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A Review of Intelligent Greenhouse Systems Based on Internet of Things Control Technology

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Abstract: With the rapid advancement of Internet of Things (IoT) technologies, intelligent greenhouses, as a critical component of modern agriculture, are progressively supplanting traditional farming practices and emerging as a cornerstone technology for precision agriculture. By integrating sensor technologies, automated control systems, cloud computing, and artificial intelligence algorithms, intelligent greenhouses facilitate precise monitoring and automated management of environmental parameters such as temperature, humidity, light intensity, and soil moisture. This integration not only enhances crop yield and quality but also minimizes resource wastage. Nevertheless, the effective amalgamation of these technologies to achieve intelligent greenhouse environment management remains a primary research focus and challenge. This paper provides a comprehensive review of the current research status of intelligent greenhouses based on IoT control technology, addressing the following aspects: first, the utilization of microcontrollers and sensor technologies for localized monitoring and control of greenhouse environments; second, the implementation of cloud computing to enable remote monitoring and management of greenhouse conditions; third, the optimization of greenhouse environmental control strategies through the integration of artificial intelligence algorithms; and finally, the design of compact intelligent greenhouses suitable for domestic cultivation. This study systematically examines the research progress of intelligent greenhouses leveraging IoT control technologies, offering technical insights and practical applications for researchers in the field. Furthermore, the proposed integration frameworks and future development directions presented herein hold significant implications for advancing the adoption and expansion of smart agriculture, thereby contributing to the realization of intelligent and sustainable agricultural production systems.

Keywords: Internet of Things (IoT), Intelligent Greenhouse Systems, Artificial Intelligence Algorithms, Cloud Computing Technology, Sensor Technology

1. Introduction

With the global population growth and escalating climate change, agricultural production is confronted with significant challenges of increasing yield, optimizing resource utilization, and minimizing environmental impact. As a critical component of modern agriculture, intelligent greenhouse systems have emerged as a pivotal technology to address these issues. Leveraging Internet of Things (IoT) technology, intelligent greenhouses integrate sensors, automated control systems, cloud computing, and artificial intelligence algorithms to achieve precise monitoring and

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automated management. This integration enhances crop yield and quality while reducing resource wastage. To date, scholars worldwide have made substantial progress in this field, including the development of microcontroller-based local control systems, cloud computing-driven remote monitoring platforms, and artificial intelligence-based optimization strategies, which have collectively advanced the capabilities of intelligent greenhouse systems. However, gaps remain in the areas of technology integration, system optimization, and practical applications.

This study employs a literature review methodology to systematically analyze and synthesize key technologies and their applications in intelligent greenhouse systems. Specifically, this paper first examines microcontroller-based local control systems, focusing on the strengths and limitations of the 89s51 and STM32 in various application scenarios. Second, it explores the role of cloud computing in remote monitoring and management, supplemented by case studies involving gateway devices such as Raspberry Pi. Third, it reviews the application of artificial intelligence algorithms, including machine learning and deep learning, in optimizing greenhouse environmental control. Finally, it presents design considerations and technical implementations for small-scale intelligent greenhouses tailored for home cultivation. By providing theoretical support for the technological advancement of intelligent greenhouse systems and practical guidance for achieving intelligent and sustainable agricultural production, this research contributes significantly to the transition towards efficient, precise, and sustainable modern agriculture.

2. Application of basic microcontroller technology and automatic control in smart greenhouses

2.1. Greenhouse monitoring system based on AT89S51

In the early years, intelligent greenhouse systems were predominantly based on the C51 series of microcontrollers. These systems utilized C language programs written into the core to read sensor data and automatically regulate various environmental parameters within the greenhouse, such as temperature and moisture levels. Here is an intelligent greenhouse monitoring system based on the AT89S51 microcontroller[1]. The system, featuring a master-slave architecture, integrates temperature and humidity sensors, an RS-485 communication network, and host computer software. It can monitor and control the greenhouse environment in real time. The slave units handle data acquisition, display, and control, while the host manages settings and coordination. The system uses the SHT75 sensor for accurate measurements and a watchdog circuit for stability. It also includes fan control and alarm functions. The software includes modular slave programs, a reliable communication program, and a user-friendly host monitoring interface developed with VB6.0. The system is simple, scalable, and anti-interference capable, but it currently only monitors temperature and humidity, and its RS-485 communication limits large-scale scalability. Future work may focus on adding more monitoring parameters and exploring wireless communication solutions.

2.2. Greenhouse monitoring system based on STM32

In recent years, the advancement of STM32 series embedded microcontroller technology has provided enhanced I/O port resources, thereby expanding the development potential for hardware design in intelligent greenhouse systems. Concurrently, this progress has enabled the software programs to achieve greater complexity and versatility in functionality. Research indicates that IoT technology can significantly enhance the intelligence of greenhouse systems, improve water resource management, and promote agricultural development towards efficiency, precision, and sustainability, exemplified by precise intelligent management of soil moisture and other conditions [2, 3]. The greenhouse monitoring system utilizing STM32F0 series microcontrollers (e.g., STM32F030F4P6 and STM32F030C8T6) demonstrates low-power consumption and high integration. The

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STM32F030F4P6 operates at 48MHz with 16KB Flash and 4KB SRAM, supporting SPI, I2C, and USART communication interfaces. Its operating voltage ranges from 2.4V to 3.6V, with a temperature tolerance of -40°C to 85°C, making it particularly suitable for resource-constrained terminal sensor nodes. In comparison, the STM32F030C8T6 offers enhanced configurations including 8KB SRAM and dual SPI/I2C/USART interfaces, supporting multi-protocol communications (LoRa, 4G, WiFi) and edge computing tasks. Both chips employ ARM Cortex-M0 cores, balancing computational performance with ultra-low power consumption (several μA in sleep mode), ensuring long-term system stability.

The system integrates multi-source sensors (e.g., environmental temperature/humidity, soil parameters, CO_2 concentration) and implements a two-tier data fusion model to enhance measurement accuracy and reliability. The primary fusion employs temporal consistency verification using median and quantile dispersion analysis to detect and correct outliers while preserving data continuity. For instance, abrupt anomalies like 32.58°C could be adjusted to 24.39°C based on historical trends, effectively avoiding information loss inherent in conventional filtering methods [4]. The secondary fusion applies differentiated processing: median filtering for single-sensor data and fuzzy proximity-weighted fusion algorithms for multi-sensor data to optimize weight allocation. Experimental results demonstrate that this approach achieves lower MAE (Mean Absolute Error) and MAPE (Mean Absolute Percentage Error) compared to traditional adaptive weighted averaging algorithms, reducing humidity measurement error from 9.73% to 8.64% with over 80% data fusion efficiency, significantly minimizing redundant data transmission and storage [4].

Field validation in strawberry greenhouses confirmed the system's high stability and practicality. The communication design features LoRa modules achieving lossless transmission within 700 meters with multi-node self-networking capability, while 4G-Cat.1 and WiFi modules enable cloud synchronization with sub-minute response times. Power management optimizations achieve sleep currents below 10μA for terminal nodes, supported by rechargeable batteries with boost circuits enabling single-charge operation exceeding one hour. Post-fusion accuracy tests show over 50% reduction in single-sensor mean squared error, with fused multi-sensor values closely approximating true environmental states. The system provides dual monitoring interfaces: local control via RS-485 industrial touchscreens for real-time monitoring and parameter configuration, complemented by cloud platforms (e.g., Alibaba Cloud) offering remote data storage, analytics, and early-warning mechanisms, further enhancing operational flexibility.

In conclusion, this system demonstrates high reliability, scalability, and cost-effectiveness in complex agricultural environments, providing a viable solution for precision and informatization in smart agriculture.

3. Intelligent greenhouse system combining cloud computing technology with raspberry pi

The Raspberry Pi, as a low-cost, high-performance embedded computing platform, provides novel technical solutions for smart agriculture. Lakshmi and Chilukuri et al. combines cloud computing with Raspberry Pi to construct an intelligent greenhouse system that achieves real-time monitoring and plant disease detection through automation and intelligent technologies [5]. This system employs Raspberry Pi as the core controller, integrates multiple sensors and actuators, and leverages cloud computing to enhance data storage, analysis, remote monitoring capabilities, and greenhouse management efficiency. The hardware design of the system utilizes Raspberry Pi as the central control unit, integrating soil moisture sensors, temperature-humidity sensors (DHT), light-dependent resistor (LDR) sensors, passive infrared (PIR) sensors, smoke detectors, and cameras to comprehensively monitor greenhouse environments. These sensors collect data on soil moisture, temperature, humidity, and light intensity, transmitting them to the Raspberry Pi for analysis. Additionally, actuators such as water pumps, fans, and LED grow lights are incorporated to

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automatically regulate environmental conditions. For instance, irrigation pumps are activated when soil moisture levels drop below predefined thresholds, while exhaust fans are triggered to mitigate smoke or abnormal temperatures.

The system is developed using Python, leveraging Raspberry Pi's computational capabilities for sensor data acquisition, analysis, and actuator control. Machine learning tools such as OpenCV and TensorFlow are integrated for plant disease detection. By analyzing color characteristics of plant leaf images captured via cameras, the system evaluates plant health status. For example, when the green pixel ratio of leaves falls below a specific threshold, the system identifies potential disease risks and issues alerts to users through web interfaces. Cloud computing serves as a critical innovation in this system, enabling long-term data storage, intelligent analytics, and remote accessibility. Users can monitor real-time greenhouse conditions, access historical data, and receive alerts via web or mobile applications. This cloud-based architecture reduces local computational burdens while enhancing system scalability, facilitating efficient greenhouse management.

Yamna Ghoul et al. further optimized Raspberry Pi-based intelligent greenhouse systems by proposing an IoT-enabled remote monitoring and climate control framework [6]. This system similarly employs Raspberry Pi as the core controller, integrating DHT11 temperature-humidity sensors, soil moisture sensors, LDR sensors, and ultrasonic distance sensors (SRF05) for real-time environmental data acquisition. Data analysis and remote monitoring are implemented through the IBM Watson IoT platform. Compared to traditional localized management approaches, this system adopts cloud-based data storage and a Node-Red-powered visualization interface, enabling intuitive environmental monitoring and automated adjustments of irrigation, ventilation, and temperature control strategies.

In practical applications, the system demonstrates robust intelligent management capabilities. Autonomous regulation allows greenhouses to maintain optimal environmental conditions without manual intervention, improving agricultural productivity. For instance, automated irrigation systems significantly reduce water waste, while remote monitoring minimizes labor costs. Cloud-based historical data analysis further supports optimized cultivation strategies. Empirical results confirm that Raspberry Pi-based greenhouse monitoring systems exhibit distinct advantages in hardware design, software development, and practical implementation. Compared to conventional STM32 microcontrollers, Raspberry Pi's superior computational power and scalability enable complex automation and data analytics. Development environments such as Python and Node-Red streamline implementation processes. Field validations demonstrate that these systems effectively enhance greenhouse management intelligence, offering robust technical support for modern agricultural production.

4. Integration of artificial intelligence algorithms and sensor technology for intelligent greenhouse control

4.1. Iot- and ai-based automated greenhouse control system

With advancements in embedded computing platforms such as Raspberry Pi, intelligent greenhouse control systems are evolving toward high-precision automation. The AutoGrow system exemplifies this trend by integrating IoT and AI technologies to optimize resource utilization and enhance agricultural productivity [7]. The hardware architecture comprises multiple sensors, controllers, and actuators. Sensors continuously monitor critical environmental parameters—including temperature, humidity, soil moisture, pH levels, and soil nutrient content (NPK)—with preliminary data processing handled by an Arduino UNO. Data is subsequently transmitted to a Raspberry Pi 3 for storage and analysis, while an ESP8266 module enables cloud connectivity (e.g., ThingSpeak) for

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remote monitoring and control. Actuators such as solenoid valves precisely regulate irrigation and nutrient supply based on system commands, ensuring stable plant growth conditions.

The AI algorithms form the system's core, optimizing control strategies through real-time data analytics. Initially, the system operates using predefined thresholds for basic regulation. Subsequently, Reinforcement Learning (RL) algorithms refine decision-making by iteratively adapting to environmental feedback. Over time, these algorithms enable adaptive control tailored to varying climatic conditions and crop growth stages, enhancing precision and efficiency. Data preprocessing steps such as denoising and normalization ensure input quality. Finally, the AI model generates control commands, transmitted via Raspberry Pi 3 and Arduino UNO to actuators, achieving dynamic optimization of greenhouse environments.

Compared to traditional manual methods, the integration of AI algorithms significantly elevates the intelligence of greenhouse management. Precise adjustments to irrigation and nutrient delivery reduce resource waste, boost crop yields, and minimize reliance on empirical human judgment, fostering scientifically grounded agricultural practices. By harmonizing IoT and AI technologies, the AutoGrow system delivers an intelligent, efficient, and sustainable precision agriculture solution, demonstrating substantial potential for broad application.

4.2. Intelligent greenhouse monitoring system based on artificial neural networks

In recent years, the advancement of artificial neural networks has propelled the development of intelligent greenhouse monitoring systems. Integrating Internet of Things (IoT) and AI technologies, this system employs distributed wireless sensor nodes to monitor real-time environmental parameters within the greenhouse, including temperature, humidity, soil moisture, and light intensity. It then leverages AI algorithms for data analysis and prediction to achieve automated control of the greenhouse environment [8].

The system is designed with a modular architecture, comprising a sensor module, a data processing and analysis module, and a control module. The sensor module is responsible for collecting environmental data and transmitting it to the data processing unit for cleaning, integration, and analysis. By combining historical data with real-time monitoring data, the AI algorithm predicts environmental trends and dynamically adjusts the temperature, humidity, lighting, and irrigation systems within the greenhouse to maintain optimal growth conditions. For instance, when the temperature exceeds the preset threshold, the system automatically activates fans for cooling; when soil moisture is insufficient, the irrigation system is triggered to supply water. A core technology of the system is the application of Convolutional Neural Networks (CNNs) in disease detection. CNNs can automatically extract features from plant leaf images captured regularly by greenhouse-installed cameras, identifying disease signs and detecting risks early. Then, alerts are sent to managers . Compared with traditional manual inspections, CNN technology significantly enhances the accuracy and efficiency of disease detection and reduces the risk of disease spread.

Moreover, the system supports remote monitoring and data visualization, allowing users to view the greenhouse status in real-time via mobile devices or web pages and make manual adjustments as needed. Experimental validation has demonstrated that the system can accurately monitor environmental parameters and automatically adjust the greenhouse conditions according to predefined rules.

Overall, the intelligent greenhouse monitoring system driven by AI and IoT offers an efficient, precise, and sustainable solution for modern greenhouse agriculture, showcasing its great potential in addressing global food security and climate change challenges. The incorporation of CNN technology further strengthens its capacity for disease monitoring, enabling it to better serve the development of precision agriculture.

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5. Design and application of a miniature rotary greenhouse

With the increasing popularity of green and sustainable living concepts, the demand for home-use intelligent mini greenhouses is on the rise. This paper introduces the design and implementation of a rotary home-use vegetable and flower integrated planting intelligent mini greenhouse. The system integrates technologies such as a Programmable Logic Controller (PLC), touch screen, and wireless communication module to achieve functions such as automatic rotation of the planting rack, watering, ventilation, heating, and data acquisition. These features effectively enhance the convenience and efficiency of home gardening [9].

The mechanical structure of the greenhouse is designed to optimize space utilization and meet plant growth requirements. It consists of an enclosed shell, a rotary planting rack, a temperature control system, a ventilation system, and a sprinkling system. The shell is equipped with an operating door only on the front side to isolate external environmental disturbances. The planting rack adopts a four-tier rotary design, with each tier divided into three sections, allowing for the cultivation of different varieties of vegetables or flowers. This design optimizes light distribution and promotes uniform plant growth. The temperature control system integrates electric heating cables, fans, and water spray valves to automatically regulate heating or cooling based on ambient temperature. Additionally, the fans' reversible rotation adjusts the carbon dioxide concentration, while the water spray valves maintain air and soil humidity levels.

The control system is the core of this greenhouse, comprising a Siemens S7-200 Smart series PLC combined with a touch screen, wireless communication module, and a sensor network. The PLC connects to temperature and humidity sensors, light sensors, and soil moisture sensors, and controls actuators such as motors, fans, and water spray valves. The system supports three control modes: manual, automatic, and remote. In manual mode, users can operate each functional module via the touch screen. In automatic mode, the system adjusts environmental parameters based on sensor data. In remote mode, users can monitor and control the greenhouse via a mobile app, which is particularly suitable for those who cannot manage the greenhouse on-site.

Data acquisition and transmission are important aspects of the greenhouse's intelligence. Sensors collect environmental data in real-time and transmit it to the cloud via WiFi. Users can check the greenhouse status anytime through the touch screen or mobile app and intervene manually if necessary. The stability of data transmission is ensured by an IoT cloud platform and a Jukong GRM530 module, guaranteeing reliable operation under various network conditions. In the foreseeable future, compared to the current WiFi technology, the advent of 5G-IoT in smart agriculture is expected to improve data transmission efficiency and real-time performance, alleviate communication bottlenecks, and enhance the efficiency of data sharing [10].

This greenhouse offers several advantages. The rotary planting rack optimizes light distribution, enhancing plant growth uniformity. Intelligent control enables automatic rotation, watering, and temperature and humidity regulation, improving operational convenience. The multi-tier, segmented planting rack allows for the cultivation of various crops, meeting the diverse needs of home users. Furthermore, remote monitoring and intelligent control reduce energy waste and optimize energy usage, providing an efficient and environmentally friendly gardening solution for households.

6. Conclusion

This paper reviews the current research status and development trends of IoT-based intelligent greenhouse systems. It covers various aspects, including local monitoring and control, remote cloud computing management, optimization using artificial intelligence algorithms, and the design of small-scale home greenhouses. The study demonstrates that IoT technology, through the integration of sensors, automatic control systems, cloud computing, and artificial intelligence algorithms, has

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significantly enhanced the intelligent management level of greenhouse environments. This advancement provides strong technical support for achieving precision agriculture and sustainable development.

In terms of technological application, local control systems based on microcontrollers offer advantages such as low cost and high reliability but are limited by their single-functionality and insufficient scalability. The combination of cloud computing and Raspberry Pi technology has improved remote monitoring and data management capabilities, enabling more efficient resource allocation. Artificial intelligence algorithms, such as reinforcement learning and Convolutional Neural Networks, have optimized environmental control strategies, increased resource utilization efficiency, and boosted crop yields. Moreover, modular and remotely controllable small-scale intelligent greenhouses have provided more convenient solutions for urban agriculture.

Despite these advancements, several challenges remain.The complexity of integrating multiple technologies and ensuring system compatibility are urgent issues that need to be addressed. The stability and real-time performance of communication in large-scale deployments require improvement. Data security and privacy protection in the cloud are still incomplete. High costs limit the widespread adoption by small and medium-sized farmers. Future intelligent greenhouse technologies will develop towards integrated innovation. The exploration of lightweight deep learning models and transfer learning algorithms will lower the barriers to applying artificial intelligence in agriculture. Additionally, the advancement of system standardization will promote device interoperability and enhance compatibility and scalability. In terms of application scenarios, emerging models such as vertical farming and urban farming will drive the diversification of greenhouse technologies. The integration of renewable energy sources like solar and wind power will enable low-carbon operations. The optimization of human–computer interaction and the popularization of low-code development platforms will also reduce the technical threshold, accelerating the promotion and application of intelligent greenhouses.

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