Low-Cost Water Quality Monitoring in Rural Areas Based on Artificial Intelligence and the Internet of Things

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Abstract: This study proposes a low-cost water quality monitoring system based on Metal-Organic Framework (MOF) materials, integrated with Internet of Things (IoT) technology and Artificial Intelligence (AI) algorithms, for real-time and accurate monitoring of water quality in rural areas. The system was tested in several rural regions, collecting data on water quality parameters such as pH, dissolved oxygen, and turbidity to validate its effectiveness. The MOF-based sensors demonstrated high sensitivity and accuracy, closely matching traditional chemical analysis methods, with good stability in detecting low-concentration pollutants. NB-IoT technology was used for data transmission, ensuring stable communication even in complex geographical conditions to meet real-time monitoring needs. AI algorithms, including Support Vector Machines, decision trees, and neural networks, analyzed water quality data in real-time, accurately identifying anomalies with an alert accuracy rate exceeding 90%. Compared to traditional methods, this system significantly reduces costs, enhances monitoring efficiency, and improves real-time capabilities, making it especially suitable for rural areas with weak infrastructure. The results demonstrate significant advantages in accuracy, efficiency, and cost control, with broad application potential. application prospects.

Keywords: Metal-Organic Frameworks; Water Quality Monitoring; IoT; Artificial Intelligence

1. Introduction

Water quality has always been a major focus in the fields of environmental protection and public health worldwide. With the rapid pace of urbanization, water pollution has become increasingly severe, particularly in rural areas of China [1]. Due to the lack of effective water quality monitoring facilities, water pollution in certain regions has not been detected and addressed in a timely manner, significantly impacting the quality of life and health of rural residents. Traditional water quality monitoring methods often rely on manual sampling and laboratory analysis, which are not only time-consuming but also expensive, making it difficult to meet the needs of real-time and large-scale monitoring [2].

In recent years, with the rapid development of the Internet of Things (IoT) and artificial intelligence (AI) technologies, water quality monitoring has gradually evolved toward intelligent and automated systems [3]. However, existing water quality monitoring systems still face challenges in rural areas, such as high costs and difficulties in maintenance. Therefore, the design of a low-cost, easy-to-maintain water quality monitoring system that can provide real-time monitoring and intelligent early warning is an urgent research problem to be addressed [4].

Metal-Organic Framework (MOF) materials, as a new class of porous materials, have extremely high surface area, tunable pore structures, and excellent chemical stability. These materials have been widely used in gas storage, catalysis, and sensing applications [5]. By incorporating MOF materials into water quality sensors and combining them with IoT technology and AI algorithms, real-time, intelligent monitoring of water quality can be achieved [6].

There has been significant progress in water quality monitoring research both domestically and internationally. Traditional water quality monitoring systems typically rely on manual sampling and laboratory analysis, which are insufficient for large-scale and real-time monitoring. With the application of IoT and sensor technologies, more water quality monitoring systems are adopting distributed sensor networks to achieve remote and real-time data collection and monitoring. The integration of IoT communication technology has greatly improved the operational efficiency of water quality monitoring systems [7].

Moreover, the introduction of AI technology enables water quality monitoring systems to automatically identify trends in water quality changes and provide intelligent early warnings. However, challenges still remain for the application of existing systems in rural areas, such as high system costs, sensor accuracy, and stability issues [8]. Therefore, the research objective of this study is to combine low-cost MOF materials with IoT technology to realize an efficient and low-cost water quality monitoring system for rural areas [9,10].

This study aims to design and implement a low-cost water quality monitoring system based on MOF IoT technology that can reduce the overall system cost while ensuring monitoring accuracy, tailored to the water quality monitoring needs of rural areas. By utilizing the high surface area and selective adsorption properties of MOF materials, sensors suitable for water quality monitoring are developed. The system integrates IoT technology with water quality sensors to enable remote real-time data transmission. AI algorithms are used to analyze and predict water quality data, enabling the timely detection of water quality changes and the issuance of early warnings. Experimental data will be used to validate the effectiveness of this system in practical applications and assess its potential for widespread use in rural areas.

2. System Design and Architecture

2.1 System Architecture Design

The design of this water quality monitoring system aims to achieve real-time monitoring and intelligent early warning of water quality in rural areas through a low-cost, high-efficiency approach. The system consists of four core modules: the water quality sensor module, data transmission module, cloud platform data processing module, and user interface module. The design concept of this system architecture is to integrate advanced Metal-Organic Framework (MOF) sensor technology, Internet of Things (IoT) communication technology, and Artificial Intelligence (AI) data analysis to achieve an intelligent management system for data collection, transmission, processing, and display. This system allows users to monitor water quality changes in real-time, detect potential water quality issues, and take effective measures to ensure the safety of rural water sources.

Within the system architecture, the water quality sensor module is the core component. Each monitoring point is equipped with a MOF-based water quality sensor capable of real-time monitoring of various water quality parameters, such as pH, dissolved oxygen (DO), turbidity, and concentrations of specific pollutants. The unique pore structure of MOF materials allows for efficient adsorption and detection of targeted pollutants in water through physical or chemical reactions, ensuring the accuracy and sensitivity of the water quality measurements. By using this approach, the system can conduct distributed monitoring across different water sources or water bodies, ensuring broad coverage and high-precision measurement results.

The data transmission module adopts Low Power Wide Area Network (LPWAN) technology—NB-IoT—which ensures efficient and stable transmission of water quality data from sensors to the cloud platform, particularly in the complex environmental conditions of rural areas. IoT technology not only guarantees remote real-time transmission but also reduces operational costs, avoiding the high requirements for infrastructure and maintenance typically associated with traditional wired transmission methods. With the integration of IoT technology, the system can perform large-scale water quality data collection and ensure real-time data transmission over long distances, significantly improving the efficiency and responsiveness of water quality monitoring.

The cloud platform data processing module serves as the brain of the system. The system transmits collected water quality data to the cloud platform via IoT technology, where the data is stored and processed in real-time. This module employs AI algorithms to conduct deep analysis, including data cleaning, anomaly detection, and trend prediction. Through data mining techniques, the platform can identify potential water quality trends from large volumes of real-time and historical data and provide intelligent early warnings based on these trends. When abnormal water quality changes or excessive pollutant concentrations are detected, the cloud platform can rapidly recognize the issue and trigger the warning mechanism, sending alerts to users in a timely manner. This feature enables water quality monitoring to rely not only on manual inspections but also on automated analysis and intelligent prediction, significantly improving response time and accuracy, ensuring that water quality issues are not overlooked.

The user interface module acts as the bridge between the system and the user. Users can access the system via a mobile app or PC to view real-time water quality data, historical data, and warning information. The system provides a user-friendly data visualization interface, helping users understand water quality changes clearly. In addition to real-time data display, the platform also supports water quality trend analysis, allowing users to view trends in water quality changes, compare data from different time points, and make informed decisions. This module not only enables regular users to stay informed about water quality but also assists water quality managers in taking necessary actions based on the real-time data provided by the platform. Through the system's intelligent warning feature, users can receive alerts before problems occur, reducing the risks posed by water quality contamination.

The overall working principle of the system is as follow Figure 1.

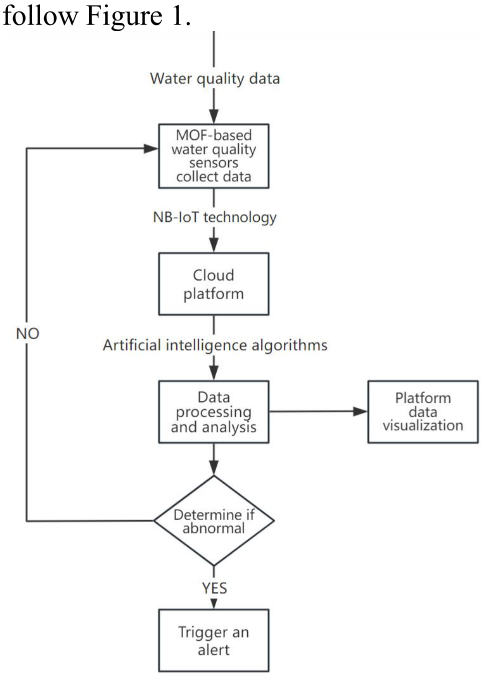

Figure 1. System Working Principle

By integrating MOF technology, IoT technology, and AI analysis, this system effectively addresses the high cost, low efficiency, and inability to perform real-time monitoring that are common in traditional water quality monitoring methods. It offers an efficient, low-cost, and easy-to-maintain water quality monitoring solution with broad application prospects.

2.2 Hardware Design

The hardware design of this system includes sensor selection and integration, data transmission module design, power management, and other aspects. During the design process, special attention was given to the practical application requirements of rural areas, with a focus on low cost, low power consumption, and system stability to ensure long-term reliable operation and high cost-effectiveness.

In the hardware design, the water quality sensor module uses sensors based on Metal-Organic Framework (MOF) materials. These sensors leverage the unique pore structure and chemical properties of MOF materials to efficiently detect various pollutants in water, such as pH, dissolved oxygen, turbidity, and other parameters. The output signals from the sensors are transmitted to the data transmission module via electrical or optical signals. This module uses Low Power Wide Area Network (LPWAN) technologies, such as NB-IoT, ensuring remote and stable data transmission in the complex environments of rural areas. To address potential power supply issues in rural areas, the system design incorporates low-power components and supports solar power, ensuring that the system can operate reliably over long periods. All sensors and communication modules are integrated into a compact device that features waterproof and dustproof characteristics, enabling stable operation in harsh environments. The entire process of data acquisition, transmission, and processing is managed by an embedded controller and processing unit, which efficiently handles sensor data and transmits it to the cloud platform via IoT protocols. The overall hardware design emphasizes modularity and low cost, ensuring that the system can maintain monitoring accuracy while reducing equipment investment and maintenance costs. This design guarantees the system's long-term operation in environments with unstable power supply, which is crucial for ensuring continuous water quality monitoring and improving the system's autonomy in rural areas. The following Figure 2 shows the hardware design diagram.

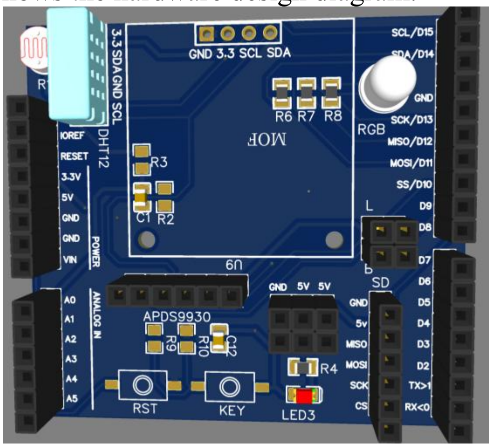

Figure 2. The Hardware Design Diagram

2.3 Software Design

The software design of this system focuses on the real-time performance, stability, and user-friendliness of the water quality monitoring process, integrating MOF sensor technology into four main modules: data acquisition, transmission, processing, and display. The overall design goal is to provide an efficient and intelligent water quality monitoring platform that ensures accuracy while reducing the application cost and maintenance complexity in rural areas.

In the data acquisition module, the system integrates IoT sensors based on MOF technology to collect water quality data in real-time. The high sensitivity and selective adsorption properties of MOF sensors allow for precise detection of pollutants in water, such as pH, dissolved oxygen (DO), turbidity, and other key water quality parameters. To meet the needs of different application scenarios, the sampling interval can be flexibly adjusted. This module also supports automation, enabling data collection to start or stop automatically based on environmental conditions and predefined rules, ensuring the efficiency and accuracy of the data collection process. The collected data is transmitted in real-time to the cloud platform, providing the basis for subsequent data analysis and early warning.

The data transmission module is responsible for transmitting the water quality data collected by the sensors to the cloud platform via IoT technology. In the system design, NB-IoT technologies were selected, as these low-power wide-area network (LPWAN) technologies provide stable remote communication, particularly suited for the complex geographical conditions in rural areas. The low power consumption of NB-IoT extends the system's service life and ensures stable data transmission even in the absence of continuous power supply. With these technologies, the system can achieve real-time data transmission across large areas, ensuring timely feedback of water quality monitoring data to the cloud platform for subsequent analysis and early warnings.

The data analysis module is the intelligent core of the system. After receiving the transmitted water quality data, the cloud platform first performs data cleaning and preprocessing, followed by in-depth analysis using AI algorithms. By applying machine learning and pattern recognition technologies, the system can predict trends and detect anomalies in water quality data, analyzing the patterns and potential risks of water quality changes. Based on these analysis results, the system generates detailed water quality monitoring reports and compares real-time and historical data to assess whether there are abnormal changes in water quality. If the system detects exceeding water quality standards or anomalies, it automatically triggers a warning signal to notify users to take appropriate action. The introduction of AI not only enhances the system's intelligence but also allows for automatic adjustments in different scenarios to more accurately predict and address changes in water quality.

The user display module provides a user-friendly interface via mobile apps or PC. Users can easily access the system to view real-time water quality data, historical data, and warning information. The system visualizes the monitored water quality data in the form of charts, graphs, and curves, allowing users to understand water quality trends. Users can also view warning notifications to be promptly informed of water quality abnormalities and take corresponding measures. This module emphasizes user experience, with a simple and clear interface that facilitates easy querying and monitoring of water quality status at multiple monitoring points. Through the user interface, the system not only provides real-time data but also helps users optimize water quality management to ensure the safety of water sources. Figure 3 shows the interface visualization diagram.

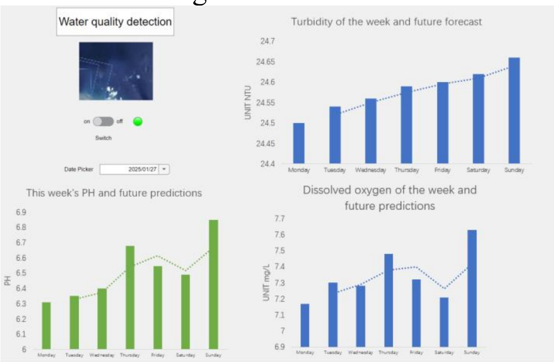

Figure 3. The Interface Visualization Diagram

3. Key Technology Research

In this water quality monitoring system, the integration and application of key technologies are essential for achieving efficient and accurate monitoring. First, MOF materials serve as the core component of the water quality sensor. Their high porosity and chemical tunability enable them to play a crucial role in water quality monitoring. The porous structure of MOF materials provides a high specific surface area, which enhances their ability to adsorb and identify pollutants in water. In this system, the structure and chemical composition of MOF materials can be adjusted to customize the detection of different water quality parameters. For example, MOF materials can be tailored to adjust their sensitivity to key water quality indicators, such as pH, dissolved oxygen, and ammonia nitrogen, for precise pollutant detection. This tunability allows MOF materials to be widely applied in various water quality monitoring scenarios and to efficiently and accurately capture changes in water, ensuring the system performs excellently in different environments.

Second, the application of Internet of Things (IoT) technology in this system forms the foundation for real-time data collection and remote monitoring. IoT technology connects the sensors to the network, enabling real-time transmission of water quality monitoring data to the cloud platform, which supports subsequent data analysis and processing. Especially in rural areas, traditional wired monitoring systems often face high construction and maintenance costs. However, IoT technology, particularly Low Power Wide Area Network (LPWAN) technologies such as NB-IoT, effectively addresses this issue. These technologies offer low power consumption, long-range communication, and high stability, making them ideal for use in rural areas with complex geographical conditions and weak infrastructure. Through IoT technology, the system can operate reliably even in environments without traditional power or network connectivity, ensuring that water quality data is transmitted to the cloud platform in a timely and accurate manner, providing real-time data support for subsequent water quality analysis and decision-making.

Finally, the introduction of artificial intelligence (AI) algorithms gives the system the ability to analyze data and provide intelligent early warnings. AI, particularly machine learning methods such as Support Vector Machines (SVM), decision trees, and neural networks, plays a crucial role in processing large amounts of water quality monitoring data. These algorithms can automatically identify trends in water quality data and predict future changes in water quality. For example, the system can train machine learning models using historical water quality data to distinguish between normal and abnormal water quality, thereby improving the system's predictive capability for water quality anomalies. Once abnormal fluctuations in water quality parameters are detected, the system will promptly notify users through the warning mechanism, helping them take immediate action to prevent further contamination or deterioration of water quality. The AI algorithms not only improve the accuracy of early warnings but also optimize the decision-making process, providing data support and intelligent analysis to assist managers in making more informed water quality management decisions.

Through the high sensitivity and tunability of MOF materials, the low-power stable transmission of IoT technology, and the intelligent analysis provided by AI algorithms, this system achieves comprehensive monitoring of water quality changes. MOF materials enhance the accuracy and sensitivity of the sensors, IoT technology ensures real-time data transmission, and AI algorithms equip the system with intelligent data analysis and early warning capabilities. The effective integration of these three technologies not only makes water quality monitoring more accurate and intelligent but also significantly improves the reliability and stability of the system, providing an efficient and low-cost water monitoring solution for rural areas.

4. Experimental Design and Results Analysis

To validate the effectiveness of the designed water quality monitoring system, this study deployed the system in several rural areas, including water sources and irrigation ponds, and collected data on multiple water quality parameters such as pH, dissolved oxygen, turbidity, and others. The core of the system is a water quality sensor based on Metal-Organic Framework (MOF) materials, which exhibit high sensitivity and selectivity, enabling effective detection of various pollutants in water. The experimental design primarily focused on verifying the accuracy of the sensors, data transmission performance, and the effectiveness of artificial intelligence algorithms in detecting water quality anomalies. To ensure the comprehensiveness of the system, the experiments included sensor accuracy testing, data transmission stability testing, and system alert performance verification.

The sensor accuracy test aimed to validate the performance of the MOF-based water quality sensors in real-world environments. By comparing the results with laboratory standard measurements, experimental data showed that the MOF-based sensors exhibited high accuracy in measuring water quality parameters such as pH, dissolved oxygen, turbidity, etc., with results closely aligned with traditional chemical analysis methods. These sensors not only stably measured various water quality indicators but also demonstrated high stability and sensitivity across different water quality environments, particularly excelling in detecting low-concentration pollutants. These experimental results validate the feasibility and effectiveness of MOF-based sensors in water quality monitoring.

For data transmission performance testing, this study used LoRa and NB-IoT low-power wide-area network (LPWAN) technologies. Given that the experimental sites were located in rural areas with complex geographical conditions, traditional wired networks could not provide stable coverage, making IoT technology a key component of the system. The experimental results showed that water quality data could be successfully transmitted to the cloud platform using LoRa and NB-IoT technologies, and that transmission delays met real-time requirements across different environments. Particularly in areas with poor network conditions, the system was still able to reliably transmit data, ensuring real-time updates of monitoring information. These results demonstrate the significant application potential of IoT technology in low-cost water quality monitoring systems, particularly in rural areas with weak infrastructure.

The data analysis module relies on artificial intelligence algorithms, particularly machine learning algorithms such as Support Vector Machines (SVM), decision trees, and neural networks. In the experiments, the system utilized AI algorithms to perform real-time analysis of the collected water quality data, predict trends in water quality changes, and issue alerts when water quality anomalies were detected. Experimental results showed that by incorporating AI algorithms, the system accurately identified abnormal changes in water quality, with an alert accuracy rate exceeding 90%. Compared to traditional water quality monitoring methods, the experimental results further indicated that traditional methods typically rely on manual inspection or periodic sampling analysis, which are slow to respond and prone to human error. In contrast, the system's automated data collection and intelligent early warning significantly improved the efficiency and accuracy of water quality monitoring. The data obtained is shown in the following Table:

Table 1. The Efficiency and Accuracy of Water Quality Monitoring

Monitoring types Comparison items	pH value	Oxygen content (mg/L),	Turbidity (mg/L)
MOF-based water quality detection	6.32~7.63	20.73~25.41	6.68~9.43
Conventional water quality monitoring	7	20~25	6~9

Further comparative analysis indicates that the system also offers significant advantages in terms of cost-effectiveness. Traditional water quality monitoring systems typically require high hardware investment and labor costs, whereas the IoT-based system using MOF sensors substantially reduces both construction and operational costs. Additionally, the system optimizes the data transmission and analysis processes, reducing reliance on manual monitoring and improving the frequency and real-time capabilities of water quality monitoring, making it more efficient and sustainable. Cost comparison analysis shows that the overall cost of this system is more than 50% lower than that of traditional water quality monitoring methods, with monitoring efficiency in different water sources more than three times higher than that of conventional methods.

5. Conclusion

This study proposes a low-cost water quality monitoring system based on Metal-Organic Framework (MOF) materials, integrating Internet of Things (IoT) technology and Artificial Intelligence (AI) algorithms to achieve real-time and accurate monitoring of water quality in rural areas. Experimental verification shows that the system can efficiently and accurately measure water quality parameters, such as pH, dissolved oxygen, turbidity, etc., and transmit the data reliably to the cloud platform through IoT technology, supporting remote monitoring and intelligent early warning. Compared to traditional water quality monitoring methods, this system not only performs excellently in terms of accuracy and efficiency but also has significant advantages in cost control, making it particularly suitable for rural areas with weak infrastructure. The application of AI algorithms in data analysis enhances the system's ability to predict and respond to water quality anomalies, ensuring the timeliness and accuracy of water quality monitoring.

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