Research on Internet-based Agricultural Environment Monitoring Systems

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Abstract This paper investigated the research status and development trends of agricultural environment monitoring systems primarily based on the internet. The issues encountered during system implementation and their corresponding solutions were analyzed by reviewing relevant domestic and international literature. Through this study, it is understood that advancements in sensor technology have significantly facilitated the collection of agricultural environmental data and real-time data processing. However, inconsistencies in data from sensors with different standards lead to incompatibility of information, thereby restricting comprehensive data utilization. Furthermore, the lack of intelligent analysis technology and the limitations of algorithms have hindered the full utilization of agricultural environmental data mining and intelligent decision support systems, severely impacting the precision management of agricultural production. Therefore, subsequent research will strengthen international technical cooperation and exchanges, promote collaborative innovation in various fields, and facilitate the introduction of new technologies such as Big Data and Cloud Computing. Establishing unified data interfaces and developing adaptive algorithm models represent beneficial attempts to break through bottlenecks and promote sustainable agricultural development. Therefore, this study provides a reference for exploring the application prospects of the internet in agricultural production, while also emphasizing the feasibility and importance of in-depth research and application of the internet to advance sustainable agricultural development.

Key words Internet; Agricultural environment; Sensors

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Under the background of global warming and limited resources, agricultural environment monitoring serves as a means to enhance agricultural sustainability. With the rise of the Internet of Things, traditional greenhouse control systems are evolving towards modernization and intelligence[1]. Effective environmental monitoring enables real-time acquisition of information within the agricultural ecological environment, provides timely warnings for potential environmental issues, and offers scientific basis for agricultural decision-making. In recent years, with the rapid development of Chinese society, agricultural supply-side structural reforms, and the transfer of rural labor to other industries[2], research on internet-based agricultural environment monitoring systems has become highly significant.

In terms of advantages, internet-based agricultural environment monitoring platforms enhance the timeliness and accuracy of environmental information through real-time collection, analysis, processing, and visualization. For instance, precision agriculture adopts modern information technology, sensing technology, and automatic control technology to achieve detailed management of field environments and intelligent decision-making[3]. Environmental monitoring systems represent recent technological innovations that hold significant importance for the development of precision agriculture and serve as a key factor in the continuous expansion of agricultural systems[4].

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Research Status Abroad

During the early stages of research and development in internet-based agricultural environment monitoring systems, numerous experts and scholars worldwide have conducted corresponding studies, laying a foundation and providing technical support for further advancements in this field. The research directions primarily include data collection, transmission, and related environmental monitoring parameters, and the main technical approaches focuses on network sharing.

For instance, Kanwalpreet *et al.*[5] established a cycle of "sensor selection-hydroponic system design-AquaCrop model validation", which for the first time resolved the IoT adaptation challenges in artificial saffron cultivation. Based on the construction of a methodology for high-value crop selection and proposing a dynamic nutrient system model for agricultural internet, the study demonstrated significant yield improvement effects in crops. Rathee *et al.*[6] utilized multi-source satellite data and developed a Filter-Wrapper algorithm incorporating a hybrid feature selection method. It led to the proposal of an agricultural monitoring model based on "perception-processing-decision-making", which addressed the bottlenecks of long cycles and low efficiency in manual sampling for satellite remote sensing. These studies highlight the value of data in crop management, providing theoretical support for subsequent system improvements.

Amid the rapid advancement of agricultural technology in recent years, sensor technology has emerged as an important tool for environmental monitoring and has been widely applied in international agricultural environmental research. Barrile *et al.*[7] applied WSN and SPH atmospheric simulation technologies to achieve precise microclimate prediction in complex regions such as Southern Italy, successfully optimizing agricultural machinery paths (resulting in a 22% reduction in energy consumption).

The application of satellite remote sensing technology in agricultural environment monitoring has also attracted widespread attention. For instance, Barbieri *et al.*[8] proposed RIICE technology, which integrates satellite remote sensing with crop models, achieving over 85% accuracy in monitoring rice cultivation areas in Nigeria.

In the process of agricultural environment monitoring, the standardization and integration of monitoring data have gained increasing attention, with their role in high-speed and high-precision data processing being undeniable. Wook *et al.*[9] combined SPE-LC-MS/MS technology with pretreatment optimization techniques to establish a highly sensitive detection index system for various antibiotics in agricultural environments, thereby providing theoretical support for subsequent integration of complex agricultural data.

Meanwhile, Muskan Porwal applied proximal sensing and "3S" integration technology to monitor crop health, diagnose nutritional status, detect crop diseases, and implement crop irrigation, significantly enhancing the precision and real-time performance of agricultural environment monitoring[10].

At the information acquisition level, with the widespread deployment of sensors based on the Internet of Things (IoT), monitoring systems can obtain environmental data such as soil and weather conditions with high frequency and precision[11]. IIoT-WSN, ML and application-specific deployments provide technical support and application scenarios for building efficient modern agricultural environment monitoring systems[12].

In contemporary agricultural environment monitoring, influenced by technologies such as "Big Data" and "Cloud Computing", future agricultural environment monitoring require improvements in prediction models, the development of artificial intelligence, and the establishment of data management standards (Table 1)[13].

Table 1 Multidimensional technical routes and characteristics of core studies on agricultural environmental monitoring abroad

Author	Research content	Research method	Advantage	Disadvantage
Kanwalpreet K	IoT adaptation issues in artificial cultivation of saffron	IoT-sensor fusion architecture, NFT (nutrient film technique), *etc.*	Reducing water and energy consumption costs	The complete growth cycle empirical data has not been demonstrated.
Komal Rathee	Predictive models combining wrapper feature selection with multiple ML classifiers	Multimodal data fusion, UAV remote sensing, satellite image	High precision and efficiency	Hardware costs are relatively high.
Vincenzo Barrile	Construction of an intelligent agricultural monitoring system integrating WSN, remote sensing, atmospheric simulation and GIS	Interdisciplinary research, system integration method	High accuracy and real-time performance, high automation degree	The technical complexity is high.
Jin-Wook Kim	Field monitoring at five sampling sites in the Muhan River Basin, South Korea, and assessment of antibiotic residues	LC-MS/MS method development: optimization of chromatographic conditions and mass spectrometric parameters (DP, CE, CXP, *etc.*)	High sensitivity and specificity, time and cost saving	The SPE procedure is cumbersome and time-consuming.
Muskan Porwal	Development of a field robot mobile platform for real-time data acquisition and execution of agricultural operations (e.g., integrated diagnosis and fertilization)	GIS spatial analysis + GPS positioning + remote sensing data, VRA (variable rate application) fertilization/irrigation system	Realizing dynamic monitoring of root zone moisture	The systems are unable to meet the adaptation needs of smallholder farmers.

Research Status in China

In recent years, advancements in technologies such as the Internet of Things, big data and cloud computing have provided new solutions for smart agriculture[14]. China began establishing intelligent agricultural bases as early as the late 1970s, and significant progress has been achieved in the development of smart agriculture to date in China[15].

The current development status of Internet of Things technology can be analyzed through its technology maturity model. In recent years, the research in China has shown that the application of IoT technology in the agricultural sector is in a phase of rapid growth. For example, Wu[16] adopted four-dimensional dynamic perception and virtual-real interaction mechanisms to embed crop coefficients for rice growth stages (seedling/tillering/irrigation/maturation) into twins, achieving adaptive irrigation decision-making at growth stages. It achieves a transition from experience-based irrigation to data-driven intelligent irrigation guided by physical principles. Huang *et al.*[17] integrated JavaWeb technology with IoT technology to enable real-time monitoring of paddy field water conditions, ultimately combining standardized rice disease data to achieve accurate prediction of rice diseases. Han[18] employed the STM32 F103 series as the main system control board and set thresholds based on tomato physiological characteristics, successfully achieving more precise monitoring in agricultural greenhouses while significantly reducing energy consumption compared with traditional greenhouses.

In recent research, multi-source sensor data fusion technology has gained widespread attention and application as a critical method in agricultural environment monitoring systems. Wang[19] implemented firmware programming on an STM32 microcontroller to achieve multi-source sensor data acquisition and processing, constructing a smart greenhouse monitoring system with high integration degree, low power consumption and off-grid availability. It successfully resolved the challenges of lack of electricity and network connectivity in remote greenhouses, achieving "energy self-sufficiency + data closed-loop". Li[20] expanded the applicability of agricultural monitoring environments by NB-IoT communication, addressing agricultural environment monitoring issues in remote areas without network coverage. The adoption of low-cost sensor combinations significantly reduced system deployment costs. Gao[3] designed a precision agriculture remote monitoring system based on LoRa + NB-IoT + Kalman filtering, which demonstrated outstanding performance in communication coverage, data fusion, and field adaptability, and achieved wide-area, multi-parameter and high-precision agricultural environment monitoring.

In terms of future development trends, international cooperation and innovation as well as collaboration with foreign technologies are also emerging trends. For instance, in the construction of intelligent and standardized monitoring systems, we can learn from international experience and establish environmental monitoring standards and interfaces tailored to China's agricultural conditions. These achivements will enable data connectivity, leverage the advantages of artificial intelligence (AI) technology, and better serve agricultural production management[21].

Research on internet-based agricultural environment monitoring systems needs to enhance China's monitoring capability and level through domestic and international comparison and reference, laying a solid foundation for the sustainable development of agriculture in China (Table 2).

Table 2 Multidimensional technical routes and characteristics of core studies on agricultural environmental monitoring in China

Author	Research content	Research method	Advantage	Disadvantage
Wu Yuhan	Multidimensional integrated monitoring of space (field water level), time (growth period), environment (rainfall/evaporation), and equipment (operational status of pump stations)	Dynamic virtual-real mapping Model lightweight technology Logical modeling method	Real-time dynamic adjustment of irrigation strategies (in response to sudden meteorological changes)	Lightweight models may sacrifice details (*e. g.*, soil micro-topography).
Huang Rui	Validating the feasibility of using ZigBee for environmental monitoring in paddy fields Establishing a fundamental "Sensing-Transmission-Analysis-Early Warning" framework	Sensor → ZigBee → PC string processing → Database storage	Low deployment cost, suitable for small-scale experimental plots	ZigBee has limited coverage range.
Han Jieqiong	Coupling crop growth models, setting thresholds based on tomato physiological characteristics, and integrating four-dimensional data (temperature/humidity/CO_2/soil moisture/light)	Sensor → STM32 serial port processing → ESP8266 transmission → PC/APP	High real-time performance, controllable cost	There is a lack of fault-tolerant mechanisms.
Wang Mingxia	Implementing multi-sensor protocol analysis (custom query frame format) and a watchdog anti-interference mechanism, Developing a script for accessing the OneNET cloud platform	Multi-protocol compatibility Dual-track monitoring: Local serial screen (high real-time performance) + Cloud platform (historical data analysis)	Achieving a network reconnection success rate of >99% by the watchdog mechanism	The sensors have insufficient accuracy.
Li Chongwei	Achieving a closed-loop process: environmental data collection (temperature/humidity/light/CO_2/soil moisture) → NB-IoT upload → Alibaba Cloud analysis → remote control	NB-IoT communication Alibaba Cloud ecosystem integration Low-cost sensor combinations	NB-IoT with strong signal penetration, suitable for metal-structure greenhouses	The data transmission rate is low.
Gao Yun	Constructing a three-tier IoT architecture ("perception layer-transmission layer-application layer") to achieve an end-to-end closed loop	Dual-mode communication synergy: LoRa for local wide-area networking and NB-IoT for remote backhaul, complementing each other's coverage and power consumption limitations	Achieving no blind spots based on LoRa with wide-area coverage and NB-IoT carrier network	DHT11's low accuracy makes it unsuitable for high-precision scientific research.

Existing Problems and Research Necessity

Current agricultural environment monitoring in rice cultivation still faces numerous technical bottlenecks, making it difficult to further improve the effectiveness of agricultural environment monitoring. Data incompatibility issues exist in the application research of agricultural environment monitoring against the backdrop of the internet, which is one of the main problems in current agricultural environment monitoring technology for rice cultivation[22], as shown in Fig. 1.

Agricultural environment monitoring systems typically adopt an integrated sensor model to collect multiple types of data simultaneously, such as temperature and humidity sensors, soil moisture sensors, and meteorological optical sensors. When collecting corresponding environmental data, these systems usually encode and transmit information based on their internal algorithms and data structures. Due to differences in manufacturers and technologies, the final data formats vary widely, which directly leads to data incompatibility in agricultural data integration and analysis.

Fan[23] also mentioned in *Study on IoT-based Agricultural Greenhouse Monitoring Systems* that the current problem in agricultural environment monitoring systems lies in their inability to adapt to greenhouse monitoring, multi-user monitoring, and regional monitoring. To integrate and analyze data from various sources, it is necessary to use other analysis tools to transform and unify the data information. It increases system complexity, leads to inconsistent system analysis results, and may cause errors in environmental analysis due to differing data sources when interpreting data from inconsistent sources.

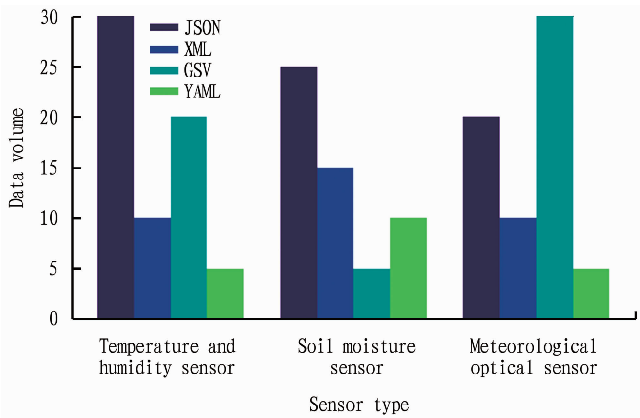

Fig. 1 Schematic diagram of inconsistent data standards among different sensors

In the era of data science, establishing comprehensive, complete and systematic data standards for agricultural monitoring systems is an urgent priority. However, as mentioned earlier, internet-based agriculture serves as the technical foundation for the transformation and upgrading of traditional agriculture into smart agriculture. Issues such as poor Wi-Fi stability and cloud history dependency still persist[24]. In the future, further integration of technologies such as AI, edge computing and green power can make the systems smarter, more reliable, and more practical.

To better apply data in complex agricultural ecosystems, future efforts should focus on exploring standard development and promotion, or developing universal executable solutions to advance the development of agricultural monitoring technology and applications.

Based on the current development status, agricultural environment monitoring systems have become an indispensable part of smart agriculture. However, the constraints of agricultural environmental data processing algorithms still severely hinder the performance development of these systems. Existing agricultural environmental data processing algorithms suffer from issues such as a lack of real-time performance. Qian[25] pointed out that traditional data processing algorithms cannot achieve real-time data processing, causing agricultural environment monitoring data to lag and affecting the timeliness and effectiveness of decision-making. Additionally, the labeling of plant images is time-consuming and prone to subjective errors.

Accuracy is one of the challenges in farmland environment monitoring. Cao *et al.* [26] believes that the current issues include insufficient monitoring, lack of management, resource waste, and low efficiency, and improvements should be made in hardware, algorithms, energy, and security to enhance accuracy.

Targeted enhancement of the intelligence level in agricultural environment monitoring is an inevitable trend in the information era. However, most studies indicate that agricultural environment monitoring generally lacks intelligent analysis technology, which is unfavorable for agricultural production and scientific management. Currently, although environmental monitoring combining the "Internet of Things" with "big data" has been achieved, the support system for intelligent analysis technology still faces numerous problems.

For the research on internet-based agricultural environment monitoring systems, the difficulties and obstacles involved should be identifyied, and the necessity and feasibility of such studies should be further explored.

Development Suggestions for Future Research Directions

Under the development of agricultural environment monitoring system construction, future efforts should strengthen the building of domestic and international cooperation platforms. International exchanges and cooperation can enable complementary advantages in agricultural technologies across different regions, addressing a series of issues such as global warming and resource scarcity. The research capacity of a single country is limited. Through integration of resources and research achievements from different regions using platforms, collaborative efforts can be formed among nations in agricultural environment monitoring technology. Cooperation with countries possessing advanced remote sensing technologies can enhance the accuracy and real-time performance of environmental monitoring data, thereby making agricultural decision-making more scientific.

The establishment of Sino-foreign joint research centers also contributes to cultivating scientific talent and research. For the training of young researchers in universities, collaboration with top international research centers enables them to receive world-leading scientific guidance and technological mentorship. Meanwhile, it helps develop their practical skills and innovative thinking. It is because collaborative research is inherently interdisciplinary. Conducted in a cross-disciplinary environment, it allows researchers to explore and contemplate issues from diverse perspectives, which facilitates the generation of new ideas and methods.

In current agricultural environment monitoring, the standardization of data interfaces serves as the foundation for enhancing system compatibility and data sharing. Therefore, standardizing data interfaces can not only enable information transfer between systems but also facilitate effective data utilization and sharing. Moreover, standardized data interfaces can facilitate the establishment of data communication channels between platforms, achieving data sharing across different terminals such as "sensor networks" and IoT terminals. The standardization of data interfaces helps reduce the complexity of device integration and processing in agricultural environment monitoring systems.

In agricultural environment monitoring, with the rapid development of modern information technology and sensor technology, adaptive algorithms and models are key to improving the efficiency and accuracy of agricultural environment monitoring systems. As we know, adaptive algorithms are defined as those capable of self-adjusting their performance based on the characteristics of relevant data in dynamic environments. The effectiveness of adaptive algorithms lies in their ability to continuously adjust to eliminate complex external factors and effectively suppress noise interference. For example, adaptive models are based on machine learning principles. Based on historical experience data and statistical learning knowledge theory, effective predictive models can ultimately be developed[27], involving steps such as data preprocessing, feature selection, and model training. Integrated learning methods including random forest and support vector machine have improved the accuracy of parameter prediction in agricultural environments and enhanced the decision-making intelligence level of decision support systems.

Conclusions

Research on internet-based agricultural environment monitoring systems is still under continuous development. Once established, such systems will serve as effective measures to address global warming and resource limitations, and represent a crucial component in achieving sustainable agricultural development. The emergence of the internet has opened vast prospects for the application of agricultural environment monitoring systems. Real-time perception, analytical processing and visual presentation provide faster and more accurate agricultural environmental data, enabling farmers to better adapt to their environment and achieve higher quality and yield in crops. Nevertheless, this technology still faces significant challenges that require further breakthroughs. The application of scientific and technological advancements remains limited, and data collection and transmission are still unstable. Users' data analysis capabilities are relatively weak, and the issue of information silos needs to be addressed. While market opportunities are abundant and government policy support is strong, offering vast development space, security and privacy concerns cannot be overlooked. Future research should focus on technological advancement, security enhancement, data standardization, and the optimization of integration technologies to provide more efficient, convenient, and intelligent agricultural environment monitoring systems. Early research has provided fundamental theoretical and technical foundations for subsequent development. Studies by foreign scholars on multi-time series modeling, intelligent decision support systems, data standardization and integration technologies and data fusion techniques have offered valuable reference and insights for the research in China. Data fusion technology is a crucial technical approach for future agricultural environment monitoring systems, serving as an important method for integrating data from multiple sensors, which can enhance system operational reliability and monitoring quality. Building on research achievements from both domestic and international sources and adapting them to specific regional environments is a crucial breakthrough for the maturity of agricultural environment monitoring technology. Strengthening the construction of Sino-foreign cooperative research platforms facilitates technology sharing and collaborative innovation, and enables global synergy in the field of agricultural environment monitoring technology to jointly drive technological advancement and breakthroughs. In summary, the research on internet-based agricultural environment monitoring systems will become increasingly refined with technological advancements and policy support, and will form the foundation for guiding the modernization of agricultural development. Strengthening research and development in this field holds significant importance for sustainable agricultural development and the advancement of agricultural technology in the world.

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pattern was largely consistent with the diurnal variation of light intensity for plants, further demonstrating that the intensity of photosynthesis determines the level of oxygen content in the forest. During early morning and evening, plants exhibit poor carbon sequestration and oxygen release capacity, resulting in the lowest oxygen content of the day. As the solar elevation angle gradually increases and light intensity strengthens, plants begin photosynthesis and release oxygen. Around midday, when light intensity peaks, oxygen release reaches its maximum. Subsequently, as the solar elevation angle decreases, the capacity for oxygen release gradually declines, dropping to its lowest level again by evening[1].

Conclusions and Discussion

(1) Regarding the overall annual variation in oxygen content in both environments, comparative analysis of the annual average oxygen concentration showed that the average inside the forest was 22.13%, while the value outside it was 21.39%. The annual average oxygen concentration inside the forest was 3.34% higher than that outside the forest. One-way ANOVA revealed a significant difference between the two.

(2) Regarding the seasonal variation in oxygen content at both sites, the oxygen concentration inside the forest was consistently higher than that outside the forest in all four seasons. The oxygen concentrations inside the forest were 22.1%, 21.9%, 21.8%, and 21.5% in spring, summer, autumn, and winter, respectively, while outside the forest, they were 22.0%, 21.8%, 21.7%, and 21.4% for the same seasons, respectively. The oxygen concentration inside the forest was higher than that outside the forest by 0.45%, 0.45%, 0.46%, and 0.46% in spring, summer, autumn, and winter, respectively.

(3) The diurnal variation trends of oxygen concentration at both sites were similar throughout all four seasons, exhibiting a single-peak and double-trough curve pattern. The peak period occurred at 13:00 in spring, summer, and winter, and at 9:00 in autumn. The trough periods were observed at 7:00 and between 21:00 and 23:00 or at 5:00. The differences in oxygen content between the peak and trough periods inside the forest was extremely significant.

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