

ADVANCEMENTS IN AI AND ML FOR WASTEWATER MANAGEMENT: A COMPREHENSIVE REVIEW

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ABSTRACT

This paper scrutinizes the rise and progressions in Artificial Intelligence and Machine Learning technologies that are renovating wastewater treatment processes. Conventional water treatment, effective as it may be, presents many challenges like being energy-intensive, expensive to sustain and requiring constant human intervention. As it is, the addition of AI and ML are novel ways to address these concerns such as process optimization, predictive maintenance, real time monitoring etc. In this work, the different AI or ML based methods have been approached for optimizing the process of treatment plant intensification and improving system deployment strategies thereby saving resources. Notable applications presented here included predictive algorithm-based equipment maintenance, intelligent control systems for treatment plant operation and data-driven models to improve the performance of chemical dosing, aeration and filtration processes. The review presents some successful case studies, and also brings forward the advantages and drawbacks of utilizing AI/ML for wastewater management as well future research opportunities. By leveraging these technologies, it is possible to make wastewater treatment more efficient and resource-efficient while incurring less cost; helping to improve water resources management on a global scale as well protecting the environment.

Keywords - Artificial Intelligence (AI), Machine Learning (ML), Wastewater Treatment, Process Optimization, Real-Time Monitoring, Data-Driven Models

1. INTRODUCTION

With the swift growth of the global population besides increasing development, the need for clean and potable water has risen dramatically. Alongside this, the volume of wastewater from industrial, agricultural, and municipal activities has also surged, posing significant challenges to current wastewater treatment systems. Traditional wastewater treatment systems, while effective, are increasingly strained by these demands. They face numerous challenges, including the need for greater operational efficiency, the ability to handle complex and variable wastewater compositions, and escalating costs. Moreover, the growing emphasis on environmental sustainability and stricter regulations has further complicated the task for treatment facilities, making the quest for innovative solutions more pressing than ever.

Water is an indispensable resource for human survival, industrial processes, agriculture, and the maintenance of ecosystems. However, treating water to make it suitable for human use, and subsequently managing the wastewater produced, remains a complex and costly endeavour. In many rapidly urbanizing regions, the infrastructure for wastewater treatment is either insufficient or under severe pressure, often struggling to keep up with the volume and complexity of modern wastewater streams.

Wastewater treatment generally follows a three-stage process i.e. (i) primary, (ii) secondary, (iii) tertiary treatments. In the primary stage, large solids are removed through sedimentation, while in secondary stage organic material is broken down with the help of biological methods. The tertiary stage utilizes advanced filtration and chemical methods to remove any remaining pollutants. Although these methods are commonly employed, they have certain drawbacks. They tend to be energy-demanding, slow in adapting to changes in wastewater composition, and require substantial chemical inputs, resulting in high operational and maintenance costs (Malviya & Jaspal, 2021). As global emphasis on sustainability intensifies, traditional systems are increasingly struggling to meet regulatory requirements, necessitating the exploration of more advanced and adaptable treatment technologies. The need for innovation in this field has never been more critical, particularly as the world faces the dual challenges of water scarcity and environmental degradation.

Artificial intelligence (AI) is transforming numerous sectors, including wastewater management. AI involves developing systems that can perform tasks typically requiring human intellect, like formulating assessments, solving problems, and diagnosing configurations. In the context of wastewater treatment, AI can be applied to model complex processes, optimize operational parameters, and automate decision-making, thus increasing the efficiency and effectiveness of treatment systems. (Li et al., 2024) The capacity of AI to analyse enormous volumes of data in real-time, leading to more precise predictions and responsive system control, is one of its greatest advantages. This ability is especially helpful in the treatment of wastewater because the composition of the liquid can change greatly depending

on where it comes from and the season. Artificial intelligence (AI) can assist in anticipating these variations and modifying treatment procedures accordingly, lowering the risk of system failures and enhancing treatment results overall. (Radović et al., 2022)

As a branch of AI, machine learning (ML) emphasizes on constructing algorithms that let systems learn from data and get better over time without explicit programming (Rajalingam et al., 2023). Because wastewater treatment processes are intricate and dynamic, ML techniques like unsupervised learning, reinforcement learning, and supervised learning are especially well-suited to these kinds of processes. To predict pollutant levels such as BOD, COD, TSS and other parameters for e.g., ML algorithms can be trained on historical data from treatment plants. This can optimize the operation of treatment processes by lowering the need for chemical inputs and energy consumption. (El Alaoui et al., 2023).

Additionally, ML can automate treatment controls, allowing for real-time adjustments using incoming data. This is particularly important in environments like industrial plants, where wastewater composition can differ greatly depending on the process. By continuously monitoring and adjusting treatment processes, ML-driven systems can ensure that treatment outcomes consistently meet required parameters, thereby reducing the risk of non-compliance with environmental regulations (Radović et al., 2022).

However, challenges remain, including the need for high-quality data to train AI and ML systems and the inherent complexity of wastewater treatment processes. Developing AI and ML models that accurately represent these processes and are generalizable across different treatment plants requires a profound understanding of the underlying science and the ability to integrate data from multiple sources (Cairone et al., 2023). The purpose of AI and ML in wastewater management is quiet in its nascent stages, yet the potential benefits are already evident. AI and ML technologies have shown great promise in optimizing nutrient removal processes, predicting and controlling pollutant levels, and improving the overall operational efficiency of treatment plants (Lowe et al., 2021). These technologies can be integrated with other evolving technologies, like Internet of Things and advanced sensor networks, to create fully autonomous treatment systems capable of operating with minimal human intervention.

2. WASTEWATER TREATMENT PROCESSES

Environmental engineering is the practice of managing environmental resources, removing pollutants in water and air. The method of treatment is normally categorized in three steps: primary, secondary and tertiary treatments. The purpose of primary treatment is to physically remove the large solids and suspended particles from wastewater, which is step one in the progression through a sewage treatment plant. This stage is basically the passing of the waste through screens and sedimentation tanks where heavier solids sink to the bottom and fats, oils, greases float up and can be skimmed away. This step is important for the purpose of lowering the Biochemical Oxygen Demand (BOD) and preliminary treatment upstream unit. Primary treatment removes about 60-70% of the suspended solids and is an essential pre-treatment step for secondary treatment (Jahan et al., 2022).

This is where the remainder of the organic matter not removed by primary treatment is made to undergo biological processes as in secondary treatment. In this stage, aerobic processes like activated sludge systems, trickling filters or biofilm reactors are typically used to biodegrade organic pollutants with microorganism. The performance of secondary treatment relies greatly on the continuous operation under ideal conditions for microbial activity (proper oxygen levels, proper pH and temperature). The secondary treatment usually removes 85–95% of BOD and other organic pollutants (Mandal et al., 2020). For high-strength industrial wastewater, anaerobic processes are also applied in some cases (Show et al., 2020).

Tertiary treatment is the last step in the heyday management process- adding up added polishing to the effluent until it exceeds high-point water quality standards before it is released or recycled. It usually requires high-level filtration, chemical treatments and chlorination or Ultraviolet (UV) disinfection. Tertiary treatment focus on residual nutrients (nitrogen and phosphorus), pathogens, and trace organic compounds remaining in the water after primary and secondary treatments inadequate completion is target to remove by this step (Zagklis & Bampos, 2022). In this stage, the objective is to produce an effluent that is devoid of contaminants about sensitive ecosystems or for use in processes such as irrigation and industrial processes i.e., (Jahan et al., 2022).

Whilst critical, most traditional wastewater treatment systems grapple with some persistent problems: Wastewater composition varies significantly based on the source—whether it be municipal, industrial, or agricultural—which translates into a range of different contaminants that need to be tackled for each. For instance, industrial wastewater is likely to have poisonous chemicals, heavy metals and other such toxic substances that the usual municipal wastewaters may not contain. For this reason, treatment plants must be very flexible and able to remove a broad spectrum of pollutants without affecting performance (Villarín & Merel 2020). Wastewater treatment is energy-intensive especially in terms

of secondary treatment processes. The aeration process — which imparts oxygen to assist microbial activity in biological treatment systems — alone may be as much as 60% of the total energy usage at a treatment plant. Also, the requirement of constant operation, maintenance and chemical for tertiary treatment make the operational cost very high. The optimal performance has a high energy consumption and maintaining effective treatment outcomes in balance with energy efficiency is still the biggest challenge of the WWTP (Kim & Oh, 2021).

Environmental regulations are becoming more and more stringent, demanding that the quality of effluents is continuously improved in wastewater treatment plants. Having been recently developed, it is not surprising that many of these regulations focus on removing trace organic contaminants—compounds found in our medications and personal care products (PCP) at concentrations too low to be detected by the human eye. These compounds are difficult to remove with traditional treatment processes because most of them were developed long before the awareness we currently have. This has been made more challenging by the fact that treatment facilities globally are expected to be environmentally friendly and energy neutral on wastewater treatment processes (Villarín & Merel, 2020). Wastewater treatment is one of the areas where AI & ML can truly transform —by providing powerful solutions to many of difficulties traditional approaches entail. Wastewater treatment processes are too dynamic and complex — they feel next to impossible. This is precisely why AI and ML technologies fit in perfectly into this domain. It comes with some significant benefits;

3. COMMONLY USED AI TECHNIQUES IN WATER/WASTEWATER MANAGEMENT

In this article we look at how can be used AI and ML models especially Artificial Neural Networks (ANNs) and Support Vector Machines (SVMs) to analyse historical data in order to predict future results. For example, in wastewater treatment applications, these models can forecast effluent quality and process performance thereby allowing operations to be optimized or proactive measures taken before system failures arise. Thus, it will be possible to anticipate and optimize more about the operation of treatment facilities (El Alaoui El Fels et al., 2023).

AI systems improve operational parameters, including chemical dosing, energy use and sludge production. AI as an intelligent system can change these parameters dynamically according to a real-time analysis and manage to achieve partial (yet relevant) cost savings benefited by treatment efficiency increase thanks to the AI capability of ongoing optimization of medical protocols itself. Real-time AI-driven automation solutions for wastewater treatment procession: The systems have been designed to automatically change treatment parameters to react to the changes in the composition of wastewater, the way providing a homogenized quality and good treatment standards (Jafar et al., 2022).

ANNs are computational models encouraged by the human being brain structure and capable of computing systems for detailed interpretation. Neural networks are essentially a series of layers of nodes (neurons) that simply accept data, process it, and make predictions based on it (Liu et al., 2024) For these reasons, ANNs, which are inherently capable of simulating complex, nonlinear relationships between input and output variables, may be advantageous for predicting treatment performance and optimization in wastewater treatment applications. As an example, ANNs have been implemented in predicting main wastewater parameters, such as COD and BOD concentrations with high potential. Predicting the outcomes of each treatment enables operators to conduct informed decision-making on treatment manipulation; which also contributes to improving process efficiency in general and minimizes non-compliance risks with environmental directives (Radović et al., 2022), (Kayı & Saleh, 2021)

SVMs are directed learning prototypes that use learning algorithms to analyse data for classification and regression tasks. SVMs are especially effective in high-dimensional input spaces with complex classification problems (Ma'aitah, 2024). In these cases, by using the SVM trained with historical data can classify effluent quality determine outcomes such as BOD and COD levels, identifying patterns that conventional analysis does not easily see. The advanced processing capabilities of SVMs that handle large database efficiently and deliver more accurate performance, allow for application to different water treatment operations toward process optimization and regulatory compliance (Nourani et al., 2021).

Predictive modelling is a powerful tool in wastewater treatment that uses statistical algorithms and machine learning (ML) to predict future outcomes by analysing past data. It plays a crucial role in foreseeing variations in wastewater composition, optimizing treatment parameters, and preventing system failures. For instance, predictive models can forecast effluent quality based on incoming water characteristics, enabling operators to fine-tune treatment processes in advance. This proactive approach minimizes the risk of non-compliance with environmental standards and enhances treatment efficiency. The successful application of predictive modelling across various wastewater treatment systems shows its potential to improve process control and operational performance (Aparna et al., 2024).

Data-driven modelling is a key application of artificial intelligence (AI) and machine learning in wastewater treatment. These models analyse massive amounts of data gathered from both historical records and real-time monitoring to make predictions and optimize operations (Bahramian et al., 2022). For example, ML algorithms such as ANNs and SVMs

are widely used to model the complex processes in wastewater treatment, helping plant operators make more precise decisions (El Alaoui El Fels et al., 2023). In one successful example, a municipal wastewater plant utilized an ML model to predict the behaviour of nitrate-reducing bacteria, which are vital in the nitrogen removal process. By analysing data like influent characteristics and operational conditions, the model accurately forecasted the activity levels of these bacteria, allowing operators to optimize the nitrate reduction process. This resulted in enhanced nitrogen removal and reduced energy consumption, demonstrating the value of data-driven modelling in improving biological nutrient removal (Inbar & Avisar, 2024).

AI and ML are also reshaping process optimization in wastewater treatment. Traditional optimization methods rely heavily on manual adjustments and operator expertise, often leading to inefficiencies. In contrast, AI-driven optimization uses real-time data to adjust operational parameters dynamically, resulting in more efficient and cost-effective treatment. A study by Silva et al. (2023) highlighted how ML models can adapt treatment processes to changing conditions, improving efficiency and reducing operational costs.

A great example of AI-driven optimization can be found in membrane bioreactor (MBR) systems, which are advanced technologies used to produce high-quality effluent. However, membrane fouling—where particles accumulate on membrane surfaces—can hinder performance and raise maintenance costs. To address this, researchers developed an ML model that predicted fouling based on operational data like transmembrane pressure and influent characteristics. The model then enabled real-time adjustments in cleaning cycles and aeration rates, reducing fouling and extending the membrane lifespan. This approach lowered both energy consumption and operational costs, making MBR systems more sustainable.

4. AUTOMATION AND REAL-TIME CONTROL

AI-powered automation systems significantly enhance the efficiency of wastewater treatment plants by reducing the need for manual oversight. Traditional systems require constant human intervention to respond to changing conditions, but AI-driven systems can autonomously adjust treatment parameters in real-time. For instance, Cao and Yang (2020) introduced an advanced control system using an Online Sequential Extreme Learning Machine (OS-ELM) that adjusts operational settings automatically based on real-time data. This system efficiently handles fluctuating dynamics without human input, improving the plant's overall performance. One practical example of AI automation is the use of predictive control for managing dissolved oxygen (DO) levels, a critical factor in aerobic biological processes. Researchers developed a control model that used past data to predict future DO needs, adjusting aeration rates in real-time. When implemented in a wastewater treatment plant, this model reduced energy consumption by 15% while maintaining treatment quality, showcasing AI's potential to improve both cost efficiency and sustainability.

5. CASE STUDIES: AI AND ML IN ACTION

Actual case findings reveal the transformative power of AI and machine learning in wastewater treatment. In one study, Kim and Oh (2021) used machine learning to enhance the performance of nitrate-reducing microbial populations in a municipal wastewater plant. By predicting bacterial activity, the ML model enabled operators to optimize nitrate reduction, resulting in improved nitrogen removal and lower energy consumption. Frontistis et al. (2023) conducted another study on optimizing MBR systems by predicting membrane fouling using machine learning algorithms. This enabled real-time adjustments to operational settings, resulting in significant savings on cleaning frequency, energy consumption, and costs. In a third study, Han et al. (2018) devised a predictive control strategy to optimize DO levels in biological systems. Implementing this model in a full-scale treatment plant resulted in a 15% reduction in energy consumption while maintaining treatment quality, demonstrating the value of AI in energy management. Wang et al. (2021) presented a machine learning framework for improving effluent quality control. This system could predict effluent quality based on several factors, providing real-time feedback to operators and assisting with regulatory compliance while improving process reliability.

6. KEY ISSUES IN APPLYING AI AND ML FOR WATER RESOURCE MANAGEMENT AND TREATMENT TECHNOLOGIES

AI and machine learning (ML) represent significant advances in water and wastewater treatment, but their widespread implementation faces several challenges. One of the main concerns is the convolution and explainability of AI/ML models, which may make it difficult for the general public and relevant professionals to fully trust and understand these systems, particularly in precarious extents such as drinking water treatment (Jones et al., 2023). Data reliability and availability are also challenges because models rely heavily on the quality and suitability of the data on which they are trained. Smaller communities may not have the resources to manage the large datasets required for successful AI/ML implementation (Smith & Baker, 2022). Furthermore, reproducibility in AI/ML remains a challenge due to custom functions and random model weights, making it difficult to apply a single model across multiple industries or replicate

results. The lack of standardized benchmarks for data selection complicates the application of AI/ML models in diverse settings, making regulatory adoption difficult (Smith & Baker, 2022). Finally, the inconsistency of statistical methods makes it difficult to evaluate and validate AI/ML models across studies.

7. CONCLUSION

In summary, the application of AI and ML in wastewater treatment marks a transformative shift in managing water resources. With traditional systems under growing strain from urbanization, tighter regulations, and environmental concerns, AI and ML present cutting-edge solutions that improve efficiency and sustainability. These tools enable concurrent data exploration and prognostic perceptions while optimizing operational parameters to enhance treatment effectiveness and lower costs. AI's ability to handle vast and complex datasets allows for a deeper understanding of the dynamic nature of wastewater. Specifically, machine learning techniques like ANNs and SVMs show great potential in forecasting effluent quality and refining treatment processes, ensuring compliance with stringent environmental standards. Although challenges such as data quality and the inherent complexity of treatment processes remain, the benefits of AI and ML are increasingly evident. By adopting these advanced technologies, we can develop more robust and flexible wastewater treatment systems capable of addressing the evolving needs of our world. Ultimately, the future of wastewater management hinges on embracing these innovations to secure a cleaner and more sustainable future for generations to come.

Abbreviations

AI – Artificial Intelligence

ML – Machine Learning

BOD – Biochemical Oxygen Demand

COD – Chemical Oxygen Demand

TSS – Total Suspended Solids

ANNs – Artificial Neural Networks

SVMs – Support Vector Machines

WWTP – Wastewater Treatment Plant

MBR – Membrane Bioreactor

DO – Dissolved Oxygen

PCP – Personal Care Products

UV – Ultraviolet

OS-ELM – Online Sequential Extreme Learning Machine

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