Evaluating low-cost internet of things and artificial intelligence in agriculture

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ABSTRACT

This article investigates the transformative impact of low-cost internet of things (IoT) solutions on the agricultural sector, with a particular emphasis on integrating artificial intelligence (AI) and machine learning (ML) technologies. The study aims to illustrate how affordable IoT technologies, when combined with advanced AI and ML capabilities, can serve as a significant asset for small and medium-sized farms. It addresses the economic and technical barriers these farms face in adopting such technologies, including high initial costs and the complexity of implementation. By conducting a comprehensive evaluation of existing IoT hardware and software, the research identifies and highlights innovative, cost-effective solutions that have the potential to drive significant advancements in agricultural practices. The findings underscore how these integrated technologies can enhance operational efficiency, increase productivity, and support sustainable agricultural development. Additionally, the paper explores the potential challenges and limitations of adopting these technologies, offering insights into how they can be mitigated. Overall, the study demonstrates that the convergence of low-cost IoT with AI and ML presents a valuable opportunity for modernizing agriculture and improving farm management.

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1. INTRODUCTION

Modern agriculture emphasizes communication, connectivity, and visibility within the supply chain. This allows farmers to communicate with each other, share information, and track various stages of the agricultural process. IoT technologies are becoming increasingly affordable and enable the automation of certain agricultural tasks. However, small farms face significant challenges: they have limited resources, use diverse machinery, and struggle to operate these devices harmoniously due to incompatibility. Furthermore, they cannot always afford to invest in expensive IoT solutions offered by large companies. Small farmers also encounter interoperability issues between existing systems [1]–[5].

To overcome these obstacles, adopting open-source platforms and solutions designed for open collaboration is suggested. Interoperability, the ability of machines to communicate and work together, is a major challenge. The use of open standards can help make these open-source platforms more popular and flexible [6]–[8]. Open-source already plays a crucial role in the development of IoT platforms and prototypes, thanks to developer communities sharing their work [1], [9]–[11]. This accelerates the adoption of new technologies, but the lack of clear instructions can sometimes be problematic [12]–[16]. GitHub is a popular platform where many open-source projects are shared. Ultimately, open-source has the potential to revolutionize modern agriculture, making it more accessible and efficient. It can help farmers, especially smallholders, make the most of new technologies to improve their work [17]–[21].

2. METHOD

This study employs a multi-faceted methodology to evaluate the effectiveness of low-cost internet of things (IoT) solutions in agriculture. Our approach is systematically divided into several distinct phases to ensure a comprehensive assessment. Each phase focuses on specific aspects of IoT implementation, allowing for a thorough analysis of how these technologies can improve agricultural practices. The approach is divided into the following phases:

2.1. Literature review

A thorough literature review was undertaken to compile existing research and data on internet of things (IoT) technologies in agriculture, with a particular emphasis on low-cost solutions and open-source platforms [22], [23]. This review incorporated a wide range of key sources, including academic journals, conference proceedings, and technical reports, which provided a comprehensive overview of the current landscape of IoT applications in agriculture [6], [24]‒[26]. By analyzing these resources, we aimed to identify trends, challenges, and opportunities associated with the implementation of low-cost IoT technologies in agricultural practices.

2.2. Technology assessment

The research assessed a variety of IoT hardware and software solutions, categorizing them according to their functionalities, costs, and ease of integration. This phase included an in-depth analysis of widely used open-source platforms, such as Arduino and Raspberry Pi, which are known for their accessibility and versatility in agricultural applications [27]‒[30]. By examining these platforms, we aimed to determine their effectiveness in addressing the specific needs of low-cost IoT implementations in agriculture.

2.3. Case Study implementation

A practical case study was conducted to implement an IoT system designed for monitoring and managing temperature and humidity levels in greenhouses. This process involved carefully selecting suitable hardware and software components, as well as configuring the system for optimal performance. Additionally, we integrated artificial intelligence and machine learning capabilities to enhance the system's responsiveness and predictive accuracy, thereby enabling more efficient climate control within the greenhouse environment [31]‒[34].

2.4. Data collection and analysis

Data was collected from the implemented IoT system over a specified period. The data included temperature and humidity measurements, system performance metrics, and user feedback. This data was then analyzed using graphs and statistical methods to evaluate the system's effectiveness and identify areas for improvement.

2.5. Evaluation and validation

The final phase involved a thorough evaluation of the results obtained from the case study, validating them against the initial objectives set for the project. This evaluation included a comparative analysis of the performance and cost-effectiveness of the implemented IoT system relative to existing commercial solutions. By assessing these metrics, we aimed to determine the viability of low-cost IoT technologies in enhancing agricultural practices and providing actionable insights for future implementations.

3. STATE OF THE ART

3.1. Hardware

This article discusses two types of hardware used in open-source IoT solutions for agriculture. The first type concerns simple platforms with low computing power, primarily used to create simple sensors. They rely on microcontrollers. The second type comprises more powerful platforms with high computing power, which can be used as open-source servers or sensors with edge processing capabilities, such as image recognition, voice recognition, and artificial intelligence. It is important to note that the line between these two types of platforms can be blurred, especially as the computing power of microcontrollers used in the first category increases.

Moreover, new platforms are emerging, sometimes falling between these two groups. Additionally, the development of low-power artificial intelligence algorithms opens new opportunities in terms of energy savings in data centers and also for low-power sensors with edge computing capabilities. Two platforms stand out in open-source projects related to agriculture: Arduino and Raspberry Pi. Arduinos are widely used and popular microcontroller boards due to their ease of use and programming. Raspberry Pi are affordable and easy-to-use single-board computers. Following these two pioneers, many other companies have launched their products on the market, offering improved features, including long-range wireless connections such as LoRa and 3G. Raspberry Pi are also used in artificial intelligence and computer vision projects [35]–[39].

Although their use in agriculture may be controversial due to their robustness and limited reliability, new boards specifically designed for agricultural environments are beginning to emerge. Arduino Portenta devices are designed for demanding agricultural applications, including edge processing of artificial intelligence and robotics. They offer versatility, capable of running Arduino, Python, and JavaScript code, as well as processes created with TensorFlow Lite. These open-source platforms offer advantages over closed commercial solutions, as they can be adapted to various applications. They are small, affordable, powerful in processing, and compatible with real-time applications, positioning them as key players in the development of future agricultural IoT systems and embedded projects.

3.2. Software

Implementing an open-source IoT system in agriculture requires integrating multiple open-source technologies. Each component performs specific functions, from data collection to creating applications for end-users. Software plays a crucial role, as most commercial IoT solutions suffer from a lack of interoperability and standards. An open-source solution called Atmosphere has been developed to address this issue. It relies on cutting-edge data management technologies and facilitates the development of various IoT applications.

Atmosphere uses APIs to set up a platform-independent interface using the HTTP protocol. The open-source database MongoDB is used to store the data. According to tests conducted by Atmosphere's creators, this tool is easy to deploy and use.

Another tool, Grafana, is an open-source solution for analytics and monitoring, allowing the creation of dashboards and visualizations for various datasets. A study was conducted to compare various open-source platforms based on technical criteria such as device management, data management, communication, intelligent data processing, security, and privacy. The needs related to the development and deployment of applications were also examined.

A recent trend in IoT involves "Edge computing" and "Fog computing." These approaches involve moving part of the processing closer to the sensors, requiring devices with more computing power. For example, image recognition is one of the most promising areas where single-board computers are used. Most commercial image recognition and artificial intelligence solutions are expensive and unaffordable for small and medium-sized enterprises. These solutions are usually custom-made.

Open-source tools such as TensorFlow, OpenCV, and Keras are widely used for research projects involving single-board computers. These projects cover a variety of applications, from fish counting in fisheries to apple counting in orchards. In addition to the previously mentioned open-source software, other commonly used open-source tools in the IoT field for agriculture and other applications include:

- Mosquitto: Mosquitto is an open-source message queue telemetry transport (MQTT) broker essential for IoT communication. It use the lightweight MQTT protocol to support real-time, scalable data exchange through a publish-subscribe model. Key features include quality of service (QoS) levels, message persistence, and secure TLS/SSL communications.
- Node-RED: Node-RED is an open-source tool for visual programmant, enabling users to create and deploy IoT applications by connecting various devices and services on a graphical canvas. It supports numerous integrations and custom node development, facilitating rapid prototyping and automation.
- Zigbee2MQTT: Zigbee2MQTT is an open-source bridge that connects Zigbee devices to MQTT networks. It converts Zigbee messages into MQTT format, allowing seamless integration of Zigbee sensors and actuators into broader IoT systems, with features for device management and automation.

By using these technologies and open-source tools, farmers can create customized IoT systems tailored to their specific needs, minimizing costs associated with proprietary solutions and leveraging the open-source community for support and regular updates [40]–[44] (Figure 1).

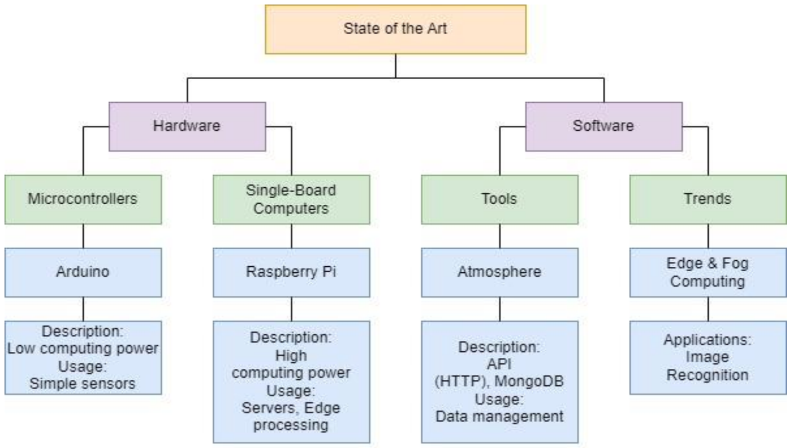

Figure 1. State of the art

4. CASE STUDY: IOT SYSTEM FOR MONITORING AND MANAGING TEMPERATURE AND HUMIDITY IN GREENHOUSES

To concretely illustrate the use of open-source solutions in agriculture, we present a case study of an IoT system for monitoring and managing temperature and humidity in greenhouses [45]–[47]. This system allows farmers to monitor and control climatic conditions in greenhouses to optimize crop growth and improve yields. Additionally, AI and machine learning are integrated to provide predictive analytics and automated decision-making capabilities [48]–[52].

4.1. Hardware used

Temperature and Humidity sensors: DHT22 sensors were employed to monitor temperature and humidity levels in the greenhouses. These sensors are cost-effective, offer reliable performance, and are straightforward to integrate into IoT systems. Arduino: An Arduino Uno board served as the interface for collecting data from the DHT22 sensors. It efficiently gathered sensor readings and transmitted them to a central server for further processing. Raspberry Pi: A Raspberry Pi acted as the central server for aggregating, storing, and analyzing the data collected from the Arduino and sensors. It provided the computational power needed for data processing and running machine learning algorithms. Wireless communication module: An ESP8266 Wi-Fi module facilitated wireless communication between the Arduino and Raspberry Pi. It ensured seamless data transfer over the network, enhancing the system's connectivity and flexibility. AI Accelerator: The Google Coral USB Accelerator was utilized to boost the machine learning capabilities of the Raspberry Pi. It provided enhanced processing power for complex tasks such as real-time data analysis and AI model inference.

4.2. Software used

Mosquitto: an open-source MQTT broker managing communication between IoT devices using the lightweight MQTT protocol. It supports real-time data exchange, QoS, message persistence, and secure communication via TLS/SSL. Node-RED: A visual programming tool for creating IoT applications by connecting nodes to automate data collection and integration. It supports rapid prototyping with a wide range of integrations and customizable nodes. Grafana: A visualization platform for creating interactive dashboards to monitor real-time climatic conditions in greenhouses. It helps in analyzing trends and metrics through customizable visualizations. TensorFlow: An open-source library for machine learning tasks, used to develop predictive models for analyzing sensor data and automating decision-making processes. OpenCV: A library for real-time computer vision and image processing, enabling tasks such as plant health monitoring, disease detection, and growth assessment through camera data. Keras: A high-level API for building and training machine learning models, used to predict temperature and humidity trends and recommend actions for greenhouse management.

4.3. Machine learning integration

Predictive analytics: machine learning models were developed using historical temperature and humidity data to predict future climatic conditions. These models helped farmers anticipate changes and take proactive measures to maintain optimal growing conditions. Automated decision-making: The system

included an AI-based decision support module that provided recommendations for actions such as adjusting ventilation, irrigation, or shading based on real-time data and predictions from the machine learning models.
Image recognition: cameras installed in the greenhouse captured images of plants, and image recognition algorithms were used to monitor plant health, detect diseases, and assess growth stages. This visual data complemented the sensor data for a holistic view of the greenhouse environment.

4.4. Results

The implemented IoT system allowed real-time monitoring and management of temperature and humidity in the greenhouses, with AI and machine learning enhancing its capabilities. The collected data was stored and analyzed to detect variations and trends, while the machine learning models provided predictive insights and automated recommendations. By using open-source technologies, the total cost of the system was significantly reduced compared to commercial solutions. Additionally, farmers were able to adapt the system to their specific needs and improve it over time thanks to the flexibility offered by open-source platforms.

The integration of AI and machine learning further optimized greenhouse management by providing actionable insights and automating routine tasks, leading to improved crop growth conditions and increased yields. This case study illustrates how open-source IoT solutions, combined with AI and machine learning, can be used to improve greenhouse management and optimize crop growth conditions. By using affordable and customizable technologies, farmers can leverage the benefits of IoT while minimizing costs and maximizing efficiency (Figure 2).

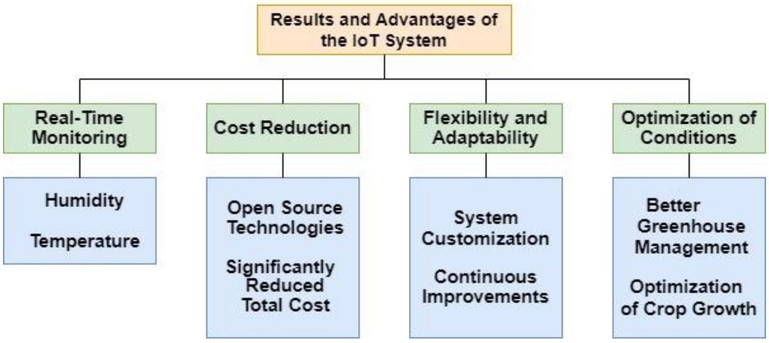

Figure 2. Results of the iot system

5. RESULTS AND DISCUSSION

This study investigated the potential of low-cost IoT solutions, integrated with AI and machine learning, to enhance agricultural management, particularly for small and medium-sized farms. While earlier research has explored the role of IoT in agriculture, few studies have specifically addressed the impact of affordable open-source technologies combined with AI on optimizing climatic control in greenhouses. This study fills this gap by demonstrating the effectiveness of these technologies in improving crop growth and operational efficiency.

The results showed that the IoT system implemented for monitoring and managing greenhouse conditions effectively enhanced agricultural outcomes. Specifically, the integration of low-cost IoT hardware (e.g., Arduino, Raspberry Pi) and AI-driven analytics provided real-time monitoring and predictive insights for temperature and humidity control. The automated decision-making process further optimized irrigation, ventilation, and shading, resulting in improved crop growth conditions and increased yields. The open-source nature of the platforms also enabled customization, adapting to the specific needs of the farm while significantly reducing costs compared to commercial alternatives.

Our findings align with existing studies that have underscored the benefits of IoT in agriculture, particularly in terms of improving resource management. However, this study advances the field by demonstrating how open-source platforms, when paired with AI and machine learning, can go beyond simple monitoring to offer predictive analytics and automation. Unlike expensive proprietary systems, this low-cost, flexible solution makes advanced agricultural management more accessible to smallholders, echoing similar conclusions from research on the democratization of technology in farming.

Although this study showcases the advantages of open-source IoT solutions, there are limitations. The system was tested in a specific environment (greenhouses), and further studies are required to validate its effectiveness in diverse agricultural settings. Additionally, while the hardware used in this study proved to be cost-effective and customizable, its robustness and reliability over long periods, particularly in harsher conditions, remain uncertain. Investigations into durability and scalability will be crucial in future research.

Our study opens several promising avenues for further exploration. Future research could focus on refining machine learning models to improve the accuracy of climate predictions across various crop types and agricultural environments. Investigating the interoperability of IoT systems and the development of open standards would facilitate broader adoption and easier integration of these technologies across farms. Expanding the use of AI in tasks such as plant disease detection and water management could also be explored.

This study demonstrates that low-cost IoT solutions, when integrated with AI and machine learning technologies, present a practical and scalable solution for modernizing agriculture. These technologies offer small and medium-sized farms the ability to optimize resource management, enhance productivity, and overcome the economic and technical barriers typically associated with advanced agricultural technologies.

6. CONCLUSION

In conclusion, this article highlighted the impact of low-cost IoT solutions in the agricultural sector, particularly when combined with AI and machine learning. The Internet of Things offers numerous opportunities for farmers, especially those with small and medium-sized farms, by helping them overcome economic and technical challenges in adopting new technologies. Open-source platforms such as Arduino and Raspberry Pi, along with open-source software tools like Node-RED and Grafana, play a crucial role in developing and implementing affordable and customizable IoT solutions. By leveraging these technologies, farmers can improve productivity, optimize resources, and contribute to more sustainable agricultural practices.

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