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IOT-BASED AUTOMATION AND MONITORING SYSTEMS FOR SMART GREENHOUSES: STATE-OF-THE-ART REVIEW

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ABSTRACT

The increasing demand for sustainable agricultural production has driven the rapid development of smart greenhouses, which offer controlled environments with significantly lower resource consumption and greenhouse gas emissions compared to traditional open-field farming. Intelligent greenhouse monitoring systems enable precise regulation of environmental factors such as temperature, humidity, light intensity, CO_2 concentration, soil moisture, and nutrient levels. These systems play a crucial role in improving crop growth efficiency while reducing the incidences of diseases and pest outbreaks. By enabling real-time data analysis and automated control, intelligent monitoring reduces the need for chemical fertilizers and pesticides, ultimately promoting safer and higher-quality food production.

With advancements in sensing technology, wireless communication, Internet of Things (IoT), big data, artificial intelligence, and deep learning, greenhouse monitoring has evolved from manual supervision to highly automated and predictive management. Modern systems integrate networks of smart sensors, cloud platforms, edge computing, and intelligent decision-making algorithms to ensure stable environmental control and optimal resource utilization. Despite significant progress, challenges remain in terms of system cost, data reliability, interoperability, and large-scale deployment.

This paper presents a comprehensive review of intelligent greenhouse monitoring systems, focusing on key environmental parameters, sensing methods, communication technologies, and system architectures. It highlights comparative studies of various monitoring and control techniques and discusses current technological trends and future development directions. The findings indicate that multi-parameter integrated monitoring and wireless sensor networks significantly enhance greenhouse efficiency and reliability. Furthermore, adopting advanced machine learning and big data analytics enables predictive control strategies and supports fully unmanned greenhouse operations.

Overall, the review emphasizes that the integration of IoT and artificial intelligence has the potential to revolutionize greenhouse management by improving productivity, reducing energy consumption, and enhancing environmental sustainability.

KEYWORDS: Smart greenhouse; IoT; Monitoring system; Automation; Wireless sensors; Climate control; Precision farming; Sustainability; Big data; Energy efficiency

INTRODUCTION

Agriculture plays a fundamental role in ensuring global food security, and with the continuous growth of the world's population, the need for efficient and sustainable food production has become more critical than ever. Traditional open-field farming is increasingly challenged by unpredictable climate change, water scarcity, soil degradation, and rising production costs. As a result, the agricultural sector is shifting toward modern cultivation approaches that maximize productivity while minimizing environmental impact. In this context, greenhouse cultivation has emerged as a highly effective solution for improving crop growth conditions and ensuring year-round production.

Greenhouses offer a controlled microenvironment in which temperature, humidity, carbon dioxide concentration, irrigation, and light exposure can be regulated according to crop requirements. This controlled environment helps increase crop yield, improves product quality, and reduces the dependency on natural climatic conditions. Moreover, greenhouses consume fewer natural resources and contribute to lower greenhouse gas emissions compared to traditional farming systems, making them an important technology for sustainable agriculture.

However, manually managing environmental variables inside a greenhouse is labor-intensive, time-consuming, and often inaccurate. Even minor fluctuations in internal climate conditions can affect plant growth and lead to major economic losses. To address these limitations, intelligent monitoring systems supported by modern technologies such as the Internet of Things (IoT), wireless sensor networks (WSN), cloud computing, artificial intelligence (AI), and big data analytics have been introduced into greenhouse operations. These technologies enable real-time monitoring, automated decision-making, and efficient control of greenhouse environments with minimal human intervention.

IoT-based greenhouse monitoring systems integrate multiple sensors to track key environmental parameters such as temperature, soil moisture, pH, light intensity, and nutrient levels. The collected data is transmitted wirelessly to a centralized server or cloud platform, where intelligent algorithms process and analyze the information. Based on these analyses, automated control strategies can be implemented, such as adjusting ventilation, regulating irrigation, or activating supplemental lighting. This leads to improved environmental stability, optimized resource usage, and enhanced crop growth performance.

In recent years, advanced computational technologies including deep learning and predictive analytics have further enhanced greenhouse automation. These techniques allow the system to detect environmental abnormalities in advance and take corrective actions proactively. By forecasting pest attacks, disease spread, or extreme climate variations, smart monitoring systems significantly reduce reliance on chemical pesticides and fertilizers. This not only lowers production costs but also supports safer, eco-friendly cultivation practices and high-quality food production.

Despite remarkable technological progress, several challenges remain in the widespread adoption of intelligent greenhouse systems. Issues such as high initial investment, system maintenance complexity, data reliability, lack of standardization, and limited technical knowledge among farmers hinder large-scale implementation. Furthermore, there is a growing need for interoperability between devices from different manufacturers and secure handling of transmitted agricultural data.

Considering these opportunities and challenges, it is essential to evaluate current greenhouse monitoring technologies and understand their development directions. This review paper aims to systematically analyze the architecture, key components, sensing technologies, and communication methods used in intelligent greenhouse monitoring systems. It also highlights emerging trends such as multi-parameter sensing, wireless communication dominance, and AI-enabled autonomous management. By discussing the practical benefits, limitations, and future scope of these technologies, this paper seeks to contribute to the effective deployment of smart greenhouse systems in modern agriculture.

Overall, the integration of IoT, AI, and advanced data analytics is revolutionizing greenhouse management by enabling higher productivity, improved resource efficiency, and better environmental sustainability. As research and innovation in this field continue to evolve, intelligent monitoring systems are expected to become the foundation of next-generation smart farming practices.

METHOD

2.1. Literature retrieval

Continuous monitoring of greenhouse environmental parameters not only enhances crop growth performance but also helps prevent damage caused by extreme climatic conditions (Cugnasca, 2006; Liao et al., 2017; Xu, 2002; Wang et al., 2008). Research evidence demonstrates that the growth rate of tomatoes cultivated in an automated IoT-based greenhouse environment is nearly twice as high as that under conventional conditions (Siddiqui, 2017; Martinović & Simon, 2014). Maintaining controlled levels of key environmental factors such as temperature and relative humidity can significantly improve plant quality and yield while conserving resources. Azaza et al. (2016) showed that implementing an IoT-enabled monitoring and control system to regulate temperature and humidity can reduce energy consumption by around 25% and water use by about 33%. Furthermore, integrating intelligent decision-making modules within these systems enhances the accuracy of control decisions and minimizes losses due to human error (Mann et al., 2006).

Over the last two decades, researchers worldwide have made substantial contributions to the development of greenhouse monitoring technologies, applying them to agricultural production and achieving considerable progress (Wang et al., 2008; Siddiqui, 2017; Martinović & Simon, 2014; Azaza et al., 2016; Yanes et al., 2020; Awasthi & Reddy, 2013; Tzounis et al., 2017). Yanes et al. (2020) emphasized the crucial importance of environmental factors in greenhouse monitoring applications. However, a limited number of studies have provided a comprehensive review addressing the full structural design of greenhouse monitoring systems, including environmental sensing, data communication, and server-side information processing.

Awasthi and Reddy (2013) examined the fundamental principles of data transmission and sensor node topology in greenhouse monitoring using ZigBee and GSM communication technologies, enabling dynamic ad-hoc clustering among sensor nodes. Tzounis et al. (2017) analyzed current innovations and future research directions and reported that the primary benefit of smart monitoring systems is enhanced operational convenience, although cybersecurity concerns must be addressed in future developments.

Therefore, while existing review studies have explored environmental variables, sensor network structure, monitoring system applications, and trends in research progress, important questions still remain unanswered: Which environmental parameters should be prioritized for monitoring? How should the overall system architecture be designed? And what types of sensing and communication technologies are most suitable for different greenhouse conditions?

The literature used in this study was collected primarily from Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar. Keywords such as “greenhouse,” “monitoring,” and “environmental efficiency” were selected to identify relevant scientific publications. The literature reviewed was limited to works published over the last 25 years (1996–2020) and focused on intelligent monitoring approaches in greenhouse agriculture. Following keyword filtering, publication year restrictions, correlation screening, and relevance evaluation, a total of 107 research articles were selected for detailed analysis, with major results summarized in Tables A.1, B.1, and C.1.

Publication trend data displayed in Figure 1(a) indicate a significant increase in research attention toward intelligent greenhouse monitoring within the last five years. According to Figure 1(b), journal publications represent the highest proportion, accounting for approximately 69.17% of the total selected articles, demonstrating strong academic engagement in the field.

2.2. Overview of the greenhouse monitoring system

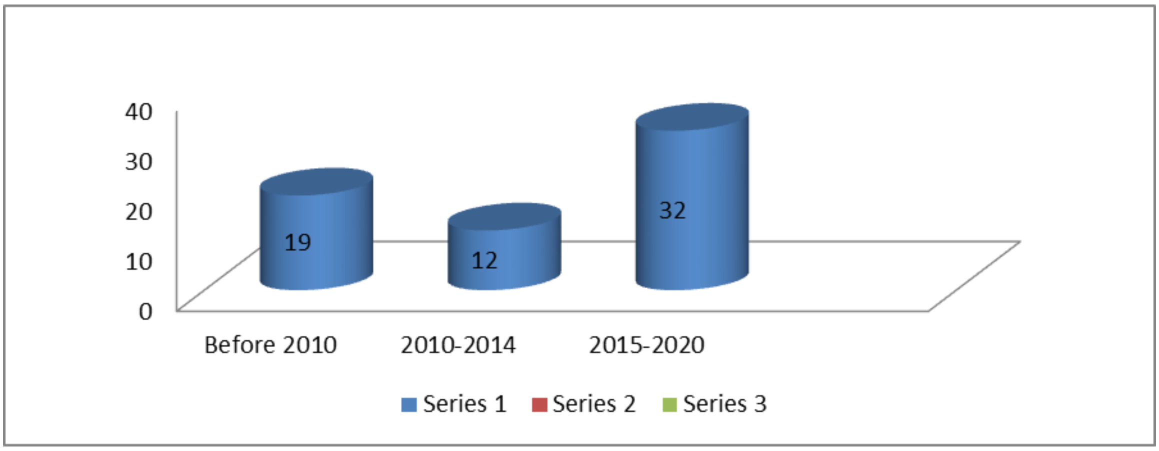
According to the findings of previous studies **(Bai et al., 2019; Liu et al., 2015; Wang et al., 2020; Lee et al., 2019)**, the architecture of a smart greenhouse monitoring system, as shown in **Figure 2**, typically consists of **three core interconnected subsystems**. The first is the **environmental awareness (monitoring) subsystem**, which is positioned inside the greenhouse and is responsible for monitoring environmental and crop-related parameters and collecting real-time sensing data.

The second subsystem is the **server-side information processing unit**, which processes the acquired information by performing data storage, analysis, visualization, and intelligent decision-making functions.

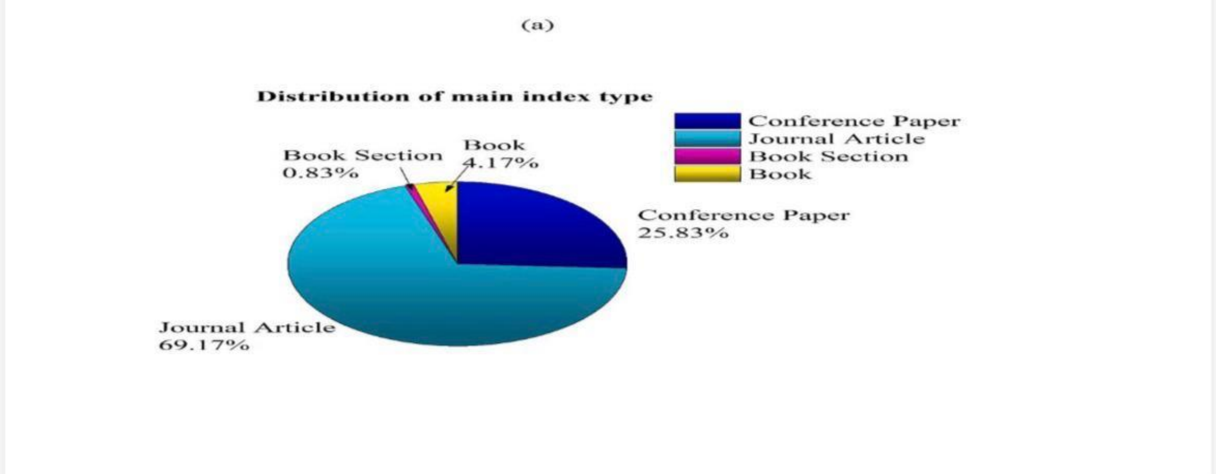
The third component is the **data communication subsystem**, which ensures efficient information transfer between the sensing and server processing units, and manages signal transmission, network routing, and actuator control.

As illustrated in **Figure 2**, the IoT-based greenhouse system architecture clearly demonstrates the functional interaction among the three subsystems: the environmental awareness subsystem, the data communication subsystem, and the server information processing subsystem. The **environmental awareness subsystem** consists of various types of sensors for monitoring environmental, soil, and crop growth parameters. The **data communication subsystem** performs tasks such as signal processing, network node management, data transmission, and control of actuator devices. Meanwhile, the **server information processing subsystem** handles data storage and retrieval, visualization, intelligent control decision-making, early-warning notifications, and system-level equipment and authority management.

Publishing year statistics



(a)



(b)

Fig. 1. Publishing year statistics (a) and distribution of main index type (b) for those selected articles in this work.

RESULTS

This section will systematically review greenhouse monitoring methods and technologies based on internet of things considering monitoring system structure, i.e., environmental awareness subsystem, data communication subsystem and server information processing sub- system. The detailed contents are demonstrated in Table 1.

- Environmetal awareness subsystem
- Data communication subsystem
- IoT communication protocol in green house
- Server information processing subsystem

3.1 Environmental awareness subsystem

The production process in a smart greenhouse is continuously monitored and precisely regulated to maintain optimal growth conditions. In such advanced automated systems, the accuracy of sensor-generated data and the reliability of decisions executed through actuators are crucial. High-quality, accurate, and effective data transmission minimizes operational errors and enhances the performance of visualization, analysis, and decision-making functions within the server-side processing system.

Plant growth and crop yield are influenced by multiple environmental parameters. Continuous monitoring of these factors provides essential insights, enabling growers to understand how each variable impacts plant development and productivity, helping them maximize yield outcomes. The sensing subsystem in a greenhouse incorporates various sensors dedicated to environmental and crop monitoring.

Greenhouse crop production is highly dependent on the surrounding environmental conditions. Conventional greenhouse monitoring systems have primarily focused on collecting basic environmental data such as temperature and relative humidity. This monitored information assists in controlling indoor conditions more accurately and identifying key parameters that affect crop growth and yield outcomes.

The major environmental parameters influencing plant growth include temperature, relative humidity, light intensity, soil moisture content, and carbon dioxide (CO_2) concentration (Fourati & Chtourou, 2007). Furthermore, these parameters are strongly interrelated and interdependent (Bennis et al., 2008; Song et al., 2013). Although the greenhouse interior is relatively enclosed, its environmental variables are dynamically coupled, making it a highly complex, nonlinear, and strongly interacting system (Bennis et al., 2008; Song et al., 2013). During the past two decades, monitoring of physiological crop responses has also been incorporated into environmental assessments, emphasizing the need to monitor crop status directly.

Currently, there is no universally applicable physical model that can accurately represent the complex relationships among these parameters, and existing mechanistic models are insufficient for operational predictions. Therefore, it is necessary to analyze different greenhouse categories and crop species to identify the essential parameters that must be monitored and select suitable sensor types accordingly. Each parameter must be measured independently and precisely, followed by detailed analysis of their interrelationships to develop greenhouse environmental models and establish straightforward and systematic formula-based relationships between the monitored variables.

3.2 Data communication subsystem

The data communication subsystem plays a critical role in ensuring efficient information exchange within an IoT-based smart greenhouse monitoring framework. It serves as the bridge between the environmental sensing subsystem and the server-side information processing subsystem, enabling reliable transmission of monitored data and execution of control commands in real time. The communication subsystem supports network topology management, data routing, signal processing, and actuator control, allowing precise adjustments to environmental conditions based on system decisions.

Effective data transmission is essential for maintaining system stability and optimizing crop growth performance. Any delay, loss, or distortion in communication signals may lead to inaccurate environmental control, reduced decision-making efficiency, and potential crop damage. Therefore, communication reliability, bandwidth efficiency, and low latency are key considerations in the design of greenhouse communication infrastructure.

Various wired and wireless communication technologies are used in greenhouse monitoring systems. Traditional wired methods such as RS-485 and Ethernet offer high stability and resistance to interference but require complex installation and maintenance. In contrast, wireless technologies such as ZigBee, Wi-Fi, LoRa, GSM, and Bluetooth are widely adopted due to low power consumption, flexibility, scalability, and suitability for distributed sensor networks. Among these, ZigBee and LoRa are commonly used for short-range and long-range multi-node communication respectively, supporting mesh network structures and enabling efficient monitoring in large-scale greenhouse environments.

The communication subsystem also facilitates bidirectional data transmission: sensor readings are sent upstream to the server for analysis, while control signals and actuator commands flow downstream to regulate greenhouse equipment such as ventilation fans, heating units, irrigation systems, and CO_2 enrichment devices. Additionally, secure communication protocols and error-correction mechanisms are required to prevent data loss and unauthorized access, ensuring dependable greenhouse automation.

In summary, the data communication subsystem forms the backbone of smart greenhouse monitoring and automation, enabling real-time connectivity, remote supervision, and intelligent control, ultimately supporting stable plant growth and improved resource utilization efficiency.

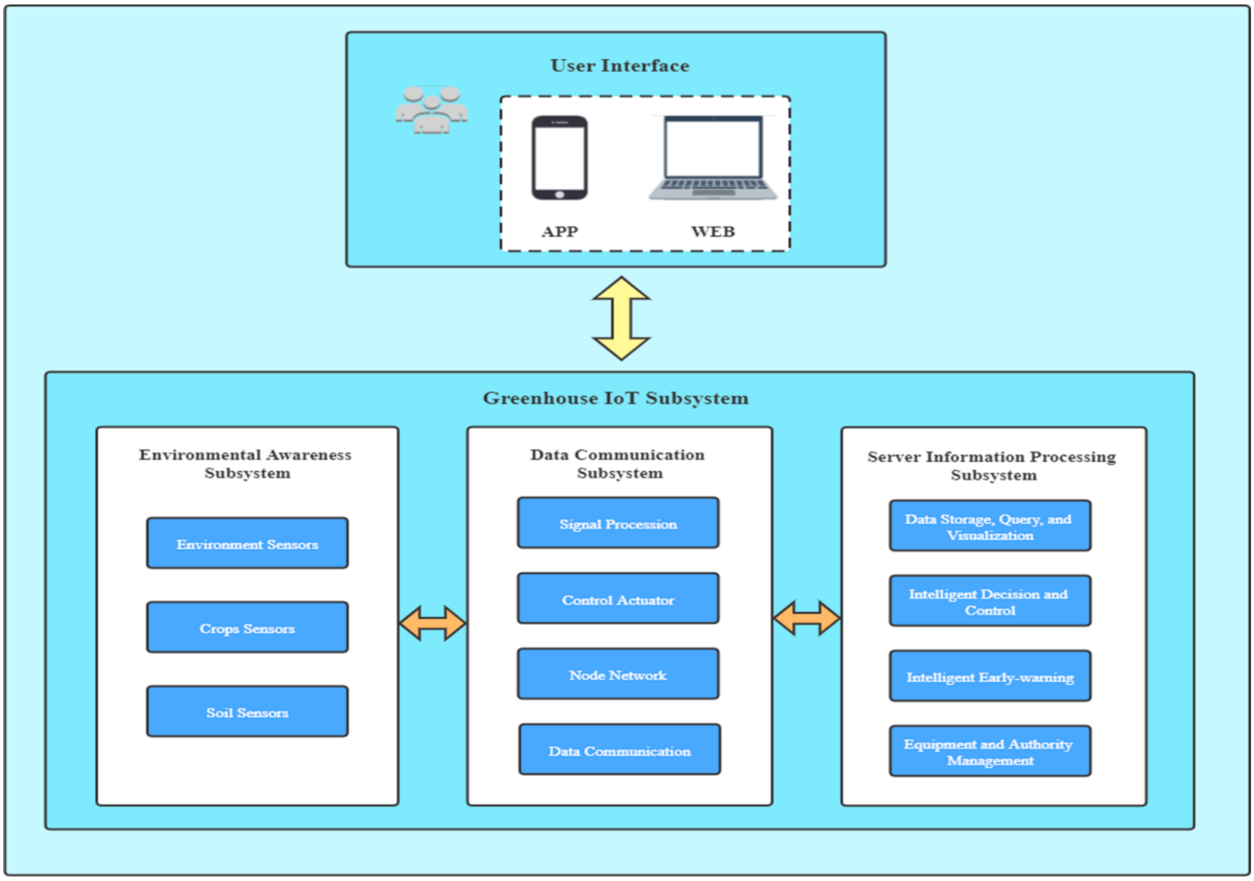


Fig. 2. Subsystem functions and correlation diagrams.

Table 1: Greenhouse monitoring system structure and review contents.

S.No	Subsystem	Review contents
1	Environmental awareness	*Monitoring Parameter*: Air temperature & relative humidity, CO_2%, light, soil temperature & humidity, leaf temperature and humidity
2	Data communication	Slave computer: microcomputer, Arduino, TelosB Platform, Raspberry Pi; IoT communication protocol: wired mode, wireless mode: Zigbee, LoRa, NB-IoT, Wi-Fi, Bluetooth, Private protocols Communication protocal between greenhouse and server
3	Server information processing	

3.3 IoT communication protocol in green house

Efficient communication protocols are essential components of IoT-based monitoring and automation systems in smart greenhouses, enabling reliable data exchange between distributed sensors, controllers, gateways, and cloud platforms. IoT communication protocols define how data is transmitted, processed, and controlled within the greenhouse environment, directly impacting system performance, scalability, communication range, energy consumption, and real-time responsiveness. The selection of an appropriate protocol depends on greenhouse size, sensor density, network structure, and required communication distance.

Various wired and wireless protocols are used in smart greenhouse applications. Wired protocols such as RS-485 and Ethernet provide stable and interference-resistant communication but involve higher installation cost, complex wiring, and limited flexibility. In contrast, wireless communication protocols are widely preferred due to their low cost, scalability, easy deployment, and network expansion capability.

Common wireless IoT protocols used in greenhouse monitoring systems include ZigBee, Wi-Fi, LoRa, Bluetooth, GSM/4G/5G, and NB-IoT.

- ZigBee supports low-power mesh networking, enabling multi-node coverage and self-healing communication, making it suitable for medium-sized greenhouses.
- Wi-Fi offers high data transfer speed and real-time response but consumes more power and has limited coverage, making it useful for indoor monitoring and control dashboards.
- LoRa provides ultra-long-range communication and low energy consumption, ideal for large-scale greenhouse farms requiring long-distance sensor connectivity.
- Bluetooth is applicable for short-range personal monitoring applications but is not suitable for large deployments.
- GSM/4G/5G and NB-IoT enable long-distance communication through cellular networks and support cloud-based remote control and analytics.

In addition to physical protocols, IoT systems also rely on application-layer communication standards such as MQTT, CoAP, AMQP, and HTTP/HTTPS, which support message handling, device management, and cloud data exchange. MQTT (Message Queuing Telemetry Transport) is widely used in greenhouse automation due to its lightweight, publish-subscribe architecture, low bandwidth requirements, and real-time performance. CoAP (Constrained Application Protocol) is suitable for resource-limited sensor devices and supports fast machine-to-machine communication. Meanwhile, HTTP/HTTPS is commonly employed for web-based monitoring dashboards but consumes more power and bandwidth.

Effective use of IoT communication protocols ensures stable real-time monitoring, reliable device control, and seamless data transmission, forming the backbone of intelligent greenhouse management and remote automation.

3.4 Server information processing subsystem

The **server information processing subsystem** is a central and vital component of an IoT-based smart greenhouse monitoring and automation system. It is responsible for receiving, storing, analyzing, and interpreting the environmental and crop-related data collected from sensors through the data communication subsystem. The primary objective of this subsystem is to convert raw sensor data into meaningful information that can support intelligent decision-making and automatic environmental control.

After data is transmitted from distributed sensor nodes, the server subsystem performs several key functions, including **data filtering, noise removal, database management, visualization, pattern recognition, and decision model execution**. Analytical algorithms process real-time data to detect environmental deviations and generate corresponding control commands for actuators such as ventilation fans, heaters, cooling systems, irrigation units, and CO_2 enrichment devices. This enables precise and timely regulation of greenhouse microclimate conditions to optimize crop growth performance.

Modern intelligent greenhouse systems increasingly utilize **cloud computing, edge computing, big data analytics, and machine learning algorithms** within the server subsystem to enhance predictive capabilities and operational efficiency. These technologies enable advanced functionalities such as **forecasting environmental trends, detecting early-stage diseases, issuing alarms, and optimizing resource utilization**. Additionally, cloud platforms support remote monitoring and real-time visualization through mobile applications or web dashboards, enabling farmers and agricultural technicians to supervise greenhouse operations from any location.

The server subsystem also manages **system security, user access control, equipment authorization, and fault detection**. Automated warning systems notify operators instantly of abnormal conditions such as sensor failures, excessive temperature fluctuations, or communication interruptions, thereby reducing the risk of crop loss. The integration of artificial intelligence-based decision models allows the server to autonomously execute control strategies with minimal human intervention, moving greenhouse operation toward fully automated and unmanned production modes.

In summary, the server information processing subsystem forms the intelligence core of smart greenhouse management by transforming sensor data into actionable decisions, enabling efficient environmental regulation, improving productivity, and supporting sustainable agricultural practices.

DISCUSSION

In the last 20 years, intelligent greenhouse monitoring systems have become essential for improving energy efficiency, reducing emissions, increasing crop yield, and enhancing product quality. Smart monitoring enables real-time remote environmental control, efficient management of greenhouse equipment, automatic alarms, coordinated control of heating, ventilation, and lighting systems, and intelligent decision-making. Studies show that IoT-based systems can reduce energy consumption by up to **22%**.

However, existing monitoring systems still face limitations:

- Most systems measure only basic environmental parameters (temperature, light, humidity).
- Limited research focuses on the importance of parameter selection.
- Early systems used simple server processing and basic user interfaces.
- Machine learning is used in around 10% of studies but rarely applied in real production.
- No system integrates all modules into one complete solution.
- Quality of data directly affects system accuracy.
- IoT communication protocols have trade-offs between distance, power, and bandwidth.

The three subsystems—environment sensing, data communication, and server processing—are independent but interdependent. The goal of IoT-based greenhouses is to enable accurate monitoring, intelligent decisions, remote and automated management, and transition from traditional agriculture to precision agriculture.

CONCLUSION

Greenhouses equipped with intelligent monitoring systems are capable of maintaining environmental stability more effectively and managing crop growth in a timely and precise manner. As a result, resource utilization efficiency is enhanced and overall energy consumption in greenhouse infrastructure is reduced. Therefore, this paper reviews existing literature on agricultural greenhouse monitoring systems with the objective of linking biological knowledge with IoT-based intelligent technologies to support future research and development in this area. This study provides agricultural specialists with technical insights into IoT and intelligent systems, while offering engineers practical reference information regarding environmental parameters to ensure accurate and high-quality data transmission and processing within greenhouse networks. Establishing standardized frameworks for greenhouse monitoring systems will accelerate progress and facilitate the transition from experimental systems to real-world industrial implementation.

Additionally, key design principles and emerging technological trends in greenhouse monitoring systems have been synthesized. The main conclusions of this study include:

- Monitoring plant physiological parameters is just as essential as monitoring basic environmental factors.
- The development and use of lower-level control units (slave computers) have become mature, diverse, functional, and cost-efficient.
- Multiple IoT communication protocols are available for greenhouse networking, each with constraints related to bandwidth, distance, and power consumption, requiring selection based on specific application needs.
- Communication between lower-level devices and servers is gradually shifting from wired to wireless technologies.
- Although the application of machine learning in greenhouse monitoring remains limited, it represents an important direction for future development.

At present, **ZigBee remains the dominant protocol** for greenhouse wireless communication, while new technologies such as **LoRa and NB-IoT** are rapidly advancing. Modern mobile communication technologies, particularly **4G and beyond**, are becoming essential for data exchange both inside and outside greenhouse systems. Based on the communication proportions observed in recent studies, **Wi-Fi is widely adopted** for both internal greenhouse networking and server connectivity. However, due to its relatively high power consumption and bandwidth limitations, Wi-Fi is not suitable for all communication scenarios or heavy-duty data transmission requirements.

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