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Survey of IoT and AI applications: future challenges and opportunities in agriculture

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ABSTRACT

The internet of things (IoT) connects physical objects through sensors, software, and communication technologies, enabling efficient data collection and sharing. This interconnection promotes automation, real-time monitoring, and improved decision-making across various sectors. In agriculture, the integration of IoT with artificial intelligence (AI) is revolutionizing resource management by providing farmers with real-time information on crop health, climate conditions, and soil quality. This paper explores how IoT and AI are transforming traditional agricultural practices to enhance both efficiency and sustainability. Through an in-depth analysis of existing literature and practical applications in the sector, this study identifies significant advancements in crop management, reduction of losses, and resource optimization. Additionally, it highlights persistent challenges such as data security and interoperability. The aim is to address these challenges and propose innovative solutions to optimize agricultural processes. The results indicate that while IoT and AI offer substantial benefits, further advancements and solutions are needed to fully leverage these technologies for sustainable agricultural development.

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1. INTRODUCTION

The internet of things (IoT) connects physical objects with sensors, software, and communication capabilities, enabling data collection and exchange [1], [2]. This fosters automation, real-time monitoring, and decision support across various sectors [3], [4]. In smart homes, IoT automates household appliances [5], [6]. In industry and logistics, it allows real-time monitoring and predictive maintenance [7]. Digital health benefits from connected medical devices and remote monitoring [8], [9]. Smart cities use IoT to optimize energy, transportation, and waste management [10], [11]. Smart agriculture, or connected agriculture, emerges as essential [12]-[15]. With IoT, sensors, drones, and monitoring tools revolutionize agricultural practices [16]. Environmental monitoring through sensors provides accurate data on soil, weather, and humidity, optimizing crop management. Smart irrigation systems adjust water based on plant needs, while livestock monitoring via RFID and sensors improves animal health tracking [17], [18]. Data analysis predicts yields and adjusts farming practices [19], [20]. IoT in agriculture enhances operational efficiency, resource optimization, reduces crop losses, and promotes sustainable practices, crucial for meeting growing food demand while preserving natural resources [21], [22]. The IoT system consists of four main sections, each playing a crucial role in the overall operation [23]-[25]. These sections are designed to collect, transfer, analyze, and visualize data, providing a comprehensive management solution through the IoT [26]-[29].

The first section focuses on data acquisition, which involves collecting information from various sources such as sensors, monitoring devices, trackers, and cameras. These sensors measure parameters like temperature, humidity, and pressure, providing a comprehensive view of the monitored environment or object. The second section is data transmission, where collected data is transferred to processing or analysis points. This transfer is managed by IoT devices including connected sensors, wireless communication modules, and gateways, using technologies like Wi-Fi, Bluetooth, cellular networks, or other specific communication protocols to ensure reliable data flow to the cloud or processing systems. In the third section, data analysis is performed using algorithms, signal processing, computer vision, and artificial intelligence (AI) to extract relevant information. For example, analyzing images captured by cameras can detect specific objects, anomalies, or trends, which is essential for making informed decisions and achieving goals. Finally, the fourth section involves visualization and operations management. The results of the analysis are presented through user-friendly interfaces such as mobile applications or online dashboards. These interfaces enable users to monitor system status in real-time, take preventive actions, and trigger responses if necessary. For instance, in agricultural monitoring systems, this section helps farmers determine the optimal time for irrigation based on sensor data [30].

The various stages of the IoT system work together to provide a comprehensive solution for data collection, transfer, analysis, and visualization. This process enables smarter and more proactive operations management, leveraging the advantages offered by the IoT as shown in Figure 1.

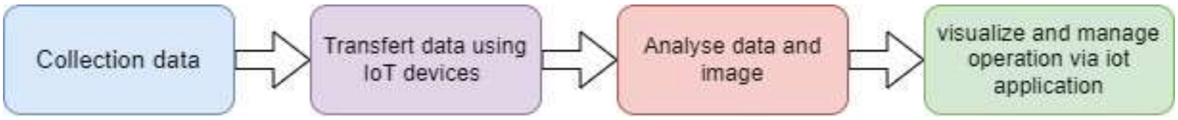

Figure 1. Application of IoT in the agricultural sector

Modern agriculture faces significant challenges such as resource and crop management in the context of climate variability and increasing food demand [31]-[34]. While smart systems and monitoring devices, such as sensors, drones, and IoT technologies, offer promising potential to improve efficiency and sustainability, they present significant constraints, including high costs, integration issues, and data security and real-time information management challenges. This paper aims to examine future challenges and opportunities of IoT and AI in agriculture, with the goal of proposing innovative solutions to optimize resource management and enhance sector sustainability.

This paper is structured into several sections: the first section provides an overview of IoT and AI in agriculture, highlighting their role in resource management, automation, and decision-making. The second section describes the methodology used, including the systematic literature review and the analysis of practical applications of these technologies. The third section examines the key components of agricultural IoT systems, including data collection, transmission, analysis, and visualization. Next, the fourth section explores various IoT applications in agriculture, such as crop monitoring, agricultural machinery, and controlled greenhouse production. The fifth section is dedicated to data analysis, highlighting machine learning and deep learning techniques used to process collected information. The sixth section addresses future challenges related to IoT adoption in agriculture, including security, interoperability, and energy efficiency issues. Finally, the results and discussion synthesize the main findings, while the conclusion summarizes the article's contributions and recommendations for future research.

2. METHOD

The method of this study involves a systematic literature review to identify solutions and challenges related to the application of the IoT and AI in agriculture. It includes analyzing IoT system components, examining practical applications such as crop monitoring and irrigation automation, as well as analyzing data collected using machine learning and deep learning techniques. Major challenges, such as data security and device interoperability, are evaluated, and innovative solutions are proposed to improve IoT system integration, enhance data security, and optimize energy efficiency. The results aim to provide practical recommendations to improve the effectiveness of IoT and AI technologies in the agricultural sector.

3. AGRICULTURAL IOT SYSTEM

In this section, we analyzed the agricultural system based on the IoT. This system comprises four essential components, crucial for any IoT system. These components include IoT devices, communication technologies, the internet, as well as data storage and processing, as shown in Figure 2. Each of these elements is indispensable to all IoT applications and will be described in detail in the following subsection.

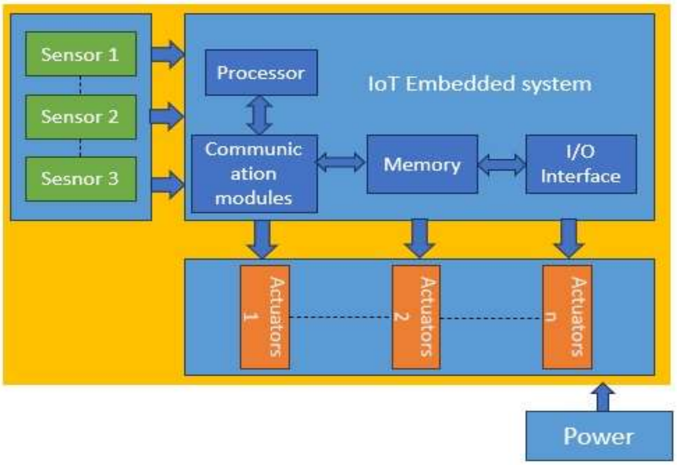

Figure 2. Architecture of the IoT application in the agricultural sector

3.1. IoT components

In this section, we detail the building blocks of applications based on the IoT. Various components are used here, including wireless sensors and actuators connected via a wireless sensor network (WSN). Figure 2 illustrates the architecture of this device, which comprises a programmable gateway, a microprocessor, a communication module, as well as memory and input/output components. Sensors play a crucial role in monitoring and measuring soil nutrients and weather conditions affecting agricultural production. Various types of sensors are used, such as location, optical, mechanical, electrochemical, and air flow sensors. These sensors collect data on weather, air and soil temperature, precipitation, leaf moisture, chlorophyll, wind direction, relative humidity, solar radiation, and atmospheric pressure.

3.2. IoT communication technology

Communication technology is fundamental for agricultural IoT applications. All devices in these applications interact through this technology, structured according to standards and spectra influencing the application. Communication standards include short and long-range transmissions [35], while the spectrum is divided into licensed and unlicensed spectrum.

3.3. Spectrum

The licensed and unlicensed spectrum differ in their regulations and uses. The licensed spectrum, managed by government agencies, is allocated under license to specific operators like mobile phone providers, ensuring strict control to avoid interference and ensure service quality. Conversely, the unlicensed spectrum, or industrial, scientific, and medical (ISM), is accessible without a license, allowing greater flexibility for technologies like Wi-Fi and Bluetooth. However, it can pose challenges in terms of interference, security, and management due to its shared use without strict regulation. Thus, the licensed spectrum offers more controlled and predictable use, while the unlicensed spectrum allows greater accessibility but with quality and frequency management challenges.

3.4. Standards

Communication standards are divided into short-range and long-range standards. Short-range standards, optimized for distances ranging from a few meters to about 100 meters, include Bluetooth, Wi-Fi, and IEEE 802.15.4/ZigBee. For example, Bluetooth covers distances up to about 10 meters, while ZigBee can go up to 100 meters. Long-range standards, such as LoRa, Sigfox, and NB-IoT, are suitable for greater distances, reaching several kilometers. LoRa, for example, can cover up to 10 km or more under certain conditions, and Sigfox and NB-IoT can also reach several kilometers.

3.5. Application scenario

Communication technology connects IoT devices in agricultural applications, using various topologies to connect devices and transfer data within the WSN.

3.6. Internet

The internet constitutes the central network facilitating the transport and exchange of information between various sub-networks. It allows IoT sensors to transmit data continuously, regardless of location, to other objects. Additionally, the internet supports cloud computing, essential for collecting, storing, and processing data collected by IoT devices. This data is then accessible from anywhere, enabling real-time monitoring and management of agricultural operations [36], [37].

3.7. Data storage and processing

Data collected from sensors and devices are stored in databases and processed through various algorithms and tools. This data processing involves analyzing large volumes of information to derive actionable insights. Cloud platforms often provide scalable storage and processing capabilities, enabling efficient management of agricultural data. Techniques such as data mining, statistical analysis, and machine learning are employed to interpret the collected data and support decision-making processes [38], [39].

4. IOT APPLICATIONS IN AGRICULTURE

The integration of IoT in agriculture encompasses several applications aimed at improving efficiency, productivity, and sustainability.

4.1. Crop monitoring

IoT sensors are used to monitor crop health and growth conditions in real-time. Parameters such as soil moisture, temperature, and nutrient levels are continuously tracked to provide insights into crop needs. This information helps farmers make informed decisions regarding irrigation, fertilization, and pest control [40], [41].

4.2. Precision agriculture

Precision agriculture leverages IoT technology to optimize the use of resources. By analyzing data from various sensors, farmers can apply fertilizers, water, and pesticides more precisely, reducing waste and improving crop yields. Techniques such as variable rate application and site-specific management are employed to enhance agricultural practices [42], [43].

4.3. Smart irrigation systems

IoT-enabled smart irrigation systems adjust water delivery based on real-time data from soil moisture sensors and weather forecasts. These systems ensure that crops receive the appropriate amount of water, reducing water waste and improving crop health [44], [45].

4.4. Livestock monitoring

IoT technologies are used to monitor the health and behavior of livestock. Wearable sensors and RFID tags track vital signs, activity levels, and location. This information helps in managing animal health, improving productivity, and preventing diseases [46], [47].

4.5. Controlled environment agriculture (CEA)

In CEA, such as greenhouses, IoT systems manage environmental conditions like temperature, humidity, and light levels. Automated systems adjust these parameters to create optimal growing conditions, enhancing crop growth and reducing resource use [48], [49].

5. ANALYSIS AND MACHINE LEARNING

The analysis of data collected from IoT devices is crucial for deriving actionable insights. Machine learning and deep learning techniques are employed to process and interpret this data, enabling predictive analytics and automated decision-making.

5.1. Machine learning techniques

Machine learning algorithms are used to analyze large datasets and identify patterns or trends. Techniques such as regression analysis, classification, and clustering help in predicting crop yields, detecting diseases, and optimizing resource usage [50], [51].

5.2. Deep learning approaches

Deep learning, a subset of machine learning, involves neural networks with multiple layers. It is particularly effective in processing complex data types such as images and videos. In agriculture, deep learning models can be used for crop disease detection, pest identification, and yield prediction [52], [53].

5.3. Predictive analytics

Predictive analytics leverages historical and real-time data to forecast future outcomes. In agriculture, this includes predicting weather conditions, crop performance, and potential risks. These predictions help farmers make proactive decisions and optimize their practices [54], [55].

6. FUTURE CHALLENGES AND OPPORTUNITIES

The integration of IoT and AI in agriculture presents several challenges and opportunities for future development.

6.1. Security and privacy

Security and privacy concerns are significant challenges in IoT applications. Ensuring the protection of sensitive data and preventing unauthorized access to IoT devices are critical. Implementing robust security protocols and encryption methods is essential to safeguard agricultural data [56], [57].

6.2. Interoperability

Interoperability between different IoT devices and systems is a challenge. Standardization of communication protocols and data formats can enhance the integration and compatibility of various IoT components, facilitating seamless operation across different platforms [58], [59].

6.3. Energy efficiency

Energy consumption of IoT devices is a concern, especially for remote sensors and devices powered by batteries. Developing energy-efficient technologies and optimizing power usage are crucial for the sustainability of IoT applications in agriculture [60], [61].

6.4. Cost and accessibility

The high cost of IoT devices and technologies can be a barrier to adoption, particularly for small-scale farmers. Reducing costs and making IoT solutions more accessible can promote wider adoption and benefit more agricultural stakeholders [62], [63].

7. RESULTS AND DISCUSSION

This study investigated the impact of integrating IoT and AI in agriculture, focusing on their effects on efficiency, resource management, and sustainability. While earlier research has explored various aspects of IoT and AI applications in agriculture, there has been limited exploration of their combined impact on operational efficiency and sustainability. This study aims to fill this gap by providing a comprehensive analysis of these technologies.

Our findings reveal that IoT and AI integration significantly enhances agricultural practices. Specifically, smart irrigation systems and precision agriculture techniques enable real-time monitoring and data-driven decision-making, leading to improved productivity and reduced waste. For example, IoT-based smart irrigation systems optimize water usage based on real-time data, and precision agriculture techniques ensure targeted application of resources, resulting in better crop yields. These advancements contribute to more sustainable agricultural practices.

The results of our study are consistent with previous research that highlights the benefits of IoT and AI in agriculture. For instance, our findings support earlier studies showing that IoT technologies improve resource management and operational efficiency. However, our study extends these findings by demonstrating that AI-driven data analysis enhances the precision of resource application and operational decisions, potentially offering additional benefits compared to traditional methods. This integration appears to address some limitations noted in earlier research, such as delayed responses and less accurate data interpretation.

Despite the promising results, there are notable limitations. The study’s scope covered a broad range of IoT and AI applications, and the effectiveness of these technologies can vary based on specific contexts and implementations. Challenges such as data security, device interoperability, and high costs were identified as significant barriers to widespread adoption. Further research is needed to explore these limitations in more detail and to validate the effectiveness of these technologies in diverse agricultural settings.

Future research should focus on addressing the identified challenges, particularly in enhancing security measures and reducing costs. Additionally, investigating new methods for improving interoperability between different IoT devices and AI systems could provide valuable insights. Exploring the long-term impacts of IoT and AI technologies on various agricultural practices and environments will also be crucial for understanding their full potential and effectiveness. The integration of IoT and AI in agriculture offers significant potential for improving efficiency, productivity, and sustainability. Our findings provide evidence that these technologies can lead to better resource management and operational practices. However, addressing the associated challenges is essential for maximizing their benefits. Future research should aim to develop cost-effective, secure, and interoperable solutions to further advance the adoption and impact of IoT and AI in agriculture.

8. CONCLUSION

The integration of IoT and AI in agriculture offers transformative potential for enhancing efficiency, productivity, and sustainability. By addressing current challenges and leveraging innovative solutions, the agricultural sector can benefit from advanced technologies to meet growing food demands and environmental challenges. Future research should focus on developing cost-effective, secure, and interoperable solutions to further advance the adoption of IoT and AI in agriculture.

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