The Application of AI Technology in the Monitoring and Treatment

Haorui Sun*
Jinan Foreign Language School, Jinan, China
**Corresponding Author*

Abstract: Water is essential to life, and its quality and efficient utilization are critical to sustainable development. Medical wastewater, with its complex composition and high environmental risk, can severely harm ecosystems and public health if discharged untreated. Traditional monitoring and treatment approaches often suffer from low efficiency, delayed feedback, limited early warning capabilities, and potential risks of secondary pollution. This study investigates the integration of artificial intelligence (AI) technologies into medical wastewater monitoring and treatment processes. A comprehensive AI-based framework is proposed, incorporating intelligent data collection, automated analysis, AI-assisted optimization of treatment processes, and smart operation and maintenance of equipment. The results suggest that AI significantly enhances the responsiveness, accuracy, and safety of wastewater management systems. By enabling real-time monitoring, predictive control, and adaptive treatment strategies, AI offers a transformative approach to overcoming the limitations of conventional methods. This research provides a novel solution to the pressing challenges of medical wastewater treatment and contributes to the advancement of intelligent, sustainable practices in environmental protection and public health management.

Keywords: AI; Medical Wastewater; Wastewater Monitoring; Wastewater Treatment

1. Introduction

1.1 Background and Current Research Landscape

Water, as the cornerstone of life and development, plays a pivotal role in environmental sustainability and public health. Among the various sources of wastewater, medical wastewater is particularly hazardous due to its complex composition and potential health threats. Generated by healthcare facilities such as hospitals, clinics, and research laboratories, this type of wastewater contains a wide range of pollutants, including pathogens, pharmaceutical residues, chemical reagents, heavy metals, and organic pollutants. If not effectively treated, these contaminants can spread through water systems, leading to ecological imbalance, public health crises, and the emergence of antibiotic-resistant bacteria.

To address these risks, many countries have formulated strict regulatory frameworks. In China, the Water Pollution Discharge Standards for Medical Institutions (GB18466-2005) and the newly issued Technical Standards for Sewage Treatment Engineering in Medical Institutions (GB51459-2024) set out clear discharge thresholds for various contaminants and require effective real-time monitoring. Despite these efforts, traditional methods of wastewater monitoring and treatment still face numerous challenges. These include inefficient manual sampling, delayed laboratory analyses, and inflexible treatment systems that cannot adapt to the fluctuating nature of medical wastewater.[1]

Currently, conventional monitoring technologies are dominated by manual sampling techniques and laboratory analysis for indicators like Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), pH, and ammonia nitrogen. Although accurate, this process is time-consuming, labor-intensive, and inefficient, often requiring hours or even days to produce results. This time lag restricts the capacity to respond to sudden pollution events. Online sensor-based monitoring has improved real-time data acquisition but still faces technical challenges such as short sensor life, signal interference, and high calibration costs [2].

Meanwhile, more advanced molecular biology techniques—like PCR and biosensors—are promising but remain in early development stages and have yet to achieve widespread industrial application.

On the treatment side, existing techniques—physical (e.g., filtration, sedimentation), chemical (e.g., chlorination, coagulation), and biological (e.g., activated sludge, biofilm reactors)—are used in combination. However, each method has its limitations. Physical methods only remove suspended solids, while chemical methods may lead to secondary pollution from excess sludge. Biological systems, though effective in organic pollutant removal, suffer from instability due to water quality and load fluctuations [3]. Thus, there is a growing need for adaptive, intelligent systems that can process large volumes of data and respond dynamically to varying conditions.

In this context, Artificial Intelligence (AI) emerges as a powerful tool to revolutionize both monitoring and treatment. With advances in machine learning (ML), deep learning (DL), data mining, and the Internet of Things (IoT), AI technologies are increasingly being applied across sectors such as intelligent manufacturing, urban planning, and now, environmental protection. In wastewater treatment, AI systems can enable continuous data collection, real-time quality analysis, automated process optimization, and predictive maintenance, significantly improving efficiency and reliability [4].

A number of studies have demonstrated the potential of AI in general wastewater management. Nourani successfully applied feedforward neural networks, support vector machines (SVM), and adaptive neuro-fuzzy inference systems to predict BOD5, CODCr, and total nitrogen concentrations, improving prediction accuracy by up to 24%. Hejabi et al. [5] and Bahrampour [6]similarly found that AI models outperformed traditional models in predicting effluent parameters. Tang Baishi et al. [7] highlighted the synergy between AI and simulation software for activated sludge systems, emphasizing enhanced system optimization. While these studies are promising, most focus on municipal or industrial wastewater. Research specific to medical wastewater, with its unique complexity and risk profile, remains scarce and underdeveloped.

Despite the limited research in this specific subfield, the broader success of AI in environmental monitoring and process optimization indicates a clear opportunity. AI's ability to process high-frequency, multi-dimensional datasets enables predictive analytics, early fault detection, and dynamic control—capabilities ideally suited to the intricate and variable nature of medical wastewater. Integrating AI into this domain represents a vital step forward, not only in improving treatment effectiveness but also in aligning with global sustainability and public health goals.

2. Objectives, Methods, and Significance of This Study

This study aims to investigate the application of AI in enhancing the real-time monitoring, adaptive treatment, predictive maintenance, and regulatory compliance of medical wastewater systems. By leveraging advanced AI algorithms in combination with sensor networks and IoT platforms, the research seeks to develop an integrated, intelligent approach to wastewater management in healthcare settings. The specific objectives are as follows:

2.1 AI-Enabled Real-time Monitoring

High-precision sensors and AI models will be used to collect and analyze key water quality parameters such as COD, ammonia nitrogen, pH, and microbial load. Unlike traditional methods, AI enables multi-parameter fusion, continuous tracking, and anomaly detection in real time. Through deep learning and pattern recognition, even minor fluctuations can be identified early, preventing environmental hazards before they escalate.

2.2 Process Optimization through Intelligent Algorithms

Using reinforcement learning and genetic algorithms, AI can simulate various treatment pathways and determine the optimal combination of operational parameters. For example, it can dynamically adjust chemical dosing and aeration intensity based on real-time influent characteristics, ensuring maximum pollutant removal with minimum energy and reagent use. Predictive models based on historical data further allow early warnings of potential pollution events, enabling timely intervention.

2.3 Smart Equipment Maintenance and Fault Prediction

AI-powered analytics can process equipment telemetry—such as vibration, energy consumption, temperature, and noise—to predict mechanical faults before they occur. This enables a shift from passive repair to proactive maintenance, minimizing system downtime and extending equipment lifespan. Accurate fault localization and cost estimation support efficient resource allocation and operational continuity.

2.4 Regulatory Compliance and Automated Reporting

AI systems can continuously log operational data, track treatment outcomes, and generate comprehensive compliance reports automatically. This not only ensures that discharge standards are met but also facilitates transparency during inspections. In doing so, medical institutions can avoid penalties, uphold public accountability, and enhance institutional reputation.

2.5 Broader Public Health and Environmental Benefits

Ultimately, the adoption of AI in medical wastewater management contributes to environmental sustainability, resource conservation, and public health protection. It enables efficient use of water and energy, minimizes secondary pollution, and helps mitigate the spread of infectious diseases—especially relevant in the post-pandemic era. Additionally, automation frees up healthcare personnel from labor-intensive tasks, allowing them to focus on core clinical and administrative duties.

3. Research Contribution and Innovation

This study contributes to the field by bridging a gap between environmental engineering and artificial intelligence in the specific context of medical wastewater. The research offers a novel, interdisciplinary framework that addresses existing limitations of both traditional monitoring systems and static treatment methodologies. Key innovations include: Integrated AI frameworks for both real-time monitoring and adaptive treatment control.

Predictive maintenance models for wastewater equipment using machine learning algorithms.

Multi-source data fusion techniques that combine chemical, biological, and operational parameters.

A regulatory-compliant system architecture capable of automated reporting and audit-readiness.

By doing so, the study not only supports the intelligent transformation of medical wastewater systems but also lays the groundwork for scalable implementations in other high-risk wastewater scenarios, such as pharmaceutical and biomedical industries.

4. Methods

4.1. Research Objectives and Assumptions

The research objectives and hypotheses of this study primarily focus on the following three aspects: first, understanding the current status of medical wastewater monitoring and treatment; second, identifying the practical issues in medical wastewater monitoring and treatment; and third, exploring how AI technology can effectively enhance the real-time monitoring and treatment of medical wastewater in healthcare institutions. This includes ensuring compliance with discharge standards, analyzing pollution levels (e.g., the number of bacteria and viruses per milliliter), and further optimizing existing wastewater treatment technologies. For medical wastewater treated by different healthcare institutions, the goal is to meet the national discharge standards GB51459-2024 and GB18466-2005 for medical institution water pollutants at the secondary or tertiary level. By leveraging AI to analyze and compute large-scale data, this study aims to provide comprehensive, precise, and fine-tuned management of medical wastewater pollutants, ensuring safe and compliant discharge. This will not only effectively reduce costs for healthcare institutions but also safeguard the health and safety of medical staff and surrounding residents.

4.2. Research Design and Methodology

4.2.1 Research review

The research review is a method of collecting, organizing and analyzing existing literature materials to obtain relevant information and knowledge of research issues, and to provide theoretical basis and background support for research. The research review method can help researchers understand the current status, development trends and existing problems in the current research field, and provide reference for subsequent research design and method selection. Firstly, conduct a literature review: Using Chinese and English keywords such as 'medical', 'wastewater', 'monitoring', 'treatment', 'artificial intelligence', etc., consult relevant literature from core databases both domestically and internationally, such as HowNet and WOS, to collect secondary data and gain an understanding of the current standards for medical wastewater treatment. For example, the following standards were reviewed: GB18466-2005 Medical Institution Water Pollutant Discharge Standard, GB51459-2024 Medical Institution Sewage Treatment Engineering Technical Standard, DB37/596-2020 Shandong Province Medical Institution Pollutant Discharge Control Standard, and others. On the other hand, it can help us to understand the research status and progress of AI technology in the field of wastewater treatment, such as the research published by Mudita Nagpal et al., as well as the research published by Tang Baishi, Hu Yibo and Jiang Haixin[8], these literatures provide the theoretical basis and research direction for this project.

Secondly, determine the research direction: Through the literature review, determine the specific application direction of AI technology in wastewater Monitoring and Treatment, such as intelligent data collection, data analytics, treatment process optimization, intelligent device operation and maintenance, etc.

Thirdly, Build a research framework: Refer to existing research models and methods to build the AI monitoring and treatment model of this project.

4.2.2 In-depth interview

In-depth interview is a method of obtaining the views, experiences and feelings of the research participants on a certain issue or phenomenon through in-depth and detailed dialogue. In-depth interview method can help researchers obtain first -hand data, deeply understand the inner world of the research participants and the problems in actual operation, and obtain richer and more specific information.

Understand actual needs: Through in-depth interviews with wastewater treatment plant managers, technicians, hospital logistics managers, etc., to understand the actual problems and needs they encounter in the process of medical wastewater monitoring and treatment. Semi-structured in-depth interviews can reveal the shortcomings of existing monitoring and treatment systems, such as low monitoring frequency and unstable treatment effect.

Acquire relevant experience: Understand the experience and prospects of professionals in the field of medical wastewater management, and provide reference for the construction and optimization of AI models.

In this study, the research team conducted in-depth interviews with three individuals: the heads of the logistics departments from two different tertiary hospitals and an executive from a wastewater treatment company. On one hand, these interviews provided unique and authentic perspectives from professionals on the current issues in medical wastewater monitoring and treatment; on the other hand, they offered valuable insights for guiding subsequent research and analysis.

4.2.3 Questionnaire survey

Questionnaire survey is a method of collecting quantitative data on the views, attitudes and behaviors of research subjects on a certain issue or phenomenon through the design and distribution of questionnaires. Compared with the in-depth interview method, the questionnaire survey method can obtain first-hand data from a large number of samples, which has higher represent ativeness and reliability and is suitable for large-scale survey research.

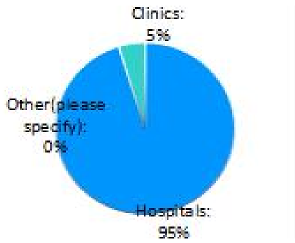

Figure 1. Institutions to which the Respondents belong

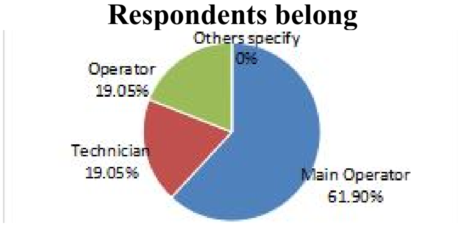

Figure 2. Positions of the Respondents

Due to the specialized nature of this study on medical wastewater, the number of questionnaires distributed was relatively small. A total of 21 questionnaires were distributed to 21 medical institutions, with all 21 questionnaires returned, resulting in a 100% response rate. Among these, 20 were from hospitals and 1 from a community clinic (as shown in Figure 1---the distribution of the questionnaire), so the results are more reflective of the characteristics and needs of hospitals. The respondents' positions were predominantly concentrated in managerial roles, which enhances the reliability of the findings. (as shown in Figure 2--Participant)

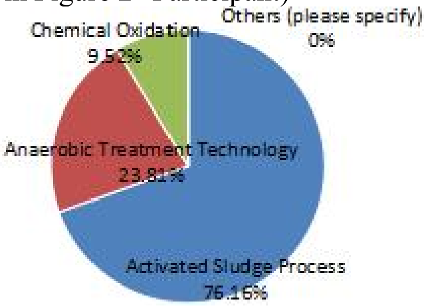

Figure 3. Wastewater Treatment Process of the Medical Institution

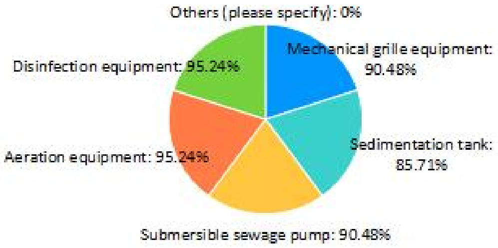

Figure 4. Device and Facilities Involved in Wastewater Treatment System

Relatively speaking, a large-scale questionnaire survey can further collect users' concerns about existing technologies in medical institutions (Figure 3---Processing Method; Figure 4---Treatment Method), collect feedback on a larger scale, and obtain quantitative results through relevant statistical analysis, providing a basis for future AI technology application strategies.

5. Research Analysis

Based on the methods of research review, in-depth interview, and questionnaire survey, we analyze and summarize the current status and issues in medical wastewater monitoring and treatment. On this basis, we propose a preliminary conceptual model for enhancing medical wastewater monitoring and treatment using AI technology.

5.1. Current Status and Challenges in Medical Wastewater Treatment

5.1.1 Weaknesses in monitoring, maintenance stability, and real-time capability

The wastewater treatment system of most institutions is mostly operated continuously (Figure 5---Operating Status of the Treatment System) and managed by outsourcing (Figure 6---Outsourcing Management Status). Some hospitals lack professional management and maintenance, which affects the stability of the system and the real-time treatment effect.

option	subtotal	proportion
non-stop	11	52.38%
intermittent	10	47.62%
Other (please specify)	0	0%
The number of times this question is effectively filled in	21	

Figure 5. Operation Status of Wastewater Treatment Systems in Medical Institutions

option	subtotal	proportion
yes	18	85.71%
no	3	14.29%
The number of times this question is effectively filled in	21	

Figure 6. Outsourcing Management Status of Wastewater Treatment Systems

5.1.2 Device and technology are relatively outdated

The survey shows that medical wastewater treatment facilities generally have problems such as outdated device, low degree of automation, and weak safety operation, and the treatment process is not perfect, (Figure 7,8---Cause of Data Exceedance) resulting in some pollutant indicators exceeding the standard.

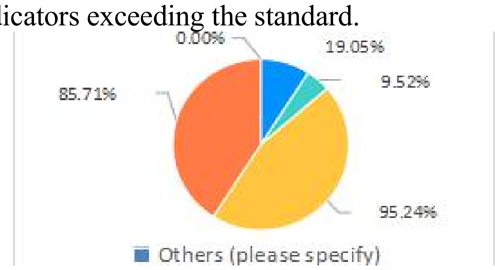

Figure 7. Problems in the Monitoring of Medical Wastewater at the Institution where it is Located

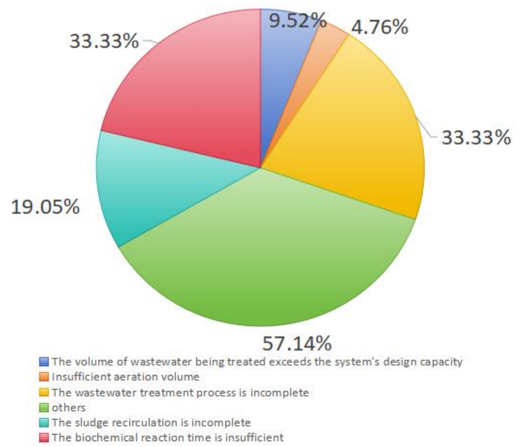

Figure 8. Problems in Medical Wastewater Treatment at the Institution where it is Located

5.1.3 The level of intelligence is obviously insufficient

The vast majority of medical institutions lack intelligent monitoring and analysis technology, resulting in insufficient real-time monitoring capabilities, especially in early warning and device monitoring. It is difficult to achieve efficient wastewater treatment and environmental protection, which affects the efficiency and safety of wastewater treatment. Although only a few institutions currently apply big data and AI technology in wastewater treatment discharge parameters, the survey results show that respondents are positive about AI technology in improving the level of medical wastewater monitoring and treatment, believing that the introduction of AI can effectively improve the current situation.

5.2. AI Conceptual Model

5.2.1 Data collection

In the future, AI-driven smart sensors can be used to integrate a variety of sensing elements and simultaneously measure dozens of key parameters such as COD, BOD, ammonia nitrogen, pathogen concentration, and antibiotic content. These sensors use AI algorithms to calibrate in real time, automatically compensate for environmental disturbances, and improve data accuracy by more than 20% compared to traditional methods, providing a solid foundation for accurately grasping wastewater quality.

Further, through the Internet of Things (IoT) technology, intelligent sensors transmit massive monitoring data to the cloud platform in real time, enabling managers to control the dynamics of medical wastewater anytime, anywhere, and realize remote and all-weather monitoring.

5.2.2 Data analysis

AI can conduct in-depth analysis of massive monitoring and treatment process data, using machine learning algorithms to provide hospital managers with detailed data trend analysis charts and predictive models, offering stronger technical support for medical wastewater monitoring and treatment. For example, by utilizing computer vision technology, the pH levels and pollutants in wastewater can be visually monitored. When combined with algorithms, more accurate pollution assessments can be made, and data analysis charts can be constructed. This enables the precise prediction of COD trends in medical wastewater for the next 24 hours, providing early warnings of water quality deterioration risks and offering a basis for timely adjustments to treatment processes, effectively preventing over-limit discharge incidents.

Furthermore, clustering analysis algorithms can classify wastewater generated by different departments and at different times, identifying high-risk pollution sources. This allows for targeted disinfection, enhanced filtration, and other measures to reduce the risk of secondary pollution.

5.2.3 Process optimization

A hybrid optimization model based on genetic algorithms and artificial neural networks (ANN) can be constructed, using treatment process parameters and water quality parameters as inputs, and treatment outcomes (such as effluent quality compliance rate, pollutant removal rate, etc.) as outputs. For example, the model can dynamically adjust aeration intensity and chemical dosing based on fluctuations in influent COD levels. This adjustment not only helps reduce treatment costs but also ensures that the effluent COD remains consistently below discharge standards.

5.2.4 Device maintenance

AI can use deep learning models to achieve early fault diagnosis based on multi- source data such as device running sound, vibration, temperature, etc. For example, identify abnormal vibration spectrum characteristics of pumps through convolutional neural networks, find potential fault hazards 3-5 days in advance, arrange preventive maintenance, reduce device downtime by 40%, and ensure continuous and stable operation of the processing system.

Based on the above analysis, this study proposes a model diagram of AI technology to enhance medical wastewater monitoring and treatment, as shown in Figure 9.

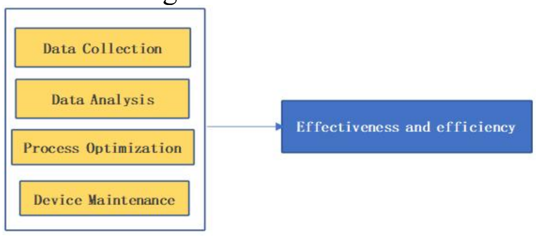

Figure 9. AI Technology Conceptual Model for Enhanced Medical Wastewater Monitoring and Treatment

6. Conclusion and Discussion

6.1. Conclusion

Currently, medical institutions have dedicated wastewater treatment systems in place, demonstrating good compliance and environmental awareness in this field. Surveys indicate that 87.71% of medical institutions outsource their medical wastewater treatment to specialized companies in an effort to enhance management effectiveness and efficiency. However, there are still issues such as weak monitoring and maintenance stability, outdated equipment and processes, and significantly low levels of automation in the overall monitoring and treatment.

The expansion of AI technology in the medical wastewater treatment field promotes the integration of multiple disciplines, including environmental science, computer science, and medicine, thereby effectively enhancing the monitoring and treatment efficiency and effectiveness of medical wastewater. Specifically, the application of AI in medical wastewater monitoring and treatment can be developed in areas such as intelligent data collection, intelligent data analysis, AI-assisted process optimization, and intelligent operation and maintenance of equipment.

6.2 Research limitations and outlook

6.2.1 Research limitations

Artificial intelligence technology is developing rapidly, but non-experts still face challenges in designing AI models with a high level of accuracy in the short term. Our project largely remains at the theoretical level and may still be some distance away from addressing practical issues.

Due to the specialized nature of the medical wastewater field, the number of questionnaires collected is relatively small. In the future, we will further leverage various social resources to increase the number of in-depth interviews and surveys with medical institutions nationwide, ensuring the scientific validity and reasonableness of the conclusions.

Medical wastewater treatment technologies are continuously evolving, but there is often a time lag in writing and publishing papers, which means that the technologies or methods described in the paper may no longer represent the most optimal choices. This delay can result in readers being unaware of the latest advancements in medical wastewater treatment technologies.

6.2.2 Outlook on future research directions

In terms of data quality and security, medical wastewater monitoring data can be affected by environmental noise, transmission interference, and other factors, leading to issues such as data loss. Establishing a strict data cleaning and verification mechanism, along with investing in high-precision calibration equipment, is key to improving data quality.

Advanced AI algorithms, such as deep learning, often operate as "black boxes," making it difficult to intuitively explain the basis for model outputs. In fields like medical wastewater treatment, where safety and reliability are paramount, this lack of transparency can hinder operators' understanding and trust in the system. Developing visualization tools to explain the internal logic of these algorithms is an urgent priority.

As the application of AI technology in the medical wastewater field becomes more widespread, relevant industry standards and regulations will continue to improve. This will help standardize the construction, operation, and management of AI systems in our research, ensuring their accuracy, reliability, and safety, while promoting the healthy development of the entire industry.

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