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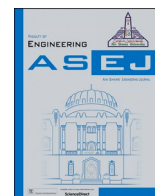
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Applications of internet of things (IoT) and sensors technology to increase food security and agricultural Sustainability: Benefits and challenges

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ABSTRACT

Agriculture must overcome escalating problems in order to feed a growing population while preserving the environment and natural resources. Recently, it has become clear that sensors and the Internet of Things (IoT) are effective tools for boosting agricultural sustainability and food security. This study provides insights into the global market size for smart agriculture in future years from 2021 to 2030. In addition, this research offered four levels of the IoT architecture for smart agriculture: the perception or sensing and actuator layer, the network layer, the cloud layer, and the application layer. The state of the art in IoT and sensor technologies for agriculture is examined in this review paper, along with some of their potential uses, including 1) irrigation monitoring systems, 2) fertilizer administration, 3) crop disease detection, 4) monitoring (yield monitoring, quality monitoring, processing monitoring logistic monitoring), forecasting, and harvesting, 5) climate conditions monitoring, and 6) fire detection. Additionally, this review offers a number of sensors for agriculture that can detect parameters like soil NPK, moisture, nitrate, pH, electrical conductivity, CO₂, temperature, humidity, light, weather station, water level, livestock, plant disease, smoke, flame, flexible wearable. Subsequently, this study highlights the advantages of IoT in smart agriculture, including superior efficiency, expansion, reduced resources, cleaner method, agility, and product quality improvement. However, there are still issues that need to be resolved in order for IoT technology to be used in agriculture where covered in this paper, and also provide insights into future research directions and opportunities. This study will contribute to helping future readers and researchers to better understand the state of academic achievement in this subject.

1. Introduction

1.1. Agriculture - Population, Climate Change, Sustainability, and Globale market size

Agriculture was one of humanity's first endeavors, and it remains a mainstay of our civilization. It has changed greatly throughout time in order to fulfill the needs of an expanding global population, adjust to shifting climatic circumstances, and solve sustainability-related issues. The relationship between agriculture and important variables including population dynamics, climate change, sustainability, and the size of the global market has had a significant impact on the agricultural landscape. The agricultural sector needs to provide enough food to cope with the

world's ever-increasing population. Innovative agricultural technologies, such as advanced technologies and crop management systems, are needed to increase productivity. Due to the high population growth, the globe will need to produce more than 70 % of food by 2050 [1]. Moreover, agriculture is also at the forefront of the fight against climate change. Agricultural yields and livestock are under serious threat from the effects of global warming, manifested in variable weather patterns, high temperatures, and changing levels of precipitation. Farmers are increasingly exposed to the risks of climate change, which requires rigorous strategies to mitigate the effects of climate change in order to maintain agricultural productivity [2,3]. It has become crucial to strike a balance between the need to produce food and the need to safeguard the environment and conserve natural resources. Sustainable agricultural methods are becoming increasingly popular as they promote ecological

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Nomenclature

Acronyms

AI	Artificial intelligence
CAGR	Compound annual growth rate
CO ₂	Carbon dioxide
COVID-19	Coronavirus disease of 2019
IoT	Internet of things
ML	Machine learning
NPK	Nitrogen phosphorus potassium
pH	Parts hydrogen
USD	United states dollar
Wi-Fi	Wireless fidelity

stability and resilience. According to Dhanaraju et al. (2022) [4] sustainable agriculture is a farming technique that tries to satisfy the needs of the present generation without jeopardizing the ability of future generations to satisfy their own needs. It focuses on reducing the negative environmental consequences of agriculture while ensuring that farmers can maintain their livelihoods and provide healthful food. It may boost the economy of nearby towns and farms, support regional food systems, promote rural development, and provide jobs for rural areas [5]. Overall, sustainable agriculture is a vital method of farming that may assist to ensure future generations have access to food and a healthy environment [6–8]. In parallel, the interconnectedness of the agricultural industry worldwide makes international trade in goods and commodities possible. To make wise choices and improve the allocation of resources among farmers and agri-food businesses, we need to understand market size, demand trends, and trade dynamics. Additionally, in the upcoming years, the value of the worldwide smart agriculture market will significantly rise. The rising need for food, the requirement for sustainable farming methods, and the adoption of cutting-edge technology in the agriculture field are all factors contributing to the market's expansion [9,10].

1.2. Application of IoT, Blockchain, Embedded electronics, Robotics, and Automation in smart agriculture

The rapid development of technology in recent years has paved the way for creative solutions in a variety of industries, and agriculture is no exception. Modern farming practices have been changed by the integration of the latest technologies, such as the IoT, robotics, blockchain, embedded electronics, and automation, giving rise to the idea of smart farming. This new paradigm involves the intelligent application of data-driven technology to improve the productivity, efficiency, and sustainability of agricultural methods. Smart agriculture will require the integration of new technologies like the IoT in order to gain a substantial competitive advantage. To meet the demands of the growing population, agricultural output must be raised [11,12]. IoT is improving farming methods by providing connectivity and intelligence through automated irrigation systems and intelligent livestock monitoring. So that the agricultural sector will benefit from important advantages such as improving operational efficiency, reducing cost and waste, and improving crop quality thanks to intelligent agriculture based on the blockchain and IoT [13–15]. The agricultural supply chain is transparent and traceable thanks to blockchain technology. Immutable records boost consumer and stakeholder confidence by confirming the provenance of products and facilitating interactions between farmers and buyers. Smart agriculture also has a connection to the utilization of digital technologies, including embedded electronics, robotics, and automation [16–20]. Embedded electronics are crucial for smart agricultural equipment and gadgets. IoT is reinforced by robotics, which automates operations such as planting and harvesting to increase

production and reduce manual labor. Automation driven by real-time data improves yields and optimizes the use of resources while reducing errors in farming practices. This technology seeks to simplify operations and improve productivity and decision-making. An agricultural control system known as “smart farming” offers a thorough approach to dealing with the geographical and temporal variability of soils and crops in order to enhance product quality, and boost profitability [21,22].

1.3. Application of sensors in smart agriculture and focus of this work

Through the use of real-time data in smart agriculture, made possible by sensor technology, agricultural yields can be increased, costs can be cut, and there is less environmental harm. By acquiring data on a range of environmental factors, including nutrients, soil moisture, temperature, and others, farmers may make decisions about irrigation, fertilization, and pest control [23,24]. Thanks to smart agriculture, farmers can continuously monitor crop growth and environmental conditions, anticipate potential problems, and take quick action in reaction to changes. This approach, which promotes efficient and environmentally friendly farming methods, is essential in light of climate change and other environmental problems. The application of sensor technology in agriculture is anticipated to have a substantial influence on future food production [25]. Every element of conventional agricultural operations has been significantly improved by the integration of cutting-edge sensors and IoT technology. Currently, smart agriculture has the potential to advance agriculture to previously unthinkable levels by seamlessly integrating wireless sensors and the IoT [26–28]. In order to promote sustainable agriculture, this survey article focuses on cutting-edge IoT and sensor applications in smart agriculture. The study also focuses on the IoT architecture for smart agriculture as well as the size of the worldwide market for smart agriculture in the next years.

1.4. Preceding affined review papers

The overview that is being provided here focuses mostly on the use of IoT and sensors in smart agriculture, such as the types of sensors and IoT applications. Table 1 also provides a description and contributions with limitations of the survey studies that have been published in the literature review.

The main IoT-based intelligent devices, communication protocols, sensors, and controllers used in sustainable and smart farming are discussed in the article [29]. Additionally, the paper provided instances of current IoT-based agricultural automation, highlighted the value of data analytics for IoT in agriculture, and highlighted significant difficulties and outstanding topics. An overview of agriculture, including new technology, security concerns, difficulties, and potential advances is given in the source [30]. IoT and data analytics' importance for smart agriculture is also emphasized. A review of the IoT ecosystem in intelligent agriculture is covered in reference [31]. They explore the most popular smart agricultural practices, their advantages, and some of the most popular IoT applications in agriculture in order to emphasize the potential of IoT in agriculture for Pakistan's long-term food security. IoT connectivity technologies for smart agriculture are examined from the scholarly literature in this review [32]. It gathers recent discoveries, analyzes the factors that sensors and communication devices used in IoT-based smart agricultural applications monitor, and investigates the variables that they track. The research also looks at challenges and offers recommendations for IoT use in agriculture. System architecture, significant technologies, and the current state of agricultural IoT are all covered in the survey paper [33]. The usage of agricultural IoT in five specific industries is also highlighted in the research. The essay concludes by analyzing the challenges facing agricultural IoT and providing a forecast for its future growth.

Given that none of the papers previously mentioned or included in the table addressed the size of the market for smart agriculture or the

Table 1
Summarize review papers on IoT and sensors in smart agriculture.

Ref.	Description and contribution	Limitations
[29]	The review examined the major IoT-based intelligent devices, communication protocols, sensors, controllers, and controllers utilized in sustainable and smart farming. The central control unit handled the sizable quantity of agricultural data that these sensors provided in order to fulfill the demand for fertilizer, pesticides, and water. The research also highlighted the value of data analytics for IoT in agriculture, presented instances of current IoT-based agricultural automation, and listed significant obstacles and open issues.	The Global Market Size for smart agriculture is not addressed. IoT architecture for smart agriculture was not covered. There were certain IoT uses for agriculture that was not covered, in particular fire detection, and climate condition monitoring. Various of the sensors agricultural such as nitrate sensor, electrical conductivity sensor, CO2 sensor, livestock sensor, water level sensor, plant disease sensor, smoke sensor, flame sensor, and flexible sensor were not addressed. Key benefits of the IoT in agriculture were not covered.
[30]	The main components of agriculture, new technology, security concerns, difficulties, and potential trends are all topics covered in the review. It seeks to support academics in choosing the appropriate technology and identifying pertinent IoT issues. The significance of IoT and data analytics for smart agriculture is also underlined.	The size of the global market for intelligent agriculture is not discussed. On the other hand, there was no discussion on IoT architecture for smart agriculture. Application of the IoT in agriculture such as fire detection was not addressed. Various of the sensors agricultural such as NPK sensor, nitrate sensor, electrical conductivity senso, light sensor, livestock sensor, water level sensor, plant disease sensor, smoke sensor, flame sensor, and flexible sensor were not addressed.
[31]	The key IoT ecosystem elements were covered in this review. What are the most popular smart agricultural practices, their advantages, and some of the most extensively utilized IoT applications in agriculture? They are attempting to emphasize the possibilities of IoT in agriculture for Pakistan's long-term food security through this review.	The Global Market Size for smart agriculture is not addressed. In addition, IoT architecture for smart agriculture was not covered. Application of the IoT in agriculture such as fire detection was not addressed. As a result, a number of agricultural sensors, including NPK, nitrate, pH, electrical conductivity, CO2, light, livestock, water level, plant disease, smoke, flame, and flexible sensors, were ignored. Important IoT benefits for agriculture were not discussed. Additionally, the primary advantages of IoT in agriculture are not fully discussed. The primary obstacles facing IoT in agriculture are not fully covered.
[32]	In this review, IoT communication technologies for smart agriculture are reviewed from the scientific literature. It compiles current research, examines the variables that sensors and communication tools used in IoT-enabled intelligent agriculture applications monitor, and summarizes recent findings. In addition, the report examines difficulties and provides suggestions for IoT applications in agriculture.	The Global Market Size for smart agriculture is not addressed. IoT architecture for smart agriculture was not covered. Further, a number of agricultural applications based on IoT like as 1) irrigation monitoring systems, 2) fertilizer administration, 3) crop disease detection, 4) yield monitoring, forecasting, and harvesting, 5) climate conditions monitoring, and 6) fire detection was not addressed in detail. Several of the sensors agricultural such as the NPK sensor, nitrate sensor, electrical conductivity sensor, CO2 Sensor, livestock sensor, water level sensor, plant disease sensor, smoke sensor, flame sensor, and flexible sensor were not addressed. The key benefits of IoT in agriculture are not covered.
[33]	In-depth reviews of agricultural IoT research are provided in this study. It covers system architecture,	The Global Market Size for smart agriculture is not addressed. Further, a number of agricultural

Table 1 (continued)

Ref.	Description and contribution	Limitations
	important technologies, and the situation of agricultural IoT today. The report also emphasizes the uses of agricultural IoT in five selected sectors. Finally, the article examines the difficulties facing agricultural IoT and offers a projection for its future growth.	applications based on IoT the like fire detection, and climate conditions monitoring was not addressed. Several of the sensors agricultural such as the NPK, soil moisture, nitrate, soil pH, electrical conductivity, CO2, temperature, humidity, light, weather station, livestock, water level, plant disease, smoke, flame, and flexible were not addressed. Additionally, the main advantages of IoT for agriculture are not discussed. The primary obstacles facing IoT in agriculture are not fully covered.

size of the market for using the IoT in smart agriculture, either now or in the future, this study varies from all of them. Also, they did not accurately and continuously describe the IoT architecture or structure in agriculture. Due to the fact that most of these articles did not cover all of the IoTs applications in smart agriculture, particularly those that deal with soil nutrition, fires, and others. Moreover, not all agricultural sensors were discussed, particularly those used for fire detection, fertilizer, weather, etc. All of this will be highlighted in this article, along with the presentation of roughly six IoT applications for smart agriculture and agricultural sensors.

1.5. Motivation of this work

The motivation of this article is to employ IoT and sensors in smart agriculture to address the issues the agricultural industry faces and to encourage sustainable agricultural practices. Subsequently, the growing global population makes it necessary to produce more food with fewer resources. Using these technologies might increase agricultural yields, cut down on waste, and encourage environmentally friendly farming methods. However, a number of issues must be resolved, including expensive pricing, erratic internet access in rural regions, and insufficient farmer training. With the help of this survey, stakeholders will be better equipped to promote sustainable agricultural practices, suggest areas for future research and development, and get a thorough understanding of the benefits and challenges of these technologies. Fig. 1 depicts the full stretch of the interaction of this paper. Fig. 1 provides a graphical summary of the IoT Architecture for smart agriculture, illuminating the broad breadth of this paper's analysis. The study also looks at the global market size for smart agriculture. The paper explores several IoT applications in smart agriculture with a focus on the following crucial areas: 1) Irrigation Monitoring Systems, 2) Fertilizer Administration, 3) Crop Disease Detection, 4) Monitoring, Forecasting, and Harvesting, 5) Climate Conditions Monitoring, and 6) Fire Detection. The study also looks at sensors in agriculture, the advantages they provide, and the difficulties. Utilizing the capabilities of the Internet of Things, the study offers a comprehensive analysis of the state of smart agriculture currently and future developments.

1.6. The necessity for an Up-to-Date review and main contribution of this survey

The issues facing the agricultural business, such as the demand for more food with fewer resources, climate change, and the promotion of sustainable farming techniques, necessitate an up-to-date review of the application of IoT and sensors in smart agriculture. Due to a number of issues, such as expensive pricing, unreliable internet access in rural regions, and inadequate training for farmers, the adoption of these technologies has been gradual. An examination of IoT and sensors in smart agriculture will give a thorough grasp of their advantages and

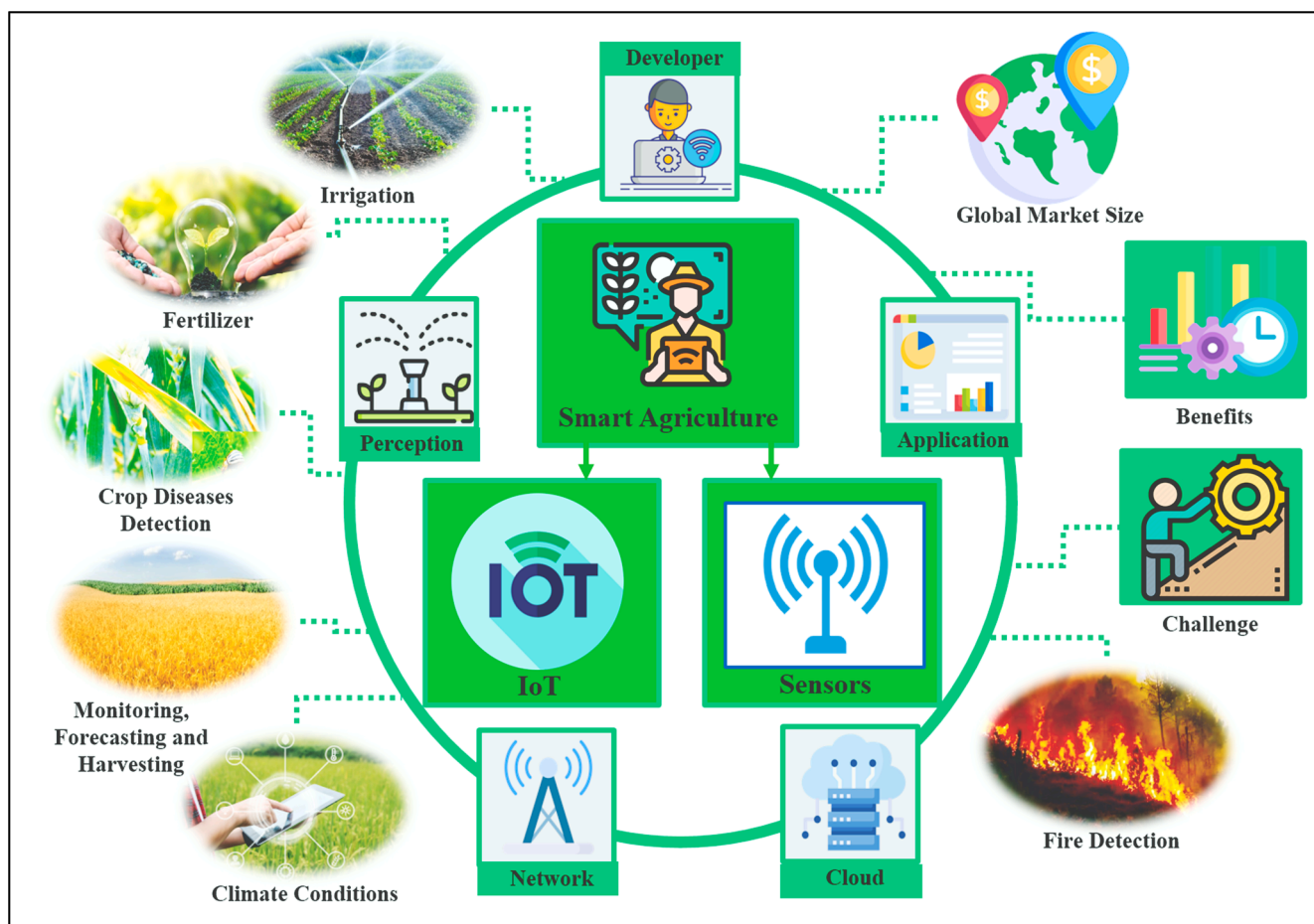


Fig. 1. Graphical abstract of the proposed review¹. ¹IoT is the acronym for the internet of things.

difficulties and point out areas that require more study and improvement. The promotion of sustainable agricultural practices and tackling the issues facing the agriculture business will be guided by this for policymakers, farmers, researchers in this field, and other stakeholders.

This study provides insights into the global market size for smart agriculture in future years from 2021 to 2030. In addition, this research offered four levels of the IoT architecture for smart agriculture: the perception or sensing and actuator layer, the network layer, the cloud layer, and the application layer. The state of the art in IoT and sensor technologies for agriculture is examined in this review paper, along with some of their potential uses, including 1) irrigation monitoring systems, 2) fertilizer administration, 3) crop disease detection, 4) monitoring (yield monitoring, quality monitoring, processing monitoring, logistic monitoring), forecasting, and harvesting, 5) climate conditions monitoring, and 6) fire detection. Additionally, this review offers a number of sensors for agriculture that can detect parameters like soil NPK, moisture, nitrate, pH, electrical conductivity, CO₂, temperature, humidity, light, weather station, water level, livestock, plant disease, smoke, flame, and flexible wearable. Subsequently, this study highlights the advantages of IoT in smart agriculture, including superior efficiency, expansion, reduced resources, cleaner method, agility, and product quality improvement. However, there are still issues that need to be resolved in order for IoT technology to be used in agriculture where covered in this paper, and also provide insights into future research directions and opportunities. This study will contribute to helping future readers and researchers to better understand the state of academic achievement in this subject.

1.7. Brief description of the review methodology

The selection criteria were based on particular traits seen in Fig. 2 that were emphasized. The primary search terms were the size of the global market for smart agriculture, IoT architecture, IoT applications in smart agriculture (such as irrigation system, fertilizer administration, yield monitoring, forecasting, harvesting, climate conditions, and fire detection), sensors, food security, and sustainable agriculture. The search included the years 2016 through 2023, and it only included English-language publications from journals that occasionally issued review papers and result papers. A concerted attempt was made to include all important factors in the search, which was conducted internationally rather than just in one area or region. The publications on themes like “Global Market Size and IoT Architecture for Smart Agriculture,” “Smart Agriculture IoT,” “Smart Agriculture Sensors,” and “Benefits and Challenges of IoT-based Smart Agriculture” served as the second selection criterion.

1.8. Formation and layout of this paper

The remainder of the essay uses a similar format to provide readers with a thorough knowledge of IoT and sensors in smart agriculture. The scale of the worldwide market and an IoT architecture designed exclusively for smart agriculture are outlined in the second section. The third section explores IoT applications in smart agriculture. The presentation of numerous sensors used in smart agriculture is the main topic of the fourth section. The fifth section discusses the benefits and challenges of integrating IoT in agriculture. Finally, the conclusion and perspective are presented in the sixth section.

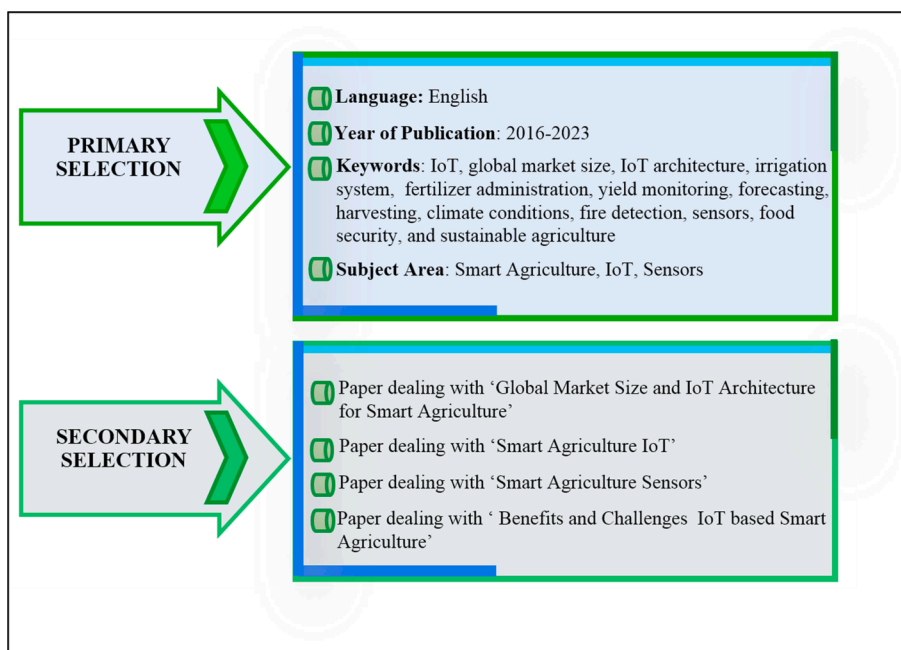


Fig. 2. Paper selection procedure.² IoT is the acronym for the internet of things.

2. Globale market size and IoT architecture for smart agriculture

The use of technology to improve agricultural processes, boost productivity, cut waste, and encourage sustainable methods is referred to as “smart agriculture.” The first half of this section examines the scale of the worldwide market for smart agriculture, while the second part focuses on the IoT architecture for smart agriculture.

2.1. Global market size for smart agriculture

Through the use of smart agriculture, farmers leverage advanced

technologies to enhance agricultural productivity. The integration of state-of-the-art solutions like the IoT, blockchain, machine learning (ML), and artificial intelligence (AI) has significantly boosted the growth of the worldwide smart agriculture market [9,33–35].

The market is expanding as a result of regional government efforts and the tax incentives and investments made available to market participants. The rigorous government rules on food safety and security had a favorable influence on the industry’s development in 2020, despite the minor market impact of the COVID-19 pandemic [36]. According to “Precedence Research”, the smart agriculture market has grown considerably over time. It was worth \$18.12 billion in 2021, then grew

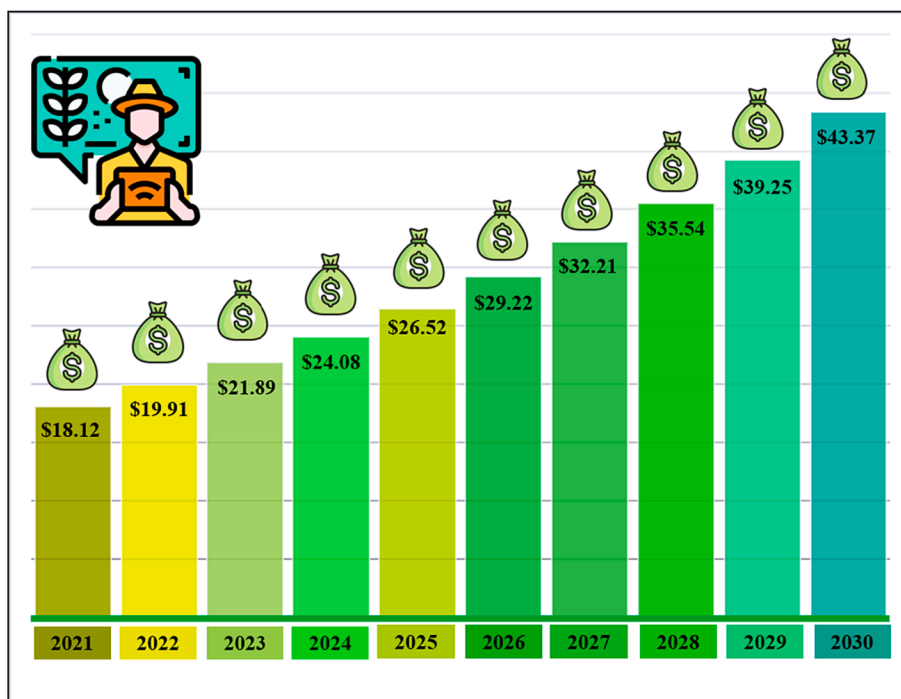


Fig. 3. The size of the global smart agriculture market from 2021 to 2030.

significantly to \$91.91 billion in 2022. However, it fell to \$21.89 billion in 2023 before dropping again to \$8.24 billion in 2024. Despite the setbacks, the market picked up again, reaching \$24.24 billion in 2025 and rising steadily to \$52.26 billion in 2026. It fell slightly in 2027 to \$21.32 billion but rose again in 2028 to \$24.35 billion. The market, valued at \$25.39 billion in 2029, is expected to rise again to \$43.37 billion in 2030, continuing its upward trend. A compound annual growth rate (CAGR) of 10.2 % between 2022 and 2030 should fuel this increase [9]. Fig. 3 illustrates this upward trend, shows the growth in market value over time, and highlights the potential and promising future of the smart farming sector.

The market is expanding because of the rising popularity of technology and the expansion of the telecommunications industry. Farmers may use smartphones to track and monitor agricultural operations and get precise data. Due to these motivating reasons, it is anticipated that demand for smart agriculture would rise throughout the predicted period. According to "Precedence Research", the size of the IoT market in agriculture has grown considerably over time. It was worth \$12.15 billion in 2021, then grew considerably to reach \$13.70 billion in 2022. However, it fell to \$15.02 billion in 2023 before falling back to \$16.46 billion in 2024. Despite the setbacks, the market recovered to reach \$18.05 billion in 2025 and steadily increased to reach \$19.78 billion in 2026. It fell slightly in 2027 to \$21.68 billion, but rose again in 2028 to \$23.77 billion. The market, valued at \$26.05 billion in 2029, is expected to rise to \$28.56 billion in 2030, continuing its upward trend. A compound annual growth rate (CAGR) of 9.62 % between 2022 and 2030 should fuel this increase [37]. Fig. 4, illustrates this upward trend, shows the growth in market value over time, and highlights the potential and promising future for the use of IoT in the smart agriculture sector.

The market for smart agriculture is expanding quickly, propelled by rising food demand. So, the need for sustainable agricultural methods, and technology improvements became necessary. Due to the intense competition in the market, many businesses engage in R&D to produce cutting-edge goods and services in this industry. With the world's population expected to exceed 9.7 billion people by 2050, the smart

agricultural sector is well-positioned to play a significant role in ensuring food security and sustainability in the years to come [38].

2.2. IoT architecture for smart agriculture

The perception, network, cloud, and application layers of an IoT architecture for smart agriculture, as shown in Fig. 5, form the foundation of smart farming. These integrated layers enable seamless user engagement, efficient data collection, secure transmission, reliable storage, and intelligent analysis while improving system performance. Agricultural practices reach new heights with the use of IoT architecture, enabling optimal and sustainable procedures that boost production and resource management.

- 1) Perception or Sensing and Actuator Layer: This layer includes the placement of sensors and actuators in the real environment in order to collect and transmit data to the IoT system. The actuators manage numerous operations, such as irrigation and fertilizer, while the sensors detect many factors, including soil moisture, temperature, humidity, light, soil pH, soil conductivity, NPK (Nitrogen, Phosphorus, Potassium) soil, etc... [39–42,44,45].
- 2) Network Layer: This layer facilitates data transfer between the sensor and actuator layer and the cloud layer. The multiple communication technologies included in this layer, including Wi-Fi, cellular, and others, allow for smooth data transfer across the various IoT system components [42,44,45].
- 3) Cloud Layer: The cloud layer processes and stores data from the sensor and actuator. Cloud systems offer the framework for data processing, storage, and analysis, enabling farmers to make rational decisions based on real-time data. Additionally, cloud platforms provide the dependability and scalability required for large-scale IoT systems [42–45].
- 4) Application Layer: Farmers and other stakeholders can communicate with the IoT system via the user terminal (interface) provided by the application layer. It consists of a number of programs and apps that

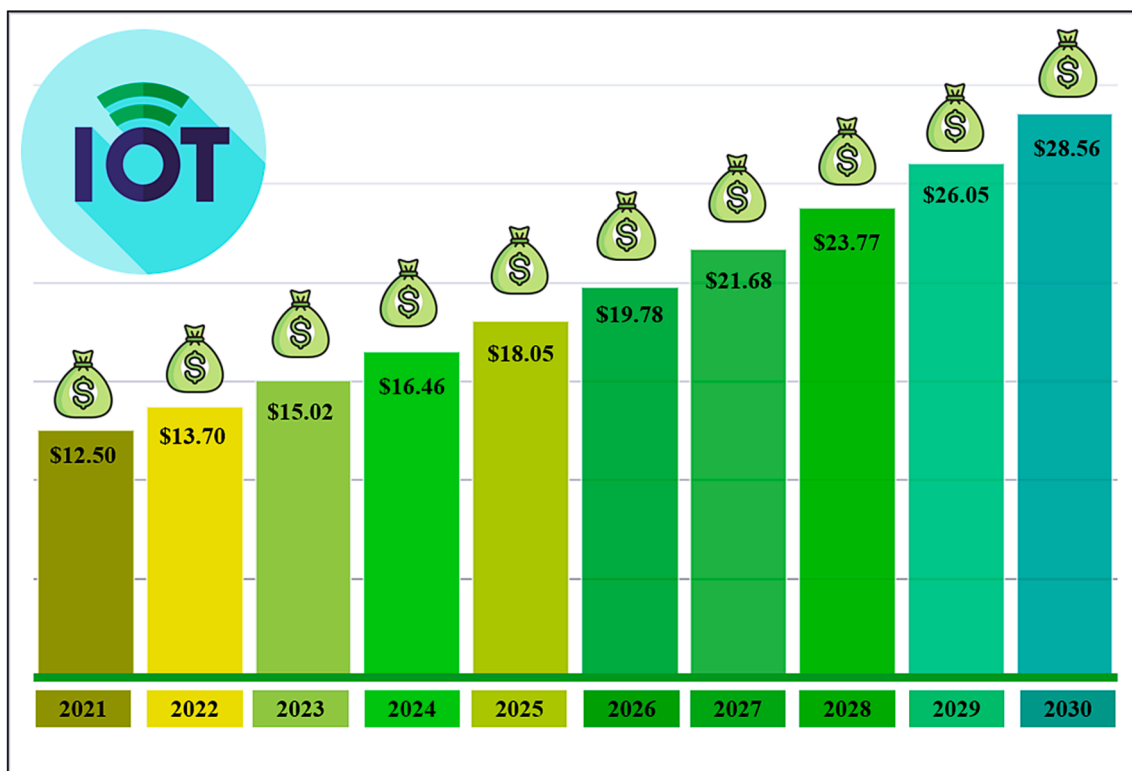


Fig. 4. The IoT in the agriculture market size from 2021 to 2030. ³IoT is the acronym for the internet of things.

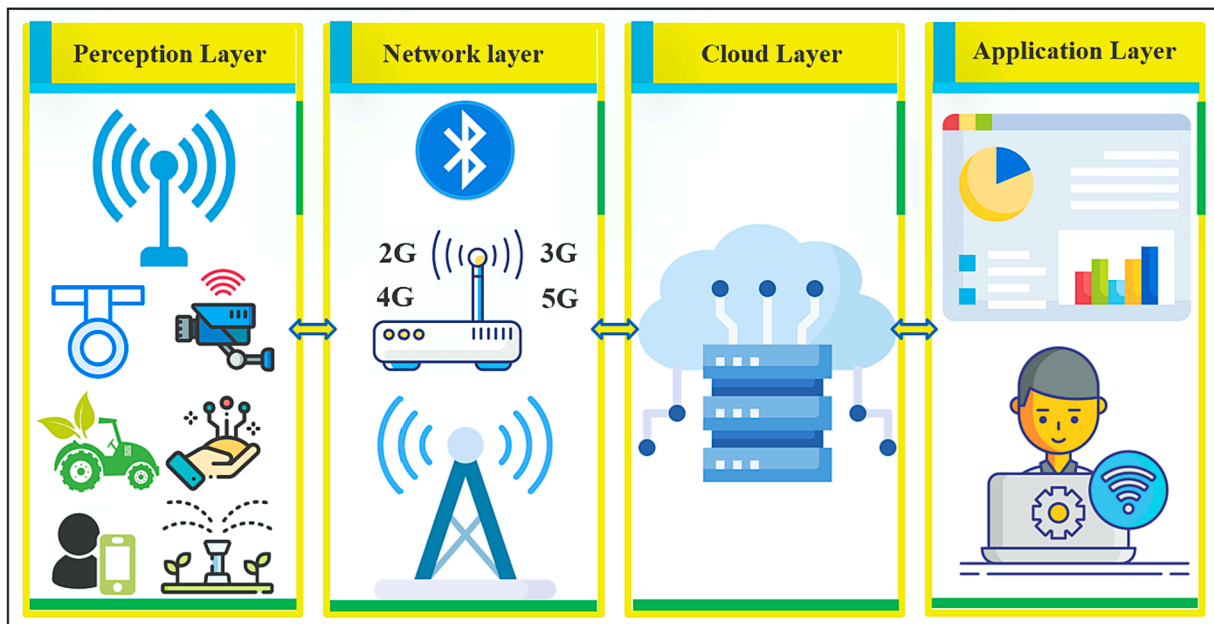


Fig. 5. IoT architecture for smart agriculture.

give farmers information on the state of their farms, empowering them to choose wisely when it comes to crop management, resource allocation, and yield maximization [43–45].

All things considered, the four-layer IoT architecture for smart agriculture offers a reliable and scalable foundation for gathering, processing, and analyzing data to enhance farming operations [46–48]. Farmers may increase efficiency, production, and sustainability by utilizing IoT technology, which will enhance food security and make the agriculture industry more sustainable.

3. IoT application in smart agriculture

The IoT has made smart agriculture, which is the most significant area for innovation in contemporary agriculture, conceivable. The combination of sensors, IoT, and data analytics technologies allows for real-time monitoring and management of farming activities, which helps to maximize resource utilization and increase crop yields. This section examines some of the most important IoT applications in smart agriculture, with a particular emphasis on 1) irrigation monitoring systems, 2) fertilizer administration, 3) crop disease detection, 4) monitoring (yield monitoring, quality monitoring, processing monitoring), forecasting, and harvesting, 5) climate conditions monitoring, and 6) fire detection. IoT technology has the potential to change the farming sector through these applications, fostering more effective, and sustainable agricultural methods.

3.1. Irrigation monitoring system

smart irrigation based on IoT is a cutting-edge technology that automates and improves irrigation systems by harnessing the power of the IoT. This system reduces waste and conserves water resources while ensuring that gardens, lawns, and crops receive the proper quantity of water. Sensors, controls, and cloud-based software are used in smart irrigation systems to gather real-time data on plant water needs, weather, and soil moisture. Using this knowledge, irrigation plans, water flow rates, and other variables are modified to ensure that plants receive enough water when required [45,49–54].

These systems may be used in a variety of contexts, including landscaping for homes and businesses, golf courses, and agriculture.

Reduced water waste, enhanced plant health, higher efficiency, and cheaper costs are all advantages of smart irrigation systems [55,56]. By doing away with manual watering, users of smart irrigation systems may save time and money. They are the best option for anybody looking to install a more ecologically friendly and economical irrigation system since they allow users to preserve water resources while enhancing plant health and production [57–60].

3.2. Fertilizer administration

Administration of fertilizers based in the realm of smart agriculture, IoT is a crucial application that makes use of IoT technology to maximize the usage of fertilizers. With the help of this application, farmers will be able to get up-to-the-minute information on the state of their soil and its nutrient content, which they can use to modify how much and what kind of fertilizer they apply to their crops [61,63,65,67]. Employing a variety of sensors, like the NPK sensors, temperature sensors, soil moisture sensors, and humidity sensors, farmers can determine when and how much fertilizer is required for their crops, resulting in more efficient and effective crop growth and development [62,64]. Increased agricultural yields are one of the main benefits of IoT-enabled fertilizer administration [65]. Farmers may optimize the usage of fertilizers, which can result in better crop growth and development, by employing IoT sensors to monitor soil conditions and nutrient levels [63,66]. For instance, NPK sensors may help farmers determine the right amount of nitrogen, phosphorous, and potassium needed for their crops [62,64,67,69]. These nutrients are crucial for plant growth [62]. Farmers may change the type and amount of fertilizer applied by using real-time data on nutrient levels, which increases crop yields and improves crop quality [62,63,68]. The decrease in fertilizer waste and associated costs is another advantage of IoT-based fertilizer management. IoT-based fertilizer administration can increase fertilizer application accuracy and precision in addition to optimizing fertilizer consumption and cutting waste [61–63,70].

Overall, IoT-based fertilizer administration is a critical smart agricultural application that may support more productive and efficient farming methods. This technology lets farmers to utilize fertilizers more intelligently by giving them real-time data on nutrient levels and soil conditions. Higher agricultural yields, improved crop quality, and less environmental impact are the outcomes of this.

3.3. Crop diseases detection

Controlling crop diseases is an essential part of contemporary agriculture. Illnesses may drastically lower agricultural production, costing farmers money and jeopardizing the world's food supply [71]. The overuse of pesticides and other chemicals can also have negative environmental impacts, such as polluting water supplies and upsetting natural ecosystems [72]. Fortunately, improvements in IoT technology are opening up fresh possibilities to tackle these problems. In the field, IoT and sensors may be used to monitor crop health in real-time and spot early symptoms of disease or insect infestation. These sensors may gather information on a variety of environmental and biological elements, including temperature, humidity, soil moisture, and plant development patterns, that have an impact on crop health [73–77]. The prevention of disease propagation and the reduction of pests' negative effects on crop yields are made possible by the use of sensors and IoT in agricultural disease and pest control [76,78,79]. Additionally, IoT technology supports data-driven decision-making for pest and agricultural disease management [73]. By analyzing data received from sensors and other sources, farmers may learn about the effectiveness of their pest management strategies and make adjustments to their operations. By evaluating the data produced by IoT and sensors using ML and other data analytics technologies, farmers may identify patterns and trends in crop health and choose efficient pest management strategies [73,80].

In terms of intelligent agriculture, the application of IoT and sensors for pest management marks a significant achievement. IoT technology provides more precise and sustainable pest management procedures, minimizing the use of toxic chemicals and fostering a more effective and environmentally friendly agriculture sector by giving farmers real-time data on crop health and insect activity.

3.4. Monitoring, forecasting and harvesting

Yield monitoring, quality monitoring, processing monitoring, logistics monitoring, forecasting and harvesting are crucial aspects of smart farming that are increasingly using IoT technology to their advantage. In the field, IoT and sensors may be used to gather information on a variety of elements that influence agricultural yields, including temperature, humidity, soil moisture, and plant development patterns [61]. In order to estimate future harvests and get real-time insights on agricultural yields, this data may then be evaluated using new technologies [81–84]. Real-time agricultural yield monitoring enables farmers to spot failing farms and make necessary adjustments to increase yields. IoT sensors may also offer information on the efficacy of various farming techniques, enabling farmers to adjust their plans for optimal output. The use of IoT in smart agriculture has the potential to transform the sector and solve pressing problems. IoT may have a significant positive impact in several crucial areas, including quality, processing, and logistical monitoring, predicting, and harvesting. Product compliance is ensured through quality control, while IoT sensors assist improve elements like soil condition. IoT-powered cameras are used for processing monitoring to guarantee constant product quality. Transportation efficiency is improved by using IoT devices like trackers for logistic monitoring. Another area where IoT technology might be quite helpful in crop forecasting [85]. Farmers may employ machine learning algorithms to anticipate future harvests by examining previous data on crop yields and climatic variables. IoT and sensors may be utilized to increase productivity and reduce waste during the harvesting process [81,83,84].

In general, smart agriculture has advanced significantly with the use of IoT technologies for Yield monitoring, quality monitoring, processing monitoring, logistics monitoring, forecasting, and harvesting. IoT technology provides more efficient and effective agricultural methods, leading to better yields, decreased waste, and increased sustainability by giving farmers real-time data on crop yields and anticipated harvests.

3.5. Climate conditions monitoring

Smart farming is greatly impacted by the weather. Due to climate changes, agricultural produce's quality and quantity may be impacted. Alternatively, farmers may place sensors like water level, humidity, and temperature sensors in the sector using the IoT as a way to gather real-time environmental data [86–89]. In contemporary agriculture, it is normal practice to utilize sensors to keep an eye on the health of crops and the environment in which they are growing. These sensors are essential for capturing real-time data, giving farmers insightful information, and assisting them in making decisions regarding their agricultural methods [86]. When a potentially hazardous environmental problem is discovered, it is either automatically fixed or a notice is provided to the farmer advising them to act quickly to avoid agricultural losses [88,90].

3.6. Fire detection

Fire detection is a significant IoT application in smart agriculture. Farmers may employ IoT devices to monitor potential fire dangers in their crops and forests [91,92,97]. These sensors are able to detect changes in flame as well as the presence of smoke and other fire-related indicators [93–96,98–101]. The IoT system may warn the farmer and/or the neighborhood fire department if a fire is found, enabling them to act immediately and stop the fire from spreading. IoT fire detection systems can monitor controlled burns, which are frequently used in agriculture to manage land and encourage new development, in addition to preventing fires from starting in the first place. These fires may be carried out safely and successfully by using IoT sensors to monitor the smoke and other parameters [93,94]. In general, adding fire detection to IoT systems in smart agriculture may aid farmers in safeguarding their land, crops, and animals as well as avoiding harm to neighboring populations and natural resources [92].

4. Sensors for smart agriculture

The way we grow our food might be completely changed by the introduction of the IoT and sensors in the agricultural sector. With the use of these technologies, farmers can gather and evaluate data in real-time on a range of environmental elements that impact crops, including temperature, wind speed, soil moisture, smoke, flame, etc. Farmers can monitor the health of their crops, spot fields that require more attention, and decide when to sow, irrigate, fertilize, and harvest their crops by employing smart agriculture sensors. As a result, there may be more production and efficiency, less waste, and less negative environmental effect.

For instance, farmers may plan when to irrigate their crops using soil moisture monitors, only applying water when it is required. In addition to saving water and money, this can avoid overwatering, which can cause soil erosion and nutrient depletion. Similarly to this, farmers may employ targeted treatments just where they are required by utilizing sensors to track soil quality and nutrient levels. This reduces the need for pesticides and fertilizers while supporting sustainable agricultural methods.

The majority of sensors widely used in smart agriculture are shown in Table. 2 name of sensors in column 1, sensor application type of data collect and description in column 2. Finally type of data collect and description in column 3.

In addition, as the world's population continues to expand, IoT and smart agricultural sensors can assist farmers in meeting the rising food demand. Farmers may boost productivity while decreasing expenses and environmental effects by implementing these technologies. On the other hand, wave-based technologies are rapidly being used in industrial applications and smart sensors, due to their efficiency in analyzing and processing complex signals [109–111]. Together, these studies highlight the variety of applications for wavelet-based signal processing, from

Table 2
Agricultural sensors: Sensor application, type of data collecting and description.

Sensor name	Sensor application	Type of data collect and description
Soil NPK Sensor	Fertilizer Administration.	Determines the concentration of potassium, phosphorus, and nitrogen in the soil to aid in fertilization. Using soil NPK sensors to track changes in soil nutrient levels over time, growers may adjust fertilizer application rates and timing. The application of soil NPK sensors can reduce fertilizer waste, enhance crop productivity and quality, and prevent nutrient runoff into nearby rivers [66].
Soil Moisture Sensor	Irrigation Monitoring Systems, Forecasting and Harvesting.	Measures the amount of water in the soil to determine when and how much to irrigate. These sensors may be positioned at various soil depths to monitor the water availability at varying depths. Soil moisture sensors can aid in crop growth optimization, water conservation, and avoiding overwatering, which can result in nutrient loss and soil erosion [19,102].
Nitrate Sensor	Fertilizer Administration, Crop Disease Detection.	Determines the nitrate content of the soil to aid in fertilizer application. Growers may alter fertilizer application rates and timing by using nitrate sensors to monitor changes in soil nitrogen levels over time. In addition to improving crop output and quality, nitrate sensors can assist minimize nitrogen runoff into surrounding waterways and decrease fertilizer waste [67,104].
Soil pH Sensor	Fertilizer Administration, Crop Disease Detection.	Determines the soil's pH level, which can aid in enhancing plant nutrient absorption. Growers may modify soil amendments and fertilizer application rates by using soil pH sensors to monitor variations in soil acidity over time. The use of soil pH sensors can improve crop production and quality, reduce nutrient deficits and toxicities, and stop soil acidification over time [104].
Electrical Conductivity Sensor	Fertilizer Administration, Quality Monitoring.	Determines the electrical conductivity of water or soil, which may be used to check salt and nutrient levels. Adjusting irrigation procedures and preventing salt accumulation in soils may both be accomplished with electrical conductivity sensors [105].
CO2 Sensor	Quality Monitoring, Processing Monitoring, Climate Conditions Monitoring.	Measures the quantity of carbon dioxide in the air, which may be used to keep track of plant development and respiration. Growing conditions may be improved by adjusting ventilation and lighting systems, which can be done with the use of CO2 sensors, which can track changes in CO2 levels over time. By adjusting ventilation and illumination as necessary, CO2 sensors can assist minimize CO2 buildup, which can result in decreased plant growth and productivity. They can also aid in lowering energy use [98].
Temperature and Humidity Sensor	Irrigation Monitoring Systems, Quality Monitoring, Processing Monitoring, Forecasting and Harvesting, Climate Conditions Monitoring.	Monitors environmental conditions by taking air temperature and humidity measurements. Extreme temperature ranges, high humidity levels, and other environmental variables that may affect plant growth and development may all be found with these sensors. Sensors for temperature and humidity can be placed in a variety of places, such as outside weather stations or within greenhouses. These sensors can aid in improving growth conditions, guarding against pests and disease, and lowering energy expenditures [98].
Sensor name	Sensor application	Type of data collect and description
Light Sensor	Quality Monitoring, Climate Conditions Monitoring.	Measures the amount of light that plants receive, which can aid in maximizing growth and output. These sensors can measure the amount of light in different parts of a greenhouse or field and may be used to modify lighting or shade arrangements to improve growing conditions. By decreasing illumination or shading as necessary, light sensors may assist producers in producing high-quality crops with optimal yield and quality while also reducing energy use [106].
Weather Station	Logistics Monitoring, Forecasting and Harvesting.	Gathers information on the wind's direction and speed, the amount of rain that has fallen, the barometric pressure, and other weather-related data that may be used by farmers to make choices about planting, harvesting, and other agricultural tasks. With the use of these sensors, producers can foresee weather-related hazards and improve crop management techniques by tracking weather trends over time. Weather stations can be set up on a farm or in a particular area and used to track regional weather patterns and microclimates [103].
Water Level Sensor	Irrigation Monitoring Systems, Logistics Monitoring.	The level of water in a tank, pond, or other body of water can be determined with a water level sensor. In order to monitor the water levels in irrigation systems and other bodies of water, water level sensors are frequently employed in agriculture [19].
Livestock Sensor	Logistics Monitoring.	Observes the health and conduct of cattle, which can aid in disease prevention and maximize output. Animal activity, body temperature, and eating habits may all be monitored with livestock sensors, among other parameters. These sensors can aid in improving feeding and breeding procedures, reducing animal stress, and promoting animal welfare [15].
Plant Disease Sensor	Crop Disease Detection	Analyzes plant tissue or soil samples to look for plant diseases. Plant disease sensors can be used to keep an eye out for illness in crops and assist producers in taking steps to stop its spread or potential harm [107].
Smoke Sensor	Fire Detection	The smoke sensor calculates how many smoke particles are present in the air at any one time, which may signal the existence of a fire. The sensor alerts the smart agricultural system when smoke particles are found so that it may take the necessary precautions to stop the fire from spreading [99,100].
Flame Sensor	Fire Detection	Using infrared light emission, the flame sensor locates fires. The sensor can recognize the infrared radiation that a flame releases when it is present. The sensor alerts the smart agricultural system when a flame is found so that it may take the necessary steps to stop the fire from spreading [99,100].
Flexible sensor	Yield Monitoring.	An advanced, flexible, wearable sensor called the plant and food quality monitor was created specifically to track the quality of plants, fruits, and food. Real-time data collection is made possible by its soft and versatile shape, which makes it easy to install easily on the surface of various food items and plants without causing any damage [108].

denoising and analysis in industrial environments to applications for smart sensors and machine learning. Given their versatility and efficiency in processing complex signals, wavelet methods are increasingly used in a variety of fields as useful tools for industrial processes and current sensor technology.

Overall, the application of IoT and smart agriculture sensors in the

agricultural business has the potential to alter the way we grow our food. These technologies can boost production and efficiency, and support sustainable farming methods by letting farmers gather and evaluate real-time data on numerous environmental conditions. This will be essential for supplying the world's growing population with food in the future.

5. The benefits and challenge of IoT in agricultural

5.1. Benefits

IoT application in agriculture, as in other sectors, provides previously unavailable efficiency, resource savings, cost, automation, and data-driven operations. IoT-enabled smart agriculture offers a number of noteworthy benefits, including superior efficiency, expansion, reduced resources, cleaner method, agility, and also product quality improvement. Numerous research papers have looked into the advantages of implementing the IoT in intelligent agriculture [30,60,112,113].

As shown in Fig. 6, the six benefits of the IoT in agriculture, we will discuss each benefit separately following:

- 1) **Superior efficiency:** Today's agriculture is competitive. Farmers must produce more despite unfavorable soil conditions, diminishing land availability, and rising weather whims. Farmers can track their fields and environmental conditions in real-time thanks to IoT-based agriculture. They can generate ideas rapidly, foresee issues before they happen, and determine how to avoid them by employing information. IoT solutions for agriculture are also introducing automation, including irrigation, fertilization, automated harvesting, etc.
- 2) **Expansion:** By the next several years, there will be 9 billion people on the planet, with 70 % of them living in cities. Thanks to systems based on the IoT, especially systems that provide food supply chains, these people can be supplied with vegetables and fruits. It is now feasible to grow food practically everywhere, even on walls and roofs, in shipping containers, and inside everyone's houses, thanks to intelligent closed-cycle farming systems.
- 3) **Reduced resources:** A lot of IoT solutions for agriculture are built to maximize the use of resources like electricity, water, and land. With the help of data gathered from numerous field sensors, IoT-based precision farming helps farmers to accurately distribute the proper quantity of resources.
- 4) **Cleaner method:** Smart agriculture that supports the IoT is an effective way to reduce the use of fertilizers and pesticides. Intelligent farming helps farmers save water, energy, and the environment while drastically reducing the usage of pesticides and fertilizers.

Compared to conventional agricultural methods, this technique enables the production of a cleaner end product to be produced.

- 5) **Agility:** IoT use in agriculture has the benefit of accelerating a number of processes. Farmers can quickly react to significant changes in weather, humidity levels, air quality, fires, and the state of specific crops and soil in the field thanks to real-time monitoring and forecasting systems. With the use of this technology, agricultural personnel may now save crops in the case of extreme weather or fires.
- 6) **Product quality improvement:** The use of sensors and the IoT in agriculture improves and raises agricultural output. Crop sensors, drone-based overhead surveillance, and farm mapping are tools that farmers may use to better understand the intricate relationships between crop quality and the environment. They may duplicate ideal circumstances and improve the nutritional value of their crops by using linked systems..

5.2. Challenges

Over the past few decades, there have been enormous technology improvements that have impacted our everyday lives. By placing resources at our fingertips, we are credited with improving the convenience of our lives. Smart sensors collect real-time data and establish connections with each other or the internet to initiate required actions. IoT has successfully captivated a vast audience due to the numerous ongoing innovations. However, the adoption of IoT technology brings both advantages and challenges. The difficulties of using the IoT in smart agriculture have been covered in several research [29,30,32,114–117].

Despite the IoT's development over the past two decades, significant conceptual, structural, and problems remain. Fig. 7 depicts the most important challenges to implementing the IoT in agriculture, like 1) superior efficiency, 2) cost and standardization, 3) heterogeneity and accessibility, 4) adaptability and energy optimization, 5) compatibility and reliability, 6) mobility and environmental conditions. Here are the most pressing immediate problems of the IoTs:

- 1) **Superior efficiency:** Agriculture is nowadays a race. Despite poor soil conditions, dwindling availability of land, and increased

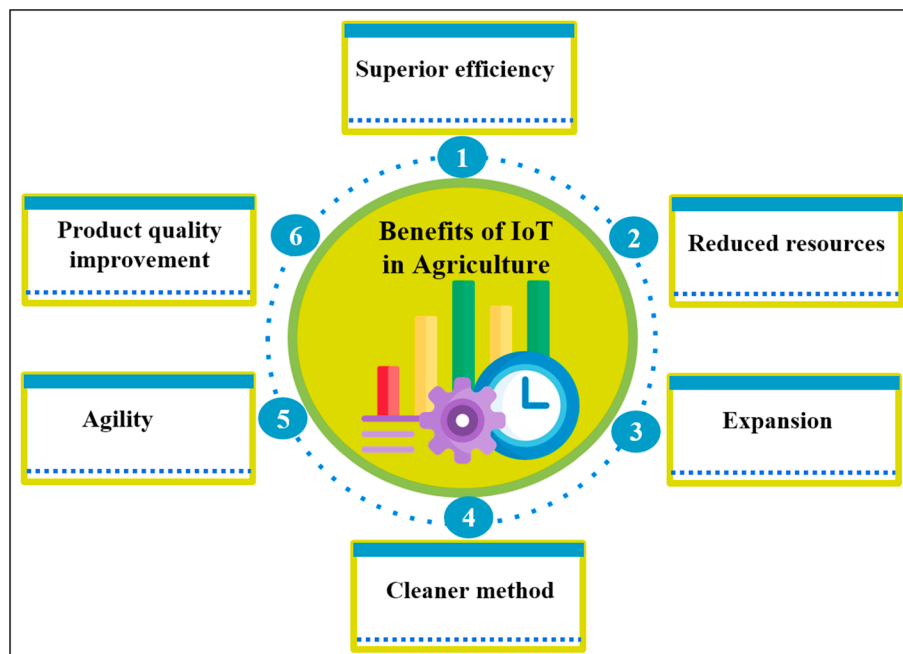


Fig. 6. The benefits of IoT in agriculture.

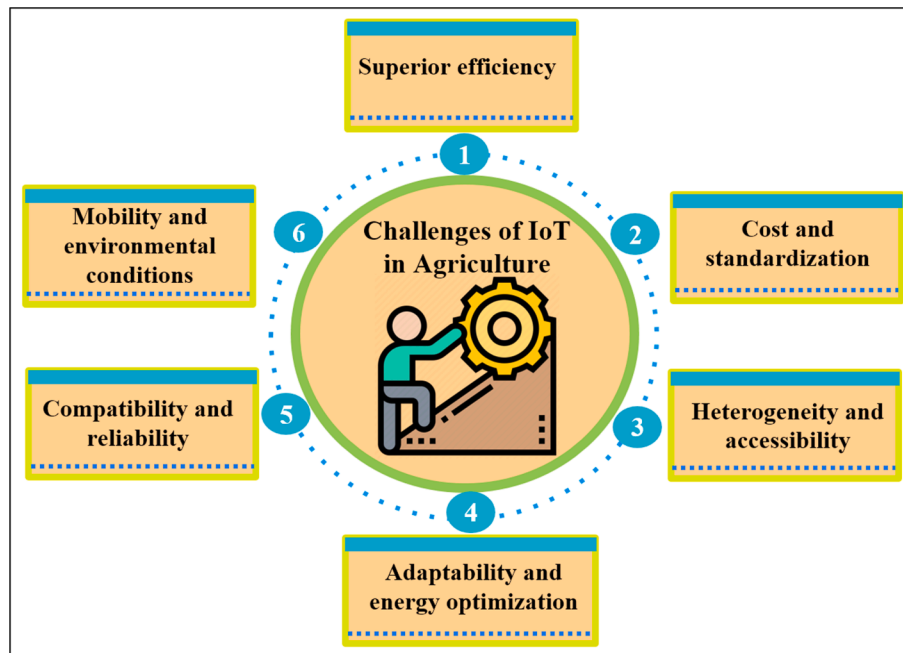


Fig. 7. The challenges of IoT in agriculture.

vagaries of weather, farmers must produce more. Farmers can monitor their products and environmental conditions in real-time thanks to IoT-based agriculture. They can quickly get ideas, anticipate problems before they arise, and decide how to prevent them from using knowledge. Automation is also being introduced by IoT solutions in agriculture, such as demand-based irrigation, fertilization, and automated harvesting.

- 2) **Cost and Standardization:** Due to regional economic disparities, creating a cost-effective strategy for IoT installations in agriculture is difficult. Economic models must be developed to control setup and operational expenses, which include the price of IoT devices, recurring subscriptions, data processing, maintenance, and energy. For devices, applications, systems, and products to function properly together, standardization is essential. Interoperability is challenging to achieve, though, because diverse IoT devices lack standardized formats and protocols. To enable the success of IoT implementations, interoperability is therefore required at the organizational, technological, semantic, and conceptual levels.
- 3) **Heterogeneity and Accessibility:** System design makes use of heterogeneous devices. Each gadget has a different set of operational and maintenance needs. Since the majority of models in agriculture use heterogeneous equipment, it is essential to create a connection between communication technologies and heterogeneous modules. The network becomes increasingly complex due to heterogeneity, which might occasionally result in the appearance of falsified results. Any IoT-based or other device-based farming decision support system must be built with the assumption that current software and hardware are always available everywhere. These problems must be fixed in order to ensure that services are available whenever and wherever they are needed. A lack of the required tools may result in chaos and service delays.
- 4) **Adaptability and Energy Optimization:** For smart farming, it is important that the devices are able to adapt to other devices in addition to the environment. Some hardware is incompatible with one another owing to the environment's continually changing, as well as occasionally because of particular hardware or connection concerns. The most recent problem with communication devices, and other IoT is energy. Up until now, the designing and operating models have been supported by traditional sources of energy.

However, with more gadgets on the market, using traditional energy is no longer a viable option. Aside from testing unconventional energy sources like solar, wind, and water energy harvesting plans, which haven't had much success, new approaches also need to be developed.

- 5) **Compatibility and reliability:** The produced models or software should be adaptable and scalable in order to comply with the criteria of fragmentation and scalability. Reliability is a vital issue for IoT devices to effectively and seamlessly transmit data. The devices must collect and communicate accurate data since judgments are made utilizing the information that has been received and analyzed. Due to system failures, node failures, battery problems, and other interventions, reliability is still a difficulty.
- 6) **Mobility and Environmental Conditions:** The generated systems or models are often static. Because most devices and applications are portable, mobility is essential for the framework's efficient implementation. The challenge of sustaining connectivity still exists in mobile models. Agricultural landscapes come in a variety. As a result, it becomes challenging to respond to those changes, which puts data and services at risk. This modifies a system's accuracy.

6. Conclusion and perspective

In conclusion, the Internet of Things (IoT) and sensor technology, then, provide significant potential for enhancing food security and sustainable agricultural methods. In addition to presenting four layers of the IoT architecture for smart agriculture, including the perception or sensing and actuator layer, the network layer, the cloud layer, and the application layer, this study also offers insights into the size of the global market for smart agriculture in the years 2021 to 2030. This review paper addressed the current state of IoT and sensor technologies for agriculture, as well as some of their potential applications, such as 1) irrigation monitoring systems, 2) fertilizer administration, 3) crop disease detection, 4) monitoring (yield monitoring, quality monitoring, processing monitoring, logistic monitoring), forecasting, and harvesting, 5) climate conditions monitoring, and 6) fire detection. A variety of sensors for agriculture are also included in this study, including those that can detect soil NPK, moisture, nitrate, pH, electrical conductivity, CO₂, temperature, humidity, light, weather station, water level,

livestock, plant disease, smoke, flame, and flexible wearable. The advantages of IoT in smart agriculture are also highlighted, particularly in terms of superior efficiency, expansion, reduced resources, cleaner method, agility, and product quality improvement. However, there are still problems that must be fixed before IoT technology can be employed in agriculture, which is what this study has discussed. Further offer hints on potential future study avenues. Future readers and scholars will benefit from this study's insights into the current status of academic accomplishment in this field.

Agriculture has the potential to be revolutionized by the development and application of IoT and sensor technologies, enabling more sustainable and effective food production. The need for food will rise as the world's population expands, and the agriculture industry must come up with novel solutions to fulfill this demand while preserving sustainability. IoT and sensors, which provide real-time monitoring and management of crops, soil, and environment, present a possible answer to these problems. However for them to be widely used and implemented, a lot of money must be spent on infrastructure, training, and research. To encourage the use of IoT and sensor technologies in agriculture and to address the difficulties facing the industry, governments, private sector players, and other stakeholders should work together to establish policies and strategies. The development of sustainable and effective agricultural techniques that can fulfill the requirements of a rising population while protecting the environment for future generations, as well as the successful integration of IoT and sensor technologies, are key to the future of smart agriculture.

Declaration of Competing Interest

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

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