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Optimization of wastewater treatment by integration of artificial intelligence techniques: recent progress and future perspectives

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Abstract: Artificial intelligence (AI) is proving useful in optimizing the process efficiency in many sectors, including wastewater treatment. The complexity of wastewater characteristics and treatment technologies leads to uncertainties and variability in the efficiency of the processes in wastewater treatment plants (WWTPs), resulting in environmental risks and increased operating costs. Many studies have shown that AI could be applied to achieve better performance in WWTPs, minimizing potential negative environmental impacts, enhancing the quality of treated wastewater, and reducing costs through efficient, innovative, and smart solutions.

This article provides a review of recent progress in the implementation of AI in wastewater treatment, giving an overview of the state of the art in this field. The analysis conducted in this review demonstrates the enormous potential of implementing AI technologies in wastewater treatment applications, obtaining technologically advanced systems that simultaneously provide high purification performance, simplified process management and reduced operating costs. Furthermore, automation of processes and improved monitoring activities can be fostered by applying AI. Finally, the future potential of the integration of AI techniques in wastewater treatment is discussed and the long-term prospects in this field are presented. Research can make great strides by addressing the challenges and overcoming the limitations that hinder their implementation in full-scale plants.

Keywords: Machine learning, Wastewater treatment automation, Wastewater data analysis, Advanced algorithms, Advanced treatment

1. Introduction

Water is an essential resource and any alteration in its quality and/or quantity can impact the well-being of living species and the quality of ecosystems (Naddeo, 2021). Ensuring enough water of good quality is crucial to support the sustainable development of the world's countries (Alcamo, 2019). However, water pollution and water scarcity across the world are problems of growing concern, threatening human health, ecosystems' quality, economic growth, and social progress (Ezbakhe, 2018; Salehi, 2022). To reduce negative impacts on human well-being and the natural environment, attention must be paid to the development of advanced strategies to protect water resources. Wastewater treatment plants (WWTPs) are crucial for water resource preservation by ensuring that wastewater is properly treated and disposed of without contaminating receiving water bodies (Obaideen et al., 2022). Consequently, if managed sustainably and effectively, wastewater treatment plants protect human health and the environment. However, improvements in wastewater treatment are becoming increasingly important due to stricter requirements on the quality of effluent, the need to minimize the consumption of energy and chemicals (Icke et al., 2020). One way to enhance the performance of WWTPs consists in implementing advanced process control strategies, based on data measured during the treatment process (Bahramian et al., 2023). Among these strategies, the technical and scientific community has shown increasing interest in recent years in integrating artificial intelligence (AI) techniques into WWTPs.

Artificial intelligence has been defined as the ability of a computer-controlled system to conduct actions typically associated with the capabilities of the human mind, such as reasoning, making decisions, or learning from past events. Many powerful and practical AI tools have been produced to overcome complex problems in many fields of science and engineering (Zhao et al., 2020). Among other fields, AI has also been applied to address the problems of monitoring, management, and labor costs in smart water services (Ray et al., 2023). This brief review provides information on current advances, opportunities, and challenges in applying AI to optimize efficiencies in WWTPs.

2. AI to optimize wastewater treatment

2.1. Current challenges in wastewater treatment

WWTPs have existed for more than 100 years, but today the sector of wastewater treatment is in full mutation: wastewater is no longer being perceived as a problem but as a resource to recover valuable products (Sin and Al, 2021). Numerous interactions between physical, chemical, and biological processes occur in WWTPs, requiring multidisciplinary approaches and expertise from different scientific fields to manage them effectively (Poch et al., 2004). The complexity of wastewater composition and wastewater treatment technologies lead to uncertainties and variations in process efficiency, resulting in fluctuations in effluent water quality, operating costs, and environmental risk (Zhao et al., 2020). If untreated or poorly treated, wastewater can damage ecosystems, causing problems such as eutrophication (Adam et al., 2019) and environmental pollution (Sathya et al., 2023; Szopińska et al., 2022), and posing risks to human health. During the COVID-19 pandemic period, SARS-CoV-2 was widely detected in wastewater, representing a useful way to estimate the amount of infected population (Corpuz et al., 2022). This has raised concerns that inadequately treated wastewater is a transmission medium of viruses, thus increasing their spread (Elsaid et al., 2021). These problems, in addition to the need to comply with increasingly strict environmental regulations, lead to the need for improved wastewater treatments to enable even higher effluent quality, to promote resource recovery, to reduce emissions, to decrease energy consumption, and to lower overall costs (Soares, 2020). To address these challenges, over the years, various research has been conducted to optimize wastewater treatment processes or to develop new and increasingly effective techniques with sustainability in mind.

2.2. Implementation of AI in wastewater treatment

The application of AI in WWTP can optimize its management and can ensure better effluent quality, and consequently can promote wastewater reuse and recovery of energy and various materials (Zhao et al., 2020). Potential benefits of the digital revolution in wastewater treatment include reducing operating costs, chemical and energy consumption, assisting in decision-making (Matheri et al., 2022), and supporting control and automation of WWTPs (Mannina et al., 2019). AI-based strategies can optimize process parameters by making automatic decisions in a short time: based on the input data, AI systems can regulate plant equipment settings as well as send alarms to operators (Viet and Jang, 2021). Artificial neural network (ANN) is the most widely used algorithm in AI applications in wastewater treatment. ANN is a non-linear statistical model based on the same approach as the human brain: it learns from data of past experiences to provide better responses in the future (Matheri et al., 2021). Most researchers have focused on predictive control of influent and effluent quality parameters such as temperature, pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), turbidity, total suspended solids (TSS), total nitrogen (TN), ammonium (NH_4^+-N), nitrate (NO_3-N), total phosphorus (TP), food to microorganism ratio (F/M), hydraulic retention time (HRT), sludge retention time (SRT), sludge volume index (SVI), and gaseous emissions (Singh et al., 2023). Yang et al. (2022) developed a dynamic model capable of predicting COD and TN in the effluent. Wang et al. (2022) used historical data to train ANN models that can predict the quality and quantity of influent wastewater and effluent to enhance the management of WWTPs and reduce waste of energy and materials. Shirkoohi et al. (2022a) noted that AI techniques have the potential to model, predict performance and optimize electrochemical processes used for water and wastewater treatment. Shirkoohi et al. (2022b) developed AI models capable of predicting the removal efficiency of phosphate from wastewaters using the electrocoagulation process. An AI model was applied by Picos-Benítez et al. (2020) to optimize the treatment of dye wastewaters and reduce energy consumption. Matheri et al. (2021) used an AI-based prediction model to investigate the interrelationship between COD and trace metals. ANN was also adopted to predict total coliforms in the effluent of the treatment process with sequencing batch reactors (SBR) (Khatri et al., 2020). AI-based models have been used to predict and optimize the performance of membrane filtration technologies for wastewater treatment. Specifically, membrane fouling control can be improved with AI-based techniques (Kamali et al., 2021) by optimizing operating conditions, and efficiency of physical and chemical cleaning operations (Niu et al., 2022). AI has also been employed to improve the fabrication of membranes (Li et al., 2022).

2.3. Current shortcomings in AI techniques applications in wastewater treatment

Although the application of AI in wastewater treatment has many benefits, some shortcomings need to be overcome to exploit its full potential in real WWTPs. Certain circumstances, such as sudden fluctuations in input variables, water quality, and operating conditions, could cause AI tools to make incorrect predictions. Artificial intelligence models have proven to be extraordinary in modelling wastewater treatment processes with a small amount of input data. However, it is important to conduct new studies to explore their implementation in real processes with a large dataset (Alam et al., 2022). In accordance with Zhao et al. (2020), there is a need to develop models that help to simultaneously address the challenges of removing pollutants, reducing costs, water reuse, and plant management. Automation of WWTPs is hindered by investment costs, lack of properly trained staff and difficulties in remote sensing (Soares, 2020). Another limitation relates to the accuracy of measurements. In fact, the data values collected by sensors installed in the treatment tanks could be imprecise and not representative of the entire process. To limit these errors, simultaneous use of sensors in different positions is recommended (Bahramian et al., 2023). In addition, it is necessary to consider that sensors require regular calibration and maintenance (due to fouling, interference, etc.) to ensure accurate measurements (Soares, 2020).

Some aspects related to artificial intelligence in wastewater treatment are mistakenly considered disadvantages, including (Ray et al., 2023):

- High operational cost: Artificial intelligence techniques can directly reduce overall operational and energy costs through alerts provided in the event of membrane failure, pipeline damage, and other unusual defects.

- Total loss of control system: AI can provide accurate and immediate response to any failure, helping operators make timely decisions.

- Unemployment: artificial intelligence will not replace human workers, who are needed to maintain and resolve complex system disruptions. However, AI ensures a faster response to handle operational challenges more quickly (Al Aani et al., 2019).

3. Conclusions and future perspectives

Artificial intelligence is proving to be a solution for automating and optimizing wastewater treatment, offering ways to combat problems of water pollution and water scarcity. The integration of AI into WWTPs has the potential to significantly reduce operating costs by optimizing chemical use and energy consumption, and improve the efficiency of treatment processes, promoting wastewater reuse and representing an important contribution to the protection of the environment and human health. In addition, its ability to analyze large amounts of data, identify problems and predict them before they occur, and take autonomous action would also improve the management of WWTPs. AI can help support the growing challenges facing today's WWTPs due to increased demand, restrictions on gas emissions, strict environmental regulations, reduced energy consumption, and lower operating costs. Consequently, AI has the potential to improve the sustainability of the wastewater treatment sector. Future research should focus on developing models that can account the overall dynamics of wastewater treatment processes, considering many parameters at the same time, as well as real-time regulation of operating parameters. Further studies are needed on the applications of AI in WWTPs, particularly in collaboration with wastewater treatment experts and computer science researchers.

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