Artificial intelligence techniques applications in the wastewater: a comprehensive review

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Abstract. There are some challenges are firms the wastewater treatment, numerous hurdles concerning the enhancement of the energy efficiency, compliance with the increasingly stringent water quality regulations, and the maximizing resource recovery opportunities. In recent years, the computational models have garnered acknowledgment as potent instruments for tackling these various challenges, bolstering of the operational and economic effectiveness of the various wastewater treatment plants ("WWTPs"). Also, the review discusses the application of the various (AI) algorithms on the various wastewater treatment plants (WWTPs), predicting ("WWTP") effluent properties, the wastewater inflows, the anomaly detecting, and the energy optimization. The critical gaps and the future directions in the (AI) algorithms for the wastewater treatment, including the explain ability of the data-driven models or transfer Learning processes and reinforcement learning, are also addressed.

1 Introduction

The growth of population and the changing in the lifestyles are make a predictable the demand on water, energy will also be increasing, making this resource very important with the expected scarcity in some regions around the world [1]. To warranty accessing to the cleanly water for the population is the challenge that contain the disposal and wastewater treatment and monitoring it [2]. Monitoring leads to detect of the failure in the ("WWTPs"), leading to improve both quality terms and in reducing the maintenance of the risks [3]. The Management of the ("WWTPs") is an exhaustive and very complicated, and it dependent on the non-controllable factors like as the unexpected conditions of the weather and the water

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leaks [4]. Wastewater treatment is a critical process for maintaining of the environmental health and ensuring the availability of clean water resources [5]. Artificial intelligence (AI) techniques have emerged as promising techniques to address these various challenges and optimize the different aspects of the wastewater treatment [6]. “AI” encompasses a range of the computational technologies that enable machines or tools or computers for performing tasks that typically required the human intelligence, such as learning from data, patterns recognizing, decisions making, prediction, and adapting to changing conditions [7].

2 Definition of the Artificial intelligence

The Artificial Intelligence (AI) is referring to the emulation of the intelligence of human operations by the systems of computers and these processes are including the learning (“the acquisition of the information and the rules for utilizing the information”), reasoning (“utilize the rules to reach approximate or definite conclusions”), and the auto-correction [8]. (“AI”) is encompasses a wide range of the technologies and paths, included the “machine learning” (ML), “natural language processing” (NLP), “computer vision”, “the robotics”, the expert systems, and so on [9]. The essential aim of the (“AI”) is to construct smart systems that can performing the tasks that typically requires the human’s intelligence, like as, the understanding of natural language, patterns recognize, decisions making, and solution the complex problems [10]. The (AI) has wide applications across various fields, such as the environmental, healthcare, transportation, education and so on [11].

2.1 Artificial Intelligence Techniques advantages in wastewater

Artificial intelligence (AI) techniques are offer several advantages in the wastewater management and treatment [12].

1. The Predictive Analytics: (AI) algorithms can analyzing the data of wastewater treatment processes [13], for predicting in the future trends, such as the changing in the levels of pollutant or equipment failures, so the predictive capability enables deal with the maintenance scheduling with high level of performance, lead to improve the efficiency and cost saving.
2. The Monitoring in the Real Time: (AI) has a vital role in the powered sensors, so the (AI) can - for example- continuously monitoring the different parameters of the wastewater quality, like the ("pH"), turbidity, and chemical concentrations, in the real-times [14]. That will allow for prompting detecting of abnormalities or pollution or unexpected cases, facilitating rapid response and mitigation measures.
3. Process Optimization: Optimization of the Processes: (AI) algorithms can optimizing a various aspects of the wastewater treatment processes, like as the adjusting of chemical dosages, controlling of the flow rates and optimizing of the energy usages [15]. By dynamically adapting for the changing conditions, also treatment efficiency enhancing, reducing the costs of operating and minimizing the various environmental impacts.
4. Detection of Anomaly: (AI) systems can detect the anomalies in wastewater treatment processes, like different malfunctions in the equipment, leaks, or deviations from expected performance [16]. Early discovering of such as these cases enables timely intervention to prevent the failures in the system or mitigating of the different prospective environmental risks.
5. Decision Support Systems: the decision support systems based on the (AI) can assisting the wastewater treatment plant operators for making the informed decisions by analyzing a large amounts of the data and providing an actionable insight [17]. These systems can help to optimize resource allocation, prioritizing maintenance tasks, and guiding long-term planning strategies.

6. Energy Efficiency: (AI) algorithms can optimizing the energy consumption in wastewater treatment plants by intelligently controlling pumps, blowers, and other equipment based on the real-time demand and process conditions [18]. This can lead to reduce of the energy costs and lower carbon emissions.
7. Adaptive Control: (AI) based on the control systems can dynamically adjusting of the operating parameters in response for changing conditions, such as the variations in the influent characteristics or weather patterns [19]. This can improve system resilience and ensures consistent treatment performance under of different operating scenarios.
8. Data-driven Insights: (AI) techniques can uncover of the hidden patterns and correlations within the wastewater data that may not be apparent through classical analysis methods [20]. By discovering and extracting valuable insights from complex datasets. Also, (AI) can support the evidence-based decision-making and facilitate continuous process improvement.
9. Remote Monitoring and Controlling: (AI) enabled remote monitoring and controlling systems allow operators to monitor and manage the wastewater treatment processes from anywhere with an internet connection [21] This can enhance the operational flexibility, enables rapid response to emergencies, and reduces the need for in-site personnel.

Totally, (AI) techniques can offer significant advantages in the wastewater management and treatment [22], including the improving of the efficiency, enhancing of the environmental protection, and better resource utilization. By take advantage of the power of ("AI"), wastewater treatment facilities can be optimizing their operations, minimizing costs, and ensure compliance with regulatory standards.

2.2 Challenges of the Artificial Intelligence Application in wastewater:

AI application in the wastewater also presents some of the challenges [23]:

1. Availability of the Data and its Quality: (AI) algorithms heavily rely on the data for training and decision - making. In wastewater treatment, data collection can be challenging [24], due to the complex nature of wastewater composition and variations in flow rates. Ensuring data quality, consistency, and availability is crucial for the successful application of (AI).
2. Data Integration and Compatibility: Wastewater treatment plants often use a variety of sensors, instruments, and monitoring systems from various manufacturers. Integrating data from these disparate sources can be challenging due to variation in data formats, protocols, and compatibility issues [25]. (AI) systems must be able to handle and integrate diverse data kinds seamlessly.
3. Model Generalization: (AI) models trained on the data from one wastewater treatment plant may not generalize well to other plants due to variations in the infrastructure, the operational conditions, and influent characteristics [26]. Developing (AI) models that can be generalizing across various plants while maintaining performance accuracy is a significant challenge.
4. The Interpretability and Explain ability: Many of the (AI) algorithms are often perceived as (black boxes) due to their complex internal workings. In critical applications like as the wastewater treatment [27], it is very important to understand how can (AI) algorithms make decisions and provide explanations for their recommendations or predictions.
5. The Operation in Real-Time: Wastewater treatment processes operate in the real time, and decisions must be made promptly for optimizing of the performance and ensure regulatory compliance [28]. (AI) algorithms need to be capable of processing data and making the predictions in the (real-time) to provide timely insights and recommendations to wastewater plant operators.

6. Regulatory Compliance and Trust: Wastewater treatment plants are subjecting to strict regulatory requirements aimed at protecting the public health and the environment. (AI) based on solutions must comply with the regulatory standards, and stakeholders need to the trust and accuracy of (AI) driven decision-making processes [29].
7. Cybersecurity Risks: As wastewater treatment plants become more interconnected and reliant on digital techniques, it become a potential aim for cyberattacks [30]. (AI) systems may introduce additional cybersecurity risks if not properly secured, potentially leading to data breaches, the operational disruptions, or the safety hazards.
8. Cost and Resource Constraints: Implementing of “AI” solutions in the wastewater treatment requires a significant investment in terms of technology, infrastructure, training, and maintenance [31]. Many of the smaller treatment plants may be facing resource constraints or lacking the expertise needed to adopting and leverage (AI) effectively. Addressing of these challenges are requires the collaboration [32], between the researchers, industry stakeholders, policymakers, and regulatory agencies for developing robust (AI) solutions that can be enhancing the efficiency, reliability, and sustainability of the wastewater treatment processes.

3 Literature Review on the Artificial intelligence in wastewater

This review is discussing the present state of the art for "AI" technologies utilized in the wastewater management, including machine learning, neural networks, genetic algorithms, expert systems and so on [33], see the Figure 1, [34]. Also, it explores specific applications of the (AI) in the wastewater treatment processes such as the pollutant detection and removal, processes optimization, predictive maintenance, and the decision support systems [35]. In addition, this review highlights on the challenges and the future research directions in the integration of “AI” techniques in the wastewater management practices. In this study, it utilized some critical applications of water and wastewater treatment were optimized, automated and modelled by utilizing the (AI) techniques and (ML) models. Wastewater characteristics prediction in the (“WWTPs”) was important and can reducing the numbers of the samplings, energy, and costs. The study reviewed (ML), deep learning, and intelligent techniques were utilized in the treatment of wastewater for generating, predicting, enhancing, and classification, providing a guide for the future of the challenges in the water resources. These models were utilized to decisions make in the water resources governance and management, but the ethics and the future directions needed to focused and addressed [36].

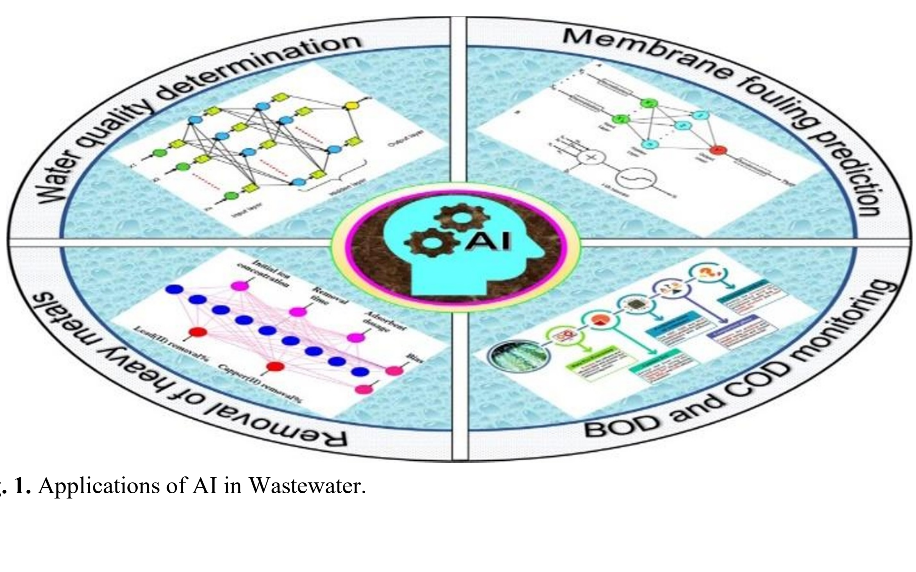

Fig. 1. Applications of AI in Wastewater.

This study was focused on the removing nitrates and phosphates from municipal wastewater, and electrocoagulation process with the (“EC - MBR”). The study was evaluated the efficiency removal process of the wastewater organic matter for (“NO^{-3}”) and (“$PO4^{-3}$”) and how it related with (ML) indicators. It utilized an (“EC-MBR”) with the operational parameters for collecting and analyzing effluent from the treated municipal wastewater by used chemical and biological methods. Based on the results, the neural network method was achieved a better accuracy than the classical methods. Also the results showed that a reactor had acceptable maximum removal efficiency [37].

This study was covered the “AI” based models utilized in wastewater treatment from different sources, and discussed the advantages, disadvantages and gaps from every model. The conclusions and discussions presented that “AI” models were beneficial to forecast the performance of “MBR” to recovered cleanly water from the polluted sources. But, further more efforts were still required to reach an optimal match between the forecasting’s that were made by ("AI") technologies and the empirical outcomes. That can be achieved by modification or integrating of the current "AI" based on methods. The developing of the appropriate variables for optimizing the performance of ("MBRs") and improved their efficiency for dealing with the recalcitrant pollutants like as the “contaminants of emerging concern” (CECs) were between the priorities for promoting the implementation of (MBR) techniques in the real scale implementations [38].

In this study it was examined the literatures from (1995 until 2019) for conducting a huge - scale bibliometric analyze of tends in the applications of “AI” technique in wastewater treatment. Also, it was presented a review of (4) aspects of the applications of (AI) in the treatment of wastewater: the technique, the economy, the management and the wastewater re-use. as a result, it was provided viewpoints on the probable future trends of the new research frontiers in utilize (“AI”) for wastewater that simultaneously address, [39].

This study was focused on the relationship between the (COD) and trace metals, that was studied by utilized the “AI” based the forecasting model with (ANNs) incorporated in (MATLAB). It utilized an algorithm belongs to the supervised learning for the training the (ANNs) and to relate the input up - to output dataset. Training was aimed to predict and validate of the parameters by using an error function minimize. Goodness of the forecasting was achieved with (R^2) of (98 % - 99 %), (SSE) of (0.00029 - 0.1598), (RMSE) of (0.0049 -0.8673), (MSE) of (2.7059 -14 - 2.3175 e-15). The (″ANNs ″) were a robust tool to predict (“WWTP”) performance [40].

This study was proposed a new novel hybrid modeling method by integrate the first basic model with the deep learning method for predicting the (“N_2O”) emissions. The proposed model implemented with successful and validated with (N_2O) emission dataset from the full-scale (WWTP). The proposed model accuracy was higher for the (N_2O) emission modeling of (WWTP) than the classical model or the pure deep learning model and it more viable than the classical model due to lower requirements of the data and classical model due to less calibration requirements. The proposed model was implemented successfully to predict of the (N_2O) flux which was showed better performance. Also the proposed model was showed a big prospect to applied for the (“N_2O”) mitigation works, [41].

In this study, K-Nearest Neighbors (KNN), Gene expression programming (GEP), multi-linear regression, multilayer perception neural networks, gradient boosting and regression trees based models, were trained to predict the (BOD5) and (COD) and it was utilized the collected data monthly from inflow of (seven WWTPs) over a three years period in “Hong Kong”. Based on various statistical parameters, (GEP) provided more precise estimations, with (R^2) values of (78.4%) and (86.1%) for the (BOD5) and (COD). Also, outcomes of sensitivity analysis were undertaken by “Monte Carlo” emulation revealed that both of the (“COD and BOD5”) were affected by the concentrations of all suspended solids, and (“10%”) increased in (“TSS”) resulted in (7.94 %) and (7.92 %) increased in values of the (BOD5) and (COD). The (“GEP”) achieved better outcomes and it can be further implementation on the other sewage sources, [42].

This study was investigated the incorporation of the techniques the ("AI"), ("ML"), “Blockchain”, and ("IoT"), to create a revolution and elevate the procedures of the wastewater treatment. It presented a promising avenue to optimize the efficiency, sustainability, and the totally performance in the infrastructure of water treatment. These techniques were facilitated the monitoring in the real-time of the water quality parameters, the enabling the dynamic adjustmentings to protocols of treatment based on the insights of data driven. Integration of blockchain technique was introduced a secure decentralized framework to manage data in the systems of wastewater treatment. Due to the immutability and transparency of the “Blockchain”, users can be tracing the life cycle of the treatment of water, from the source until the discharge. Also, the ("IoT") was contributed to construct an infrastructure connected and responsive for treatment of wastewater. The embedded sensor networks throughout the process of the treatment could enable the collection of data in the real time, the facilitating of the remote controlling and monitoring. The easy communication between (IoT) devices ensure prompt identification of the anomalies and prospective failures in system, allowing for timely intervening and averting of the hazards environmental. The study was emphasized the significance of integration for addressing the challenges in wastewater treatment for more environmentally sustainable, [43].

This study aimed to investigated the effect of 6 (“FS”) methodologies of “categorized as Wrapper, filter and embedded methods" on the accuracy of (3) supervised "ML" to predict the total suspended solids "TSS" of municipal treatment of wastewater. Based on the features proposed by each "FS" method, five distinct scenarios were defined. Within each scenario "ANN- MLP", "KNN" and "AdaBoost" implemented. The features utilize to predict "TSS" concentration in "WWTP" effluent included: "BOD5, COD, TSS, TN, NH_3" in the influent, and “BOD5, COD”, residual "Cl_2, NO_3, TN, NH_4" in the effluent. The dataset divided randomly into: training, testing and "K-fold" cross validation were employed for controlling in the overfitting and under fitting. The evaluation metrics that were utilized: (RMSE), (MAE), and ("R^2"). The best scenario was fourth scenario, with the "FS" method. The features selected: "CODe, BOD5e, BOD5i, TNi". The “ANN-MLP" algorithm provided the best implementation, achieved highest "R^2", also it provided acceptable Implementation in both of the training and testing sub-sets (R^2 =0.78) and (R^2 =0.8), [44].

In this study it was developed, validated, and comprehended of “ML” models capable to predict of the “chemical oxygen demand concentration” in the effluent "CODout" of the ("WWTP"). The parameter ("CODout") chosen as an aim. A calibrated "WWTP" model obtainable on "WEST" software "DHI" is developed by used the ("Umbilo WWTP / South Africa") as an important reference, served as a source of the effluent and influent dataset. The data-set was organized by the day and by hour for training the ("ML") predictive models. It used the below ("AI") technologies: ("SVM, LSTM, MLP and RF"). Also, the "exploratory data analysis" was used for discovering and determining the multicollinearity among some of the model's input variables. In case of "CODout" predictions use the daily data-set, the "MLP" model was proved more effective than the clssical "ML". And when the hourly data-set applied, the ("LSTM") models performed were better by incorporating historical data-set into the structure of the model. When real measurements effluent was utilized for predicting "CODout", "SVM" model had superior results, even better than the classical models. Analysis of variable importance was showed the active influence of influent "TSS" to forecast "CODout". Also, it demonstrated the successful applicability of "ML" techniques to forecast "CODout" in "WWTPs" and provided important insights for improving the wastewater treatment [45].

4 Conclusion and future works

From this study, ("AI") for the (WWTPs), many important points can be concluded as below: Nearly, all of the "AI" applications in the "WWTPs" consisting on the forecast process. The outputs from "AI" models were including the effluents produced by "WWTPs": the ("COD", "TSS", "BOD5", "NH4", etc.), the energy consuming, mass flow, influents "COD" operation in the real time, filamentous sludge and sludge bulking. Different of the "AI" models "simple, assemble, hybrid models, supervised and unsupervised learning algorithms" were used on the real "WWTP" studies, for which "ANN" was the most well-known algorithm. The utilize of ("SVM and IoT") algorithms in "WWTPs", such as "LSTM", "CNN", hybrid models and so on, has been explored. Sensors based on the ("AI") were more important and activity as a practical support and active in operation of the WWTPs", also the direct application of sensors for the "WWTP" operation by the intelligent controlling is provided more efficiency and improved of the ("WWTP"). The comprising between algorithms for various studies were relative, although the "R^2" values and the errors provided acceptable outcomes. Also ("IoT") sensors were played an important and vital role to discover a huge numbers of data points to build data-driven ("AI") models. Also the datasets provided a trustworthy information that supported the operation of the WWTPs" especially in defectives detection or the anomalies. In general, the "AI" algorithms and techniques were provided better performance than the classical techniques in the sectors of wastewater. The using of ("AI") for processing or analysis the images like as the detection of biofilms and sludge in ("WWTPs") and predicting effluents still requires more studying. As a conclusion of recent applied ("AI") studies with the "WWTPs" some recommendations can be providing for the future: It is necessary to design and produce data solutions with the care and understanding of the data and processes involved in the WWTPs" with the sharing and collaboration the datasets on a wide scale. More of the new techniques of "AI" should be applied in the future studies on the ("WWTPs"). With the availability of the ("IoT") and modern on-line sensors in the ("WWTPs"), the detection of data driven models by the on-line learning and training by allow the models to directly applying the real-time data is a useful direction to the future studies. The applications of "AI" technologies in patterns reorganization and images analysis of the various parameters of the wastewater will be very important it will be helping for optimizing the maintenance, operation and increasing the performance of ("WWTPs").

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