized, saving time, labor, and resources (Chen et al., 2021). Thus, it becomes possible to achieve technological competitiveness even for small and medium-sized farmers.

In terms of environmental sustainability, reducing carbon emissions is also one of the important contributions of smart agricultural technologies. In particular, electric agricultural robots and drones are helping to reduce the carbon footprint by replacing machines that consume diesel fuel (Roman et al., 2025). At the same time, less compaction and efficient use of soil supports the protection of the ecosystem. Smart agricultural technologies offer multifaceted benefits in terms of protecting environmental resources, increasing economic productivity and supporting sustainable agricultural policies. The expansion of these benefits both accelerates agricultural development and reduces the pressure on natural resources (Bhuyan et al., 2024).

One of the main problems encountered in the dissemination of smart agricultural technologies is the inadequacy of farmers' digital literacy levels. The lack of knowledge about using technology, especially among farmers in rural areas, limits the effective use of smart systems. This situation prevents the full exploitation of the potential of the technology (Amirinezhadfard et al., 2025).

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A basic level of technology knowledge and data literacy is required to be able to use digital agriculture applications. However, many farmers struggle to interpret sensor data, use mobile apps, or understand cloud-based agriculture management systems (Kumari & Praveen, 2024). This deficiency creates an inequality in the digitalization process of agriculture. In this context, the restructuring of training and extension services is of great importance. Providing agricultural consultancy services through digital platforms and preparing visual educational materials in local languages will make it easier for farmers to adopt technology. Such practices are also an effective way to deal with technological resistance (Fizza et al., 2022).

In addition, technology training programs should be organized at the local level through collaborations between public institutions and the private sector. Farmers' skills can be increased through hands-on training through agricultural cooperatives (Mowla et al., 2023). In this way, a transformation can take place at the level of both individual and collective consciousness. Without investment in digital literacy and education, even the most advanced smart agriculture systems will not have the expected impact. Access to technology, as well as the capacity to use it, is at the heart of sustainable agriculture transformation (Miles et al., 2020).

One of the biggest obstacles to the adoption of smart agricultural technologies is the inadequate technological infrastructure in rural areas. Internet access, electrical infrastructure, and data transmission capacities are among the key factors that hinder the smooth operation of smart devices (Papazoglou et al., 2025). This slows down the digital transformation process. Installation and maintenance of high-tech systems requires high costs. Especially for small-scale producers, equipment such as sensor systems, drones, and automatic irrigation systems pose a serious financial burden (Mandrone et al., 2021). For this reason, state-supported incentive and subsidy policies are of great importance.

In addition, costs can be reduced by supporting the domestic production of technological products. In developing countries, smart agricultural devices imported are becoming difficult to access due to the high exchange rate difference. Economic products developed with domestic engineering solutions can offer a permanent solution to this problem (Karam et al., 2024). In addition, infrastructure investments should not only be physical, but also software-based. Software solutions such as data storage, analysis, and cloud services play a central role in the digitalization of agricultural production (Chen,

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Zhang, Chen, & Zhong, 2021). For this reason, a holistic planning should be adopted in digital infrastructure investments. In order for smart agricultural technologies to be implemented sustainably, both physical and economic infrastructure must be strengthened. Technology benefits not only when it is accessible, but also when it can be used sustainably (Botero-Valencia, Mejia-Herrera, & Pearce, 2022).

With the spread of smart agricultural systems, large amounts of data are collected and processed. This data includes sensitive information such as soil analysis, weather data, and product development records. This brings data security and privacy issues to the fore (Cheng et al., 2023).

Obtaining or unauthorized use of farmers' data by malicious people may cause production strategies to be exposed and competitiveness to be damaged. These risks are especially increased in the use of cloud-based systems (Gan et al., 2023). In this context, it is important to use strong encryption systems and security protocols. Data security should be ensured not only by technological measures, but also by legal and ethical regulations. The establishment of data protection policies specific to the agricultural sector will ensure that farmers' rights are guaranteed (Tang et al., 2025). In addition, it should be clearly defined who owns the data and who can use the data. This problem also directly affects farmers' trust in technology. Mistrust can make it difficult to adopt technological innovations. Therefore, transparent data management principles should be adopted, and users should be informed about the process (Luo, 2025).

3. Conclusion and Evaluation

Smart agricultural technologies are leading to radical changes in the agricultural sector by transforming traditional production methods. Technologies such as sensors, remote sensing, robotic systems, and data analytics enable production processes to become more precise, efficient, and sustainable (Gan et al., 2023). This transformation brings not only an increase in efficiency, but also a more efficient use of resources. With technological integration, agricultural activities are carried out in a more planned and controlled manner. Thus, critical applications such as irrigation, fertilization and spraying are carried out at the required time and amount, reducing resource waste and environmental damage caused by unnecessary interventions (Karam et al., 2024). These systems minimize errors by contributing to farmers' decision-making processes with data support. The spread of digitalization accelerates the flow of agricultural information and facilitates farmers' access to new information. Thanks to mobile applications and cloud-based management systems, producers can instantly monitor changes in their fields and take quick action (Marković et al., 2024). This supports the sustainability of production even in times of crisis. The transformative effect of smart agriculture is not limited to the production dimension, but also includes the optimization of supply chains. Quality tracking, logistics planning, and marketing processes of products are supported by digital data, thus minimizing waste (Feng, 2022). In this context, the agricultural sector is gaining a more competitive and flexible structure.

While sustainable agriculture aims to protect natural resources and transfer them to the future, food security means that everyone has access to sufficient, safe and nutritious food. Smart agricultural practices bridge these two main goals, both increasing production capacity and reducing environmental impacts (Li et al., 2022). The data-driven approaches offered by technology ensure that agricultural activities remain within environmental limits. For example, practices such as effective use of soil and water resources and reducing the use of pesticides prevent environmental pollution and maintain ecosystem balance (Chen et al., 2021). This is one of the cornerstones of sustainable agriculture in the long term. In addition, in the face of global challenges such as climate change and increasing population, smart agricultural technologies play a critical role in ensuring the continuity of food production (Tang et al., 2025). Forecasting models and early warning systems contribute to minimizing agricultural risks, thus securing food supply.

In terms of food safety, monitoring the quality of products and preventing diseases are also advantages of smart technologies. Precision agriculture practices reduce chemical residues in products and protect consumer health (Bhuyan, Beg, Farooq, & Haq, 2024). Thus, both producers and consumers win, and the agricultural sector contributes positively to public health. Various technical, economic and social challenges are encountered in the dissemination of smart agricultural practices. In order to overcome these difficulties, first of all, infrastructure deficiencies must be eliminated. Concrete steps should be taken, such as increasing internet access in rural areas and improving electricity infrastructure (Papazoglou et al., 2025). Education and awareness-raising efforts are also critical. Disseminating digital literacy and technology use trainings for farmers will support the effective and sustainable use of technology (Luo, 2025). In addition, the practical benefits of the technology should be demonstrated concretely through hands-on training. It is also

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imperative to develop economic support mechanisms. Subsidies, low-interest loans, and public-private partnerships should be encouraged to facilitate small and medium-sized enterprises' access to technology (Kumari & Praveen, 2024). Thus, the return on investments will be accelerated and the adaptation process will be facilitated.

In terms of data security and privacy, legal regulations and technological solutions should be handled together. Transparency in agricultural data management should be ensured, users' rights should be protected, and security standards should be raised (Amirinezhadfard, Niazi Tabar, Bashir, & Yang, 2025). This will increase users' trust in the technology. Finally, university-industry-government collaborations should be strengthened and R&D activities should be supported. The development of indigenous technologies and the acceleration of agricultural innovations will shape the future of sustainable agriculture (Rehman et al., 2021). This multifaceted approach will enable smart agriculture to achieve lasting success.

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