INFLUENCE OF ARTIFICIAL INTELLIGENCE ADVANCES IN WASTEWATER TREATMENT THROUGH EVALUATING TECHNIQUES FOR SUSTAINABILITY GLOBALLY.

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ABSTRACT:

Efficient wastewater treatment is becoming increasingly important as the world's water supply continues to decline. To optimise processes, improve predictive capacities, and enhance informed decision-making in this crucial domain, advanced artificial intelligence (AI) techniques could be a game-changer. This study offers a comprehensive bibliometric analysis of 368 publications from the Scopus database between 2015 and 2024, focussing on research trends and developments in the use of AI for wastewater treatment. Research production increased significantly, reaching a peak of 93 articles in 2023, according to the data. This indicates that there is a rising tide of enthusiasm for using AI methods to solve problems in wastewater management. It has been determined that the Journal of Environmental Management, Chemosphere, and Water Science and Technology are the preeminent journals in this domain. China, India, and the United States all had substantial roles in the research, but the University of Johannesburg stood out as the most important participant. The analysis of keywords indicates that the technological techniques being examined are "artificial intelligence," "wastewater treatment," and "machine learning," which appropriately highlight the major research direction in this subject. Methods including anaerobic digestion, adsorption, and microalgae are becoming more popular. Over the past few years, heavy metals and fertilisers have dominated the research on wastewater contamination. Insights gained from this analysis can help direct future studies, stimulate the creation of useful AI-driven solutions, and lead to greener water management.

Keywords: Artificial intelligence (AI) Bibliometric analysis Machine learning (ML) VOSviewer Wastewater treatment

Introduction:

Natural and man-made pollutants pose serious risks to water, a resource crucial to human life and many industrial processes [1]. Water pollution has worsened due to the growing human population, increased industrialisation, faster urbanisation, and the far-reaching effects of climate change. This has caused ecological degradation, particularly from the discharge of fertilisers into water bodies [1-3]. There are both quantitative and qualitative constraints on water supplies as a result of the combined effects of these causes [4]. The lack of drinkable water sources is a constant problem in developed countries as a result of pollution from cities and industries, however it is more of an issue in developing nations [5]. The release of extremely harmful and non-biodegradable effluents is one way in which the excessive water consumption of different industrial sectors endangers ecosystems and contributes to environmental degradation [6]. One of the most pressing issues facing humanity in the twenty-first century is the need to mitigate the effects of water shortage on a worldwide scale [4,7,8]. Safe drinking water, healthy ecosystems, and human health are all dependent on effective wastewater treatment [7-9]. Nevertheless, conventional wastewater treatment techniques frequently fail to tackle the intricate problems presented by contemporary pollutants [8,9]. A key answer to this problem is the increasing emphasis on recovering and reusing treated wastewater [10]. When it comes to solving the problem of water scarcity, wastewater reclamation is generally considered to be among the best options [11]. This method is essential for the long-term management of water resources since it allows for their reutilization for various purposes [11]. To that end, cutting-edge methods for improving and developing wastewater treatment technologies in a sustainable manner are desperately needed [12,13]. At its core, this problem stems from the rising worldwide urgency of protecting water quality [14]. The fact that existing technology can only provide partial parametric quality measurements just makes the problem worse [15]. For years, scientists all around the globe have been looking for ways to improve water treatment methods [16–20].

To tackle the problems that come with wastewater treatment, people have been trying to create smart models that are optimal, affordable, and efficient [21, 22]. Recent years have seen the rise of an exciting new area at the crossroads of AI and wastewater treatment, which has the potential to completely alter our approach to environmental management and mitigation. The need for effective and long-term wastewater treatment solutions is greater than ever before due to the increasing industrialisation and urbanisation that is occurring alongside the continued rise in worldwide populations [1]. Ineffectiveness, high energy usage, and high costs are common complaints levelled against conventional wastewater treatment systems [22]. A new paradigm for tackling these issues has emerged with the incorporation of AI technologies, which automate and improve wastewater treatment operations while also increasing efficiency and accuracy. Pollutant identification, process control, resource recovery, and system optimisation are just a few of the areas that AI can improve upon in wastewater treatment with the use of machine learning (ML) algorithms, predictive modelling approaches, and advanced data analytics [23]. Wastewater treatment plants (WWTPs) may lower their environmental effect, increase operational efficiency, and meet regulatory requirements with the use of AI-driven insights. Algorithms trained by AI may perform tasks and draw conclusions that have historically required human expertise, in contrast to ML's emphasis on smart systems that adapt their behaviour based on training data [23].

Academic and industrial settings are adopting AI and ML due to their potential to enhance knowledge and streamline operations in various sectors, including wastewater treatment [24,25]. In instance, ML has demonstrated potential in tackling problems like WWTP system control, process optimisation, and pollution detection [26]. With their robustness and ease of use, AI, ML, and smart approaches can model and solve complex problems in wastewater treatment applications. This, in turn, leads to cost reduction and improved operational efficiency [27]. Prior studies have shown that AI models may effectively treat wastewater; however, most of the published works only cover particular methods or process designs; there is scant discussion of well-known AI models, their pros and cons, or any suggestions for improvement. Much of the prior research on ML algorithms and performance measures has been rather technical. Although these studies are insightful, they don't always cover all the bases when it comes to discussing the ethical implications, practical difficulties of implementation, and scalability of ML solutions in the real world. Also, in a crucial field like water treatment, there is a dearth of studies that assess the dangers of being too reliant on automated technologies. By undertaking a thorough bibliometric analysis, this study hopes to fill a knowledge vacuum by revealing prevalent themes, seminal works, and potential future directions for the use of artificial intelligence and machine learning in wastewater treatment.

The objectives of this research are threefold: (1) to draw a synthesis of existing literature on the topic of machine learning (ML) applications to water scarcity and wastewater treatment problems; (2) to catalogue possible difficulties and ethical issues associated with ML implementation in this field; and (3) to serve as a guide for the advancement of AI-powered wastewater treatment systems. This paper will analyse the current literature to investigate the various uses of artificial intelligence (AI) in wastewater treatment, including control and monitoring in real-time as well as optimisation and predictive modelling. Data availability, model robustness, scalability, and regulatory approval are some of the limitations and problems that will be examined in relation to the use of AI technology in real wastewater treatment settings. The purpose of this paper is to provide researchers, practitioners, policymakers, and industry stakeholders with the information they need to understand these factors and use AI to solve the complex environmental problems associated with wastewater management. Our goal in taking stock of where things stand and where they're headed is to encourage more cross-disciplinary work and new ideas in this important field so that we can find wastewater treatment solutions that are better for the environment and people.

Materials and methods:

When applied to large literature collections, bibliometric analysis yields insightful results from quantitative and qualitative perspectives. In order to visually display the structures, knowledge frameworks, interconnections, and overlaps that exist within the literature, this method employs data mining, processing, and mapping approaches. It achieves this by combining mathematical, statistical, and visual ideas [28,29]. There is a lot of consensus and good evidence supporting bibliometric analysis as a useful tool for gauging the health of various research disciplines, publications, institutions, and trends in research topics [30]. For the purpose of comprehending the interconnections among journal citations and offering a synopsis of the present or future state of affairs pertaining to a specific research subject, it is a common and accurate way to examine and analyse large amounts of academic data. By looking at previous studies and how they progressed, bibliometric analysis aids future research via its indicators [31]. The broad acceptance of bibliometric techniques across numerous domains might be attributed to these qualities [32]. Scopus was chosen for its extensive coverage of academic articles across disciplines, especially in technology-related literature [33], so this study could use bibliometric analysis to outline trends and advancements in AI-driven wastewater treatment research using its data. Scopus was chosen because of the breadth and depth of its coverage of academic works in technology as well as its accumulation of works from a variety of fields [34–36]. When compared to Web of Science (WOS), Scopus offers around 20% more coverage, while the levels of precision with which Google Scholar finds results vary [35, 36]. Articles written between 2015 and 2024 were the primary focus of the search, which took place in April of 2024. The search term string that includes both "artificial intelligence" and "AI" as well as "wastewater treatment" Along with Pubywar, PURBYER

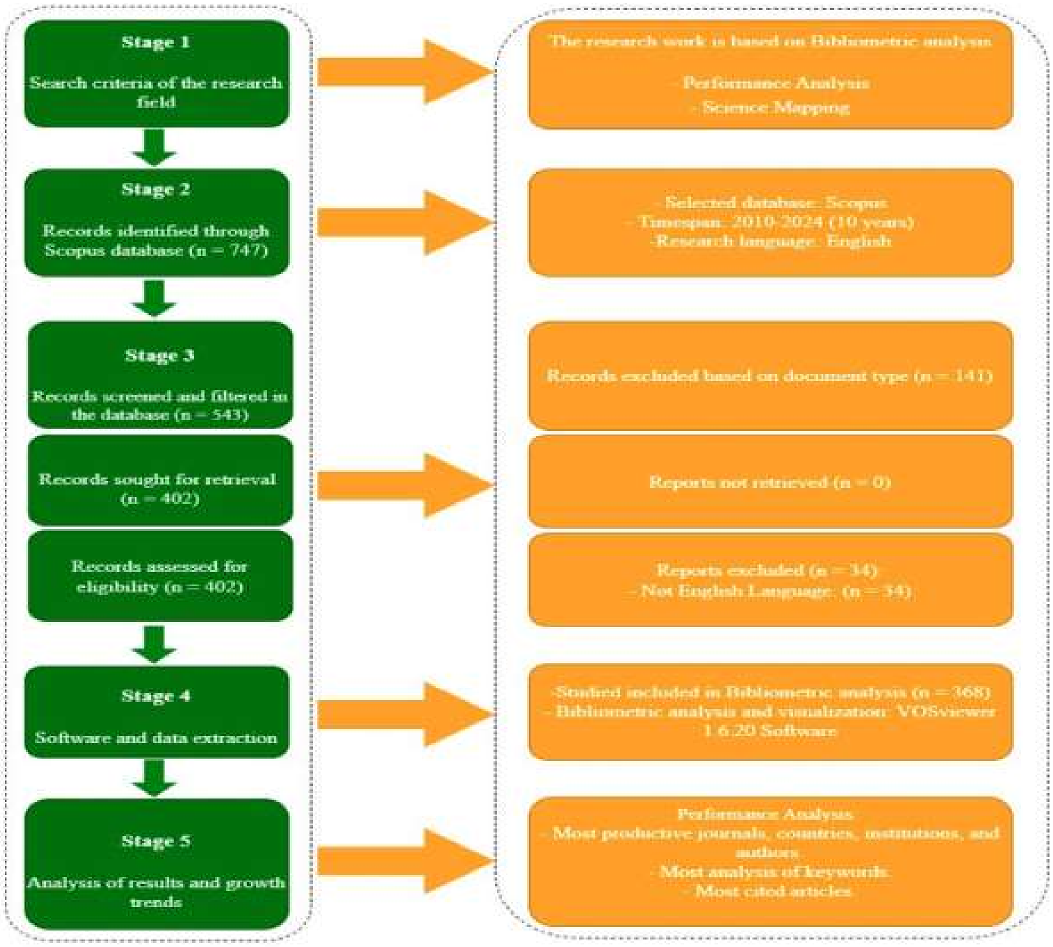

Fig. 1. Research methodology.

The first search we conducted using the keywords produced 747 publications, including articles, conference papers, review articles, and book chapters (see Fig. 1). We only looked at results from 2015 to 2024. After running the filter, 204 documents were eliminated, leaving 543 that could be further analysed. Only publications and conference papers were considered. Included were publications from peer-reviewed journals because of the high quality and validity of the research they include. We also included conference papers because they are a great source for new, innovative ideas that haven't been published in journals yet but are presented at conferences. By combining them, we can guarantee that you will have a thorough understanding of all the current and future research in the topic. After applying this filter, 141 documents were eliminated, leaving 402 documents. Lastly, only publications published in English were considered. The research needed to be thoroughly evaluated and comprehended, therefore this conclusion was made. Although there is excellent literature in other languages, this restriction was imposed due to the practical requirement of linguistic ability. After applying this filter, 34 further documents were deleted, resulting in a final set of 368 documents that could be analysed.

The data was saved in CSV format so that it could be analysed with VOSviewer, a tool that is becoming more and more popular for creating and viewing bibliometric maps [34-36]. Articles pulled from databases can be organised, mapped, and data mined using this technique. Algorithms allow for continuous label adjustments, which enhance the representation of co-occurrences. In order to ensure the dataset's accuracy and reliability, the research selection process employed numerous phases of data filtering. The process began with the elimination of duplicate records. The data gathering process was then fine-tuned by using inclusion and exclusion criteria based on factors such as document type, source, and language. Each metadata field, including the publication year, source title, author names, and affiliations, was meticulously reviewed when the remaining filtered entries were acquired. Furthermore, the titles, abstracts, and keywords of the documents were reviewed to assess their quality. Afterwards, during this data cleaning stage, we eliminated any incorrect or missing items, leaving a revised dataset that is now suitable for future research.

A total of 368 documents, including 313 journal articles and 55 conference papers, were obtained from the search. All told, 178 separate publication sources or venues contributed to the collection of these materials. The subject's literature is enriched by the contributions of 1621 authors, who hail from 168 diverse institutions and organisations across the globe. Significant contributions to the literature were made by authors from 80 different nations. The influence of these 368 documents across the academic community was highlighted by the sum of 5407 citations, indicating their cumulative impact. By analysing the 1176 distinct terms included in the author-supplied keywords, further information about the literature's research focus was revealed. Table 1 provides a concise summary of the main bibliometric results from the literature review on artificial intelligence in wastewater treatment.

Results and discussion:

As shown in Figure 2, the pattern of yearly publications about artificial intelligence in wastewater treatment provides useful information about the development and changes in this area of study throughout the last ten years. From 2015 onwards, the number of publications rose gradually, with a significant acceleration in the rate of publishing beginning in 2020. Specifically, the number of articles peaks at 93 in 2023, marking a considerable jump. In that year, there was a noticeable uptick in the use of artificial intelligence (AI) in wastewater treatment. This could be due to more funding, better AI, or just more people realising how AI could solve difficult problems in this area. It should be noted that the data only extends until April 30, 2024, with respect to 2024. There has been ongoing study in the topic, as evidenced by the 50 papers documented for the year so far.

This may be a lower figure than the high in 2023, but keep in mind that the year is far from over and more publications could be on the way.

Hence, the total number of publications in 2024 can end up being higher than the current total. In general, the trend of yearly publications shows a positive trajectory, suggesting that there has been persistent growth and interest in researching the use of AI in wastewater treatment. The significance of artificial intelligence as a potential tool for optimising wastewater treatment operations, increasing efficiency, and tackling environmental concerns is highlighted by this increased trend. Publications pertaining to artificial intelligence (AI) in wastewater treatment are likely to increase in quantity as academics delve further into this topic, which should lead to more developments and breakthroughs in the industry.

With respect to academic publications and citation figures, Table 2 gives a thorough review of the top nations in the area of artificial intelligence (AI) wastewater treatment. Out of all the documents produced in this subject, the top 10 countries account for 323—or 86.77% of the total. Among all the countries represented, China ranks first with 74 documents, or 20.11 percent of the total, and an average of 12.5 citations per document. The United States and India come in second and third, respectively, with 45 documents (12.23 percent of the total) apiece. The United States has 12.02 citations per document, compared to 10.22 in India. With 30 papers and an impressive average citation per document of 21.77, Iran has significant influence and impact. South Korea offers 29 documents, while Saudi Arabia provides 29.

Table 1
Summary of key bibliometric results.

Description	Results
Documents (313 journal articles, and 55 conference paper)	368
No of Citations	5407
Authors	1621
Author Keywords	1176
Publication venues (Sources title)	178
Authors' Affiliations	168
Countries	80

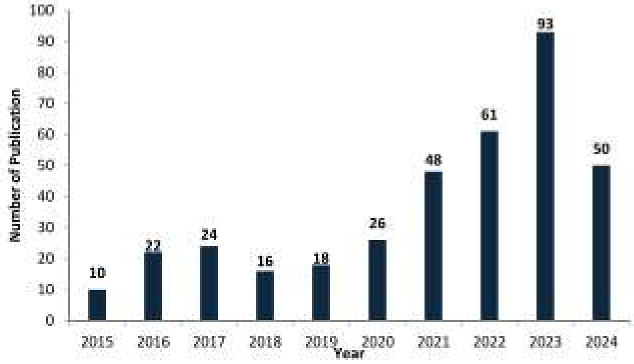

Fig. 2. Annual publications related to AI in wastewater treatment based on Scopus data (until April 2024).

Table 2
Leading 10 countries through collaboration and publishing on AI related wastewater treatment.

Country	Total Link Strength	Documents	% Of Total Documents	Citations	Average Citations
China	2267	74	20.11 %	892	12.05
India	1341	45	12.23 %	460	10.22
United States	1225	45	12.23 %	541	12.02
Iran	1004	30	8.15 %	653	21.77
Saudi Arabia	2233	29	7.88 %	213	7.340
South Korea	400	22	5.98 %	522	23.73
Italy	308	21	5.71 %	623	29.67
Spain	451	20	5.43 %	460	23.00
Malaysia	1061	19	5.16 %	240	12.63
Egypt	1164	18	4.89 %	222	12.33
Total		323	87.77 %	4826	

Italy provides 21 papers with an outstanding average citation per document of 29.67, Spain provides 20 papers with an average citation per document of 23, while the United States provides 22 papers with a high average citation per document of 23.73. With an average of 12.63 citations per document and 18 documents from Egypt, respectively, these two countries have made substantial contributions to the area. Figure 3 shows the results of the network analysis, which show that ten countries are very interested in studying wastewater treatment with artificial intelligence. Research in this area is likely to be spearheaded by the most influential countries, as seen by their bigger nodes and thicker connecting networks. Gaining a better understanding of the worldwide research scene and the key figures propelling the development of AI-related wastewater treatment is possible with the use of this data. Figure 3 shows the diagrammatic nodes representing bibliographic coupling links between each of the ten countries. The nation co-occurrence network map revealed four distinct clusters, each with its own colour indicating its degree of similarity to the other clusters in the study region. Diverse areas of research into artificial intelligence (AI) for wastewater treatment are represented by the different coloured nodes that make up each cluster. Thicker connecting lines indicate more significant linkages, whereas larger nodes indicate more frequent occurrences. In sum, the findings demonstrate the worldwide enthusiasm and cooperation for furthering studies at the crossroads of artificial intelligence and wastewater treatment. Contributing to the development of novel ideas and technologies for sustainable wastewater, the leading countries in this field bring unique viewpoints and ways to addressing difficulties.

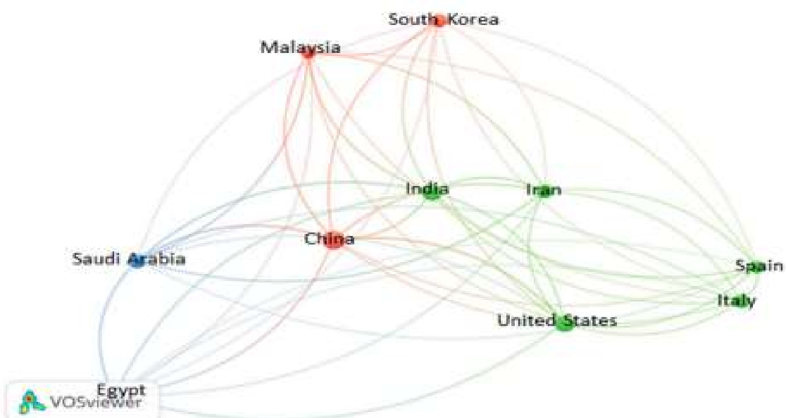

Fig. 3. A network visualization displaying the primary nations taking part in the research examining the AI related wastewater treatment.

medical care. Furthermore, the number of citations show how influential and impactful these countries' research is in the academic world, which in turn shows how important and high-quality their contributions are. The scholarly publications pertaining to the junction of artificial intelligence and wastewater treatment, together with the countries and the number of publications from each affiliation, are summarised in Table 3. With eight publications apiece, the top affiliations are the University of Johannesburg in South Africa and King Khalid University in the Kingdom of Saudi Arabia (KSA). Next in line with seven publications apiece are the People's Republic of China Ministry of Education and Prince Sattam Bin Abdulaziz University in Saudi Arabia. Among the significant contributions, you may find six papers from Yakın Dogu ˘ Üniversitesi in Cyprus, King Fahd University of Petroleum and Minerals in KSA, and the Chinese Academy of Sciences in China. The following institutions also contribute five publications: South Korea's Kyung Hee University, Iran's University of Tabriz, Spain's Universitat de Girona, China's Harbin Institute of Technology, Egypt's Alexandria University, Vietnam's Ton-Duc-Thang University, and Iran's University of Tehran. These prominent affiliations showcase international cooperation and joint endeavours to advance research at the crossroads of artificial intelligence and wastewater treatment, representing a varied array of universities from different nations. Their dedication to solving important problems and fostering innovation in this area is demonstrated by their substantial contributions.

You can learn a lot about the most influential writers who have contributed to scholarly articles about applying AI for wastewater treatment from the data presented in Table 4. The authors' extensive body of work in this area attests to their extraordinary commitment and mastery of the subject. There is a large amount of research output in artificial intelligence applications for wastewater treatment by Abba, S.I., who is at the top of the list with six documents ascribed to their name. Next in line are Nasr, M., Nourani, V., and Poch, M.; each of these authors has contributed five papers to the body of literature in this field. Choo, K.H., Heo, S.K., Jang, A., Nam, K.J., Rezk, H., and Wei, H. are a group of writers who have regularly added to the academic conversation about artificial intelligence in wastewater treatment; each of these authors has four papers. Thanks to their combined work, we now have a better grasp of how AI technology may improve wastewater treatment by solving problems and enhancing procedures. In general, the findings show that a wide range of authors have contributed significantly to the development of artificial intelligence applications in wastewater treatment research. They have worked together in an interdisciplinary fashion to advance this new area of study, which has the ability to greatly enhance wastewater treatment procedures and solve environmental problems; their work reflects this commitment to innovation and advancement.

Table 3
Top 13 affiliation according to authors' affiliation (5 or more articles).

Affiliation	Country	No
University of Johannesburg	South Africa	8
King Khalid University	KSA	8
Ministry of Education of the People's	China	7
Prince Sattam Bin Abdulaziz University	KSA	7
Yakın Doğu Üniversitesi	Cyprus	6
King Fahd University of Petroleum and Minerals	KSA	6
Chinese Academy of Sciences	China	6
Kyung Hee University	South Korea	5
University of Tabriz	Iran	5
Universitat de Girona	Spain	5
Harbin Institute of Technology	China	5
University of Tehran	Iran	5
Alexandria University	Egypt	5
Ton-Duc-Thang University	Vietnam	5

Table 4
Most productive authors collaboration from 2015 to 2024.

Author Name	No of Publication
Abba, S.I.	6
Nasr, M.	5
Nourani, V.	5
Poch, M.	5
Choo, K.H.	4
Heo, S.K.	4
Jang, A.	4
Nam, K.J.	4
Rezk, H.	4
Wei, H.	4

The most widely referenced papers in artificial intelligence for wastewater treatment, as shown in Table 5, shed light on important findings that have shaped the field's academic conversation and progress. Out of all the citations, the 2019 article "The application of machine learning methods for prediction of metal sorption onto biochars" stands out with 191. Predicting metal sorption onto biochars using ML algorithms is the main emphasis of this paper, which provides insights into predictive modelling strategies for wastewater treatment applications [37]. "Machine learning algorithms for the forecasting of wastewater quality indicators" (2017) is another significant contribution, with 171 citations. This article delves into the application of ML algorithms to predict wastewater quality indicators and offers helpful methods and approaches for water quality parameter prediction [38]. It was published in 2017. Another article with 164 citations is "Wastewater treatment plant performance analysis using artificial intelligence - An ensemble approach" (2018). Optimising wastewater treatment processes by advanced data analysis and modelling approaches, this work presents an ensemble approach to analysing WWTP performance using AI techniques [39]. Additionally, with 110 citations, "Green Approach to Dye Wastewater Treatment Using Biocoagulants" (2016) offers novel approaches to eco-friendly wastewater treatment [40]. Additionally, the 98-citation work "Modelling and prediction of water quality by using artificial intelligence" (2021) helps improve decision-making and process optimisation in wastewater treatment by contributing to the improvement of predictive modelling methodologies [41].

Writing about novel photocatalytic approaches to wastewater treatment, "Visible-light photocatalytic degradation of multiple antibiotics by AgI nanoparticle-sensitized Bi5O7I microspheres" (2017) delves into the topic of antibiotic contamination and new pollutants [42]. In addition, a soft-sensing estimation method for forecasting effluent concentrations in biological WWTPs using neural networks is proposed in "Soft-sensing estimation of plant effluent concentrations in a biological wastewater treatment plant using an optimal neural network" (2016) [43]. Furthermore, a machine learning framework is presented in "A machine learning framework to improve effluent quality control in wastewater treatment plants" (2021) with the goals of improving WWTP effluent quality control, guaranteeing compliance with regulations, and optimising treatment processes [44]. Furthermore, predictive modelling approaches for optimising nutrient removal processes in biological WWTPs are the subject of "Artificial intelligence models for predicting the performance of biological wastewater treatment plant in the removal of Kjeldahl Nitrogen from wastewater" (2017) [45]. Last but not least, "Towards better process management in wastewater treatment plants: Process analytics based on SHAP values for tree-based machine learning methods" (2022) presents cutting-edge analytics methods for improving decision-making and process management in wastewater treatment operations [46]. The understanding and implementation of artificial intelligence (AI) in wastewater treatment has been greatly advanced by these highly-cited articles, which have contributed to the field and paved the way for more efficient, sustainable, and effective methods of treating wastewater.

A number of important issues have attracted a lot of attention from researchers, and the most cited papers in the area of artificial intelligence in wastewater treatment provide some insight into these issues. These encompass the use of ML processes for a variety of goals in wastewater treatment, such as optimisation of operations and prediction and forecasting. In order to keep water quality regulations and treatment processes efficient, many studies centre on the prediction of wastewater quality indicators. Researchers have also concentrated on evaluating WWTP performance with AI techniques to enhance overall efficiency and optimise operations. Biocoagulants and other sophisticated photocatalytic degradation technologies are examples of environmentally friendly wastewater treatment approaches that are the subject of ongoing study. Researchers are focussing on improving control mechanisms utilising ML frameworks to meet regulatory criteria and minimise environmental effect in effluent quality management, which is emerging as another crucial field. To comprehend and efficiently manage wastewater treatment operations, predictive modelling of water quality metrics is crucial. Researchers also focus on certain areas, such as biological wastewater treatment, which uses predictive modelling to improve treatment efficiency and optimise nutrient removal. As a last step towards making wastewater treatment more effective and sustainable, researchers are looking into advanced analytics methods like SHAP values for tree-based ML techniques to help with process management and decision-making.

Table 5
Details of article citations.

Document Title	Year	Citations	Ref.
The application of machine learning methods for prediction of metal sorption onto biochars	2019	191	37
Machine learning algorithms for the forecasting of wastewater quality indicators	2017	171	38
Wastewater treatment plant performance analysis using artificial intelligence - An ensemble approach	2018	164	39
Green Approach to Dye Wastewater Treatment Using Biocoagulants	2016	110	40
Modelling and prediction of water quality by using artificial intelligence	2021	98	41
Visible-light photocatalytic degradation of multiple antibiotics by AgI nanoparticle-sensitized Bi_5O_7I microspheres	2017	95	42
Soft-sensing estimation of plant effluent concentrations in a biological wastewater treatment plant using an optimal neural network	2016	93	43
A machine learning framework to improve effluent quality control in wastewater treatment plants	2021	92	44
Artificial intelligence models for predicting the performance of biological wastewater treatment plant in the removal of Kjeldahl Nitrogen from wastewater	2017	91	45
Towards better process management in wastewater treatment plants: Process analytics based on SHAP values for tree-based machine learning methods	2022	85	46

Table 6 offers an overview of the top sources that have been prolific in publishing academic literature focused on the integration of AI in wastewater treatment, along with the corresponding number of

Table 6
The top 14 sources of AI in wastewater treatment (ranked according to total link strength (TLS)).

Source Title	TLS	No. of Publications	Total Citations
Chemosphere	71	18	285
Water Science And Technology	8	18	396
Journal Of Environmental Management	103	15	314
Journal Of Water Process Engineering	64	15	82
Water Switzerland	11	15	391
Desalination And Water Treatment	12	12	96
Science Of The Total Environment	47	12	332
Journal Of Cleaner Production	36	9	334
Sustainability Switzerland	10	8	126
Journal Of Environmental Chemical Engineering	36	7	137
Water Research	11	7	131
Journal of Physics: Conference Series	3	6	27
Process Safety and Environmental Protection	31	6	144
Environmental Research	17	5	89

papers that were cited by each author. Notable contributions to the dissemination of research in this sector include 18 articles each by "Chemosphere" and "Water Science and Technology," which rank first and second, respectively. These journals are closely followed by "Journal of Environmental Management," "Journal of Water Process Engineering," and "Water Switzerland," all of which have 15 publications apiece, demonstrating their important role in publishing academic work on artificial intelligence applications in wastewater treatment. Notable sources also include "Science of the Total Environment" and "Desalination and Water Treatment," both of which have 12 publications apiece, highlighting the extensive and thorough nature of the research published in these esteemed journals. Furthermore, "Journal of Environmental Chemical Engineering" has made a substantial impact on the academic conversation with 7, "Sustainability Switzerland" with 8, and "Journal of Cleaner Production" with 9 publications, respectively. Primarily, we looked for journals that published five or more articles in this area between 2015 and 2024. As shown in Figure 4, fourteen of the sources that were located met these criteria. These fourteen articles are not only important to the development of the discipline, but also serve as the principal resources for studies pertaining to the use of AI in wastewater treatment. Taken as a whole, these leading publications provide excellent venues for academics to share their results, add to the body of knowledge, and encourage discussion amongst peers on the potential of artificial intelligence to enhance wastewater treatment methods. Their dedication to promoting knowledge sharing and fostering innovation in this vital field of environmental science is demonstrated by their regular publication output.

The value of co-occurrence analysis in assessing the development of research frontiers in a particular field of study and illuminating research themes has been highlighted by numerous scholars [30–32,35]. We set a minimum threshold of 5 occurrences for finding keywords in our use of Scopus data using VOSviewer. Consequently, 46 keywords were extracted from the dataset consisting of 1,176 author keywords. Figure 5 shows a network visualisation of the co-occurrence patterns of terms in research on artificial intelligence applied to wastewater treatment. Figure 5 shows the elements' co-occurrence patterns as diagram nodes. Using a colour-coding system that indicates how similar one cluster is to the others in the study area, the keyword cooccurrence network map revealed six separate clusters. Diverse areas of research into artificial intelligence (AI) for wastewater treatment are represented by the different coloured nodes that make up each cluster. Thicker connecting lines indicate more significant linkages, whereas larger nodes indicate more frequent occurrences. In Table 7, you can see all of the terms that met or surpassed the criteria. Keep in mind that this study only looked at author keywords, not index keywords. Table 7 displays the 46 most important terms, ordered by TLS descending. The order in which these keywords appear is determined by a comprehensive scientific analysis that considers factors such as the total link strength, the number of links referring to each keyword, and how often they appear. Using a keyword co-occurrence analysis, we can see which terms are most often used when discussing wastewater treatment studies pertaining to artificial intelligence.

The prominent position of these technologies in this field is shown by the fact that "artificial intelligence," "wastewater treatment," and "machine learning" are the top three keywords. Table 7's most popular terms include: "artificial intelligence," "machine learning," "artificial neural network," "decision support system," "deep learning," "principal component analysis," "support vector regression," "genetic algorithm," "internet of things," "quorum sensing," "adaptive neuro-fuzzy inference system," "ANFIS," "anomaly detection," "automation," "big data," "digital twin," "industry 4.0," "sensitivity analysis," and "uncertainty." All of these terms are directly related to the study of AI and its uses in wastewater treatment. Wastewater treatment makes extensive use of ML algorithms for a variety of purposes, including modelling, prediction, and optimisation [47-49]. Deep learning (DL) and artificial neural networks (ANNs) are also popular ML models [50]. When it comes to wastewater treatment, fuzzy logic—another AI-based approach—can be helpful for managing chemical dose or modifying process parameters due to its ability to predict and regulate systems with uncertainty and imprecision [51,52]. Improved decision-making, more efficient processes, and better management of the inherent complexity and unpredictability in wastewater treatment systems are all possible outcomes of incorporating these cutting-edge AI-powered tools and approaches [53,54]. With 141 TLS, the term "artificial intelligence" is the most prominent, followed by "wastewater treatment" (83 TLS), and "machine learning" (68 TLS). The conceptual roots of AL-related effluent treatment can be traced back to this keyword. Figure 5 and Table 7 display the 15 most popular keywords in the Scopus database.

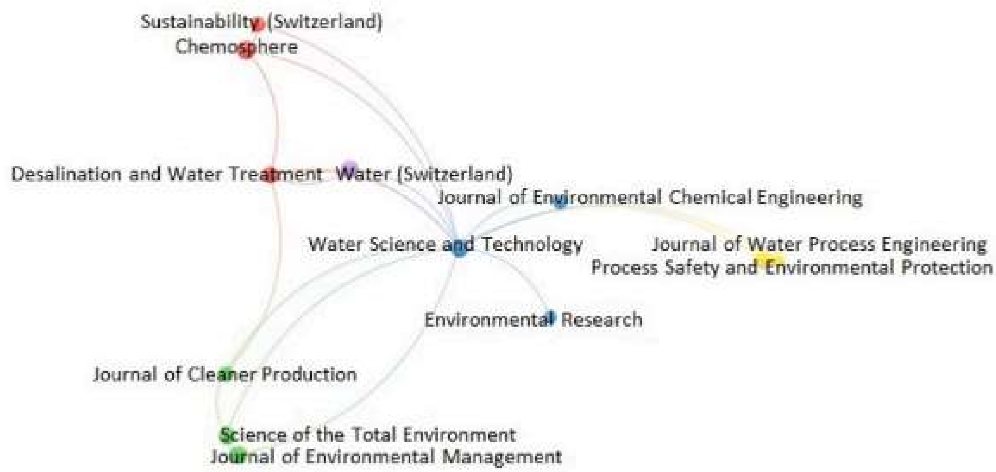

Fig. 4. Co-occurrence map of journals from 2015 to 2024 that have more than five publications pertaining to the application of AI to wastewater treatment.

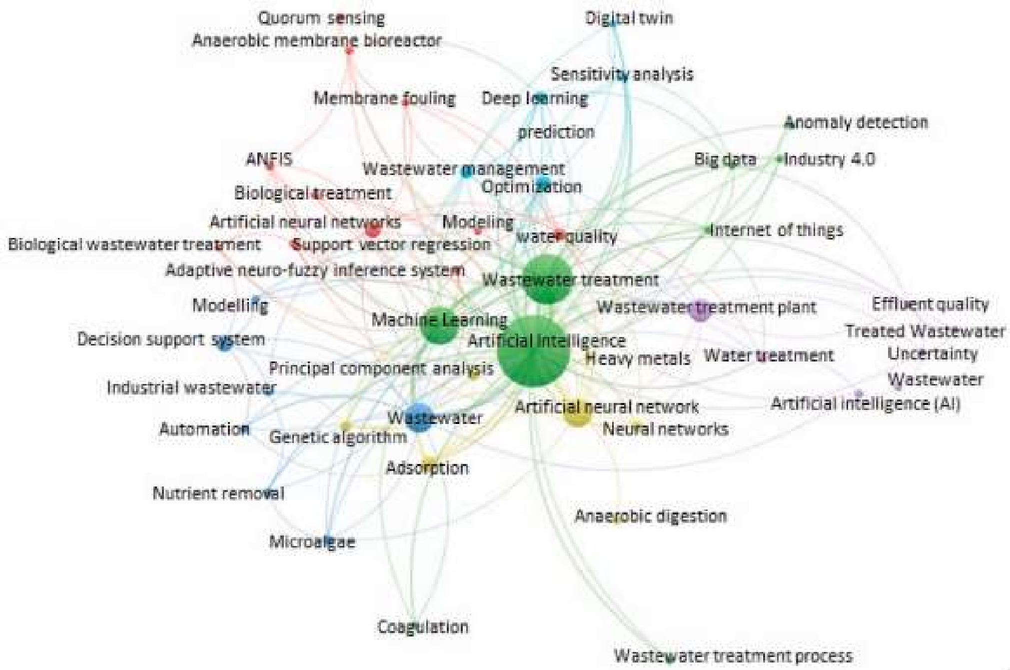

Fig. 5. Network visualization with author keyword co-occurrence clustering.

it is believed that current research is centred around creating AI-powered models to optimise processes, make predictions, and assist with decision-making in the wastewater treatment industry. The extensive research on the integration of adsorption, microalgae, anaerobic digestion, biological treatment, and coagulation into a cost-effective and efficient method for heavy metal and nutrient removal from wastewater is reflected in these 46 most popular substantives. Examining the frequency with which certain keywords appear in a set of research articles is one approach to discovering common themes [55]. Figure 5 shows that there are six significant clusters connected to wastewater treatment in the network map of this study. In other words, the red cluster 1 stands for "biological and membrane techniques for wastewater treatment." The green-hued Cluster 2 stands for "artificial intelligence and machine learning applications in wastewater treatment." The third cluster, represented by the blue colour, is concerned with "nutrient modelling and removal in wastewater treatment." Cluster 4, also known as the yellow one, is all about "biotic and mechanistic technologies for wastewater treatment." Purple represents Cluster 5, which is all about "improvement in treatment plants." The sixth cluster, represented by the pale blue colour scheme, is devoted to "modelling and optimisation techniques for wastewater treatment." One of these groups contains a lot of terms related to advanced techniques, like "artificial neural networks," "modelling," "support vector regression," "anaerobic biological membranes," "adaptive neuro-fuzzy inference system," "biological wastewater treatment," "membrane fouling," and "water quality."

Improving the effectiveness of wastewater treatment through the use of biological approaches and membranes is the primary focus of this cluster's research and development efforts. Research in this cluster focusses on biological treatment methods like activated sludge and anaerobic digestion, as well as the use of artificial neural networks (ANNs) for process optimisation and performance prediction, modelling and support vector regression for treatment parameter simulation and forecasting, combining anaerobic biological methods with membrane separation technologies, and using adaptive neuro-fuzzy inference systems for intelligent decision-making [52,56-60]. Ensuring compliance with environmental standards and appropriateness for reuse or disposal, this cluster also addresses the difficulties of membrane fouling and the impact of treatment procedures on treated water quality [58]. Keywords in cluster 2 include "artificial intelligence," "wastewater treatment," "machine learning," "Internet of Things," "anomaly detection," "big data," "coagulation," "Industry 4.0," together with "wastewater treatment plant." These innovations improve wastewater treatment efficiency by utilising AI and ML [27,52].

The buzzwords point to an emphasis on using these cutting-edge technologies to enhance process control, decision-making, performance optimisation, predictive maintenance, real-time monitoring, and wastewater management in general. For the purpose of driving innovation and sustainability in WWTPs, researchers in this domain are developing complete solutions that integrate Internet of Things (IoT) devices, big data analytics, and Industry 4.0 concepts [27,60-64]. To improve the overall performance and environmental impact of wastewater treatment systems, key areas of focus include using data-driven decision-making, optimising coagulation, and anomaly detection with AI algorithms and ML models [65,66]. The third cluster includes terms like "wastewater," "decision support system," "microalgae," "modelling," "nutrient removal," "automation," and "industrial wastewater." Wastewater treatment, and more specifically the removal of excess nutrients, is the primary goal of this cluster's research and development efforts in advanced modelling and decision support systems [59]. Wastewater systems can be better understood and controlled with the help of cutting-edge mathematical and computational models that simulate and optimise different treatment processes [67–69]. Treatment methods based on microalgae, which take advantage of the organisms' inherent metabolic capacities to efficiently

Table 7
Top 46 keywords from use the AI in wastewater treatment processes research paper (ranked according to TLS).

Keywords	Cluster	TLS	Occurrence	Avg. Citations
Artificial Intelligence	2	141	106	13.59
Wastewater Treatment	2	83	63	13.35
Machine Learning	2	68	41	21.88
Wastewater	3	36	28	22.18
Artificial Neural Network	4	32	27	12.22
Wastewater Treatment Plant	5	17	20	17.70
Artificial Neural Networks	1	12	12	14.17
Decision Support System	3	6	12	37.00
Adsorption	4	19	11	14.00
Optimization	6	19	11	10.18
Prediction	6	16	9	9.00
Modeling	1	13	8	7.25
Deep Learning	6	14	7	11.71
Heavy Metals	4	9	6	25.67
Microalgae	3	8	6	12.67
Neural Networks	4	7	6	39.17
Principal Component Analysis	4	10	6	16.50
Support Vector Regression	1	9	6	48.50
Anaerobic Digestion	4	1	5	15.60
Anaerobic Membrane Bioreactor	1	6	5	15.00
ANFIS	1	7	5	37.60
Artificial Intelligence (AI)	5	4	5	1.60
Biological Treatment	1	7	5	14.20
Genetic Algorithm	4	7	5	19.00
Internet of Things	2	10	5	18.80
Modelling	3	5	5	6.20
Nutrient Removal	3	7	5	16.00
Quorum Sensing	1	2	5	13.20
Water Treatment	5	9	5	22.60
Adaptive Neuro-Fuzzy Inference System	1	5	4	36.25
Anomaly Detection	2	3	4	8.75
Automation	3	7	4	9.00
Big Data	2	10	4	26.75
Biological Wastewater Treatment	1	5	4	23.00
Coagulation	2	4	4	28.25
Digital Twin	6	8	4	12.00
Effluent Quality	5	8	4	28.50
Industrial Wastewater	3	5	4	11.25
Industry 4.0	2	7	4	8.25
Membrane Fouling	1	7	4	10.50
Sensitivity Analysis	6	8	4	9.00
Treated Wastewater	5	3	4	11.50
Uncertainty	5	6	4	19.50
Wastewater Management	6	2	4	13.75
Wastewater Treatment Process	2	3	4	1.75
Water Quality	1	9	4	68.00

Discussion:

Industrial wastewater presents unique problems and treatment needs due to the wide variety of toxins it may include [52]. Improved performance, sustainability, and environmental effect in industrial wastewater treatment are the goals of the researchers as they integrate decision support systems, advanced modelling, and nutrient removal technologies. Anaerobic digestion and adsorption are the main areas of concentration in Cluster 4 for wastewater treatment. In this group of related keywords, we find terms like "artificial neural network," "adsorption," "heavy metals," "neural networks," "principal component analysis," "anaerobic digestion," and "genetic algorithm." The goal of this group is to treat wastewater by using adsorption and anaerobic digestion. One of the main areas of study is the improvement of adsorption methods for the removal of contaminants such heavy metals. This process is often enhanced by ANNs and ML models [68]. According to the research, adsorption is perhaps the most studied approach due to its low cost and extensive use. In addition, by utilising the metabolic capabilities of anaerobic microbes, the researchers are investigating the feasibility of anaerobic digestion as a strategy for wastewater treatment and management. Scientists are using cutting-edge data analysis methods like artificial neural networks (ANNs), principal component analysis (PCA), and genetic algorithms (GA) to improve these biotic and mechanistic therapy strategies even more [64]. To tackle the numerous issues in this domain, the researchers are aiming to develop effective and complete solutions for the removal of various contaminants from wastewater by integrating these complementary technologies. Keywords related to Cluster 5 include "wastewater treatment plants," "artificial intelligence," "water treatment," "effluent quality," "treated wastewater," and "uncertainty." This particular cluster of studies is concerned with the use of AI to improve the efficacy and reliability of wastewater treatment facilities. Optimisation techniques and models based on artificial intelligence are being investigated by researchers in this field as a means to enhance treatment facility design, operation, and control [69–71].

The objective is to enhance the overall effluent quality and resource utilisation within the facilities by using these cutting-edge strategies [72]. The cluster is also committed to creating AI-driven systems that can precisely regulate and anticipate the treated wastewater's quality, guaranteeing compliance with all applicable environmental norms and standards [65,73]. In addition, by using state-of-the-art methods, the researchers are attempting to comprehend and lessen the effects of the inherent uncertainties and variability in wastewater treatment operations. In the end, Cluster 6 is all about improving the performance and management of wastewater treatment by using cutting-edge modelling and optimisation approaches. Included in this group are the terms "optimisation," "prediction," "deep learning," "digital twin," "sensitivity analysis," and "wastewater management." In order to make precise predictions about how plants will act, scientists create data-driven and simulation-based models, such DL and digital twins. In addition, they use state-of-the-art optimisation techniques, such as mathematical programming and met heuristics, to find the best strategies for design, operations, and control [66,73-76]. Notably, this study tackles interrelated problems by combining modelling and optimisation with a comprehensive view of wastewater management [77-81]. The main objective is to make better use of these advanced computational tools to make wastewater treatment methods more efficient, use resources more effectively, and comply with environmental regulations. An increasing number of innovative technologies and applications are constantly appearing in the ever-expanding realm of AI-driven wastewater treatment research.

The study summarises all of the artificial intelligence methods currently in use for water treatment and monitoring. It focusses on the ways these methods are used and how they contribute to different parts of water management. Modelling, pattern analysis, classification, and regression are just a few of the many AI applications used in water treatment and monitoring. The capacity of these technologies to tackle different water management concerns in such a flexible and adaptable manner is demonstrated here. The majority of these approaches rely on supervised learning methods, which train models with the help of labelled data. This highlights the significance of accessible and high-quality data in producing trustworthy outcomes. Hydroponics, environmental, and chlorine dosage set point control systems all make use of AI approaches for decision-making and system control. This shows how AI could automate and improve water treatment processes. There is great promise for further improving the efficiency, resilience, and sustainability of water treatment plants through the increasing trend of integrating AI with other technologies such as the internet of things, blockchain, and digital twins.

Conclusion:

Particularly in domains like real-time monitoring, predictive maintenance, and the automation of complicated treatment protocols, this trend indicates an increasing awareness of the possibility for ML to optimise and improve the efficiency of these systems. Several interesting avenues for further study in the field of artificial intelligence (AI) driven wastewater treatment have emerged in light of recent developments. a. The use of predictive models is becoming increasingly popular, and this tendency is most noticeable in the field of wastewater treatment research. With the help of predictive models, we can better anticipate when systems will fail, optimise the dosage of chemicals, and predict the results of treatments. In addition to improving treatment process efficiency, this helps save money and is better for the environment. To make these models more accurate and resilient, researchers should look at using more diverse datasets and fixing problems with data availability and quality in the future [65]. b. Another new development that shows promise for making wastewater treatment systems more responsive and adaptable is real-time monitoring made possible by ML. This trend is gaining increased attention. More consistent and dependable treatment outcomes are achieved by ML algorithms' ability to analyse data streams continually, spot irregularities, and make real-time adjustments to operations. But, in order for real-time monitoring systems to be successfully implemented, it is necessary to create solutions that are both cost-effective and scalable, so that they may be used by a variety of treatment facilities, even in places with low resources [58]. c. Ethical Considerations and Model Transparency: Concerns about the interpretability and transparency of ML models are brought up by the increasing usage of ML in vital water treatment applications. Human operators and regulators must be able to comprehend these models' activities for them to be integrated into decision-making processes. To make sure that automated decisions follow ethical and regulatory criteria, future studies should focus on building interpretable models [66, 77].

d. Consensus with Other Emerging Technologies: The integration of ML with other emerging technologies, including the IoT and big data analytics, is another noteworthy trend. More comprehensive water management solutions that are up to the task of today's complicated wastewater treatment problems may be possible as a result of this integration. Investigating the potential benefits of combining these technologies for wastewater treatment is an important area for future study [65]. e. Data Fusion and Intelligent Sensor Networks: 1. Building trustworthy sensor networks that use Internet of Things (IoT) and edge computing to monitor wastewater treatment plant operations in real-time [61]. 2. Improving the precision and consistency of process control and monitoring through investigating data fusion methods, which integrate data from sensors with records from the past and models of the process [61]. f. Using AI that can be understood for wastewater treatment: 1. Improving the openness and reliability of AI-based wastewater treatment decision-making by pushing the creation of AI models that can be understood and explained, like hybrid physics-informed neural networks [24]. 2. Trying to figure out how to make machine learning, domain knowledge, and causal reasoning work together to give plant operators and decision-makers better, more actionable insights [25, 60]. g. Optimising Biological Processes with the Help of AI: 1. Modelling the intricate metabolic pathways and microbial population dynamics in biological wastewater treatment procedures, including activated sludge systems, algalbacterial processes, and anaerobic digestion, using deep learning and other artificial intelligence techniques [43]. 2.

Use of artificial intelligence to improve biological treatment systems' design, operation, and control for better nutrient removal, resource recovery, and process robustness [45]. h. Management of Assets and Predictive Maintenance: 1. Making proactive and cost-effective maintenance strategies possible by creating predictive maintenance models based on artificial intelligence to estimate the remaining usable life of important equipment and infrastructure in WWTPs [24]. 2. Using GIS and BIM in conjunction with AI-driven asset management tools can aid in making comprehensive decisions regarding infrastructure investment and planning [46]. The potential for AI to transform multiple areas of wastewater treatment, including process management and optimisation, predictive maintenance, and public health monitoring, is shown by these future research directions. Wastewater management systems can be made smarter, more resilient, and more sustainable if researchers and practitioners tackle AI's shortcomings while capitalising on its virtues. 5. There are a number of significant obstacles to incorporating AI-based solutions into wastewater treatment systems, which are found to include. 1. A thorough cost-benefit analysis is necessary before implementing AI into wastewater treatment. It is common for AI-driven solutions to need a sizable initial investment in hardware, software, data storage, and processing power, in addition to continuing expenditures for system upkeep and upgrades. These expenses must be carefully considered in light of the possible advantages, such as higher productivity, lower operating costs, and stricter adherence to environmental laws. Research in the future should centre on creating all-encompassing cost-benefit models that decision-makers can use to evaluate the practicality of artificial intelligence technologies in various wastewater treatment facilities, especially smaller and medium-sized plants with limited budgets [42,66].

2. The quantity and quality of available data: Many wastewater treatment facilities lack comprehensive historical data, especially for newly identified pollutants and more recent process configurations [44,46]. The creation and training of precise AI models can be impeded by sensor data that is susceptible to mistakes, missing values, and uncertainty [62]. Data interoperability is a concern when integrating diverse datasets from different sources, such as online sensors, laboratory analyses, and operational logs [49]. 3. The capacity to analyse and explain models: Many state-of-the-art AI models, such deep neural networks, are stereotyped as "black boxes," whose inner workings and the logic underlying their predictions are not readily apparent [53,54].

In order to foster responsibility and confidence in the decision-making process, regulatory authorities and plant operators may favour models that are more transparent and easy to understand [53]. The technological challenges, extensive coordination, and system-level thinking involved in seamlessly integrating AI-powered solutions with legacy control systems, SCADA platforms, and other operational technologies in WWTPs are well-documented [11,54]. It can be a tedious and complicated process to tailor AI-based solutions to each wastewater treatment plant's unique operating limits and needs [49]. 6. Considering the potential consequences of automated, data-driven decision-making processes, authorities may encounter regulatory obstacles while trying to approve AI-based decision-making systems for use in wastewater treatment [17]. The competent and trustworthy use of AI in the water sector requires the resolution of legal and ethical challenges, including data protection, liability, and transparency [17]. 7. Managers and operators of wastewater treatment plants may not have the knowledge or experience to properly install, operate, and understand AI-based solutions, which can lead to capacity building and other problems [17,64]. For collaboration and implementation to be effective, it is essential to bring together data science/AI professionals and domain experts in wastewater treatment [17]. 8. Strong cybersecurity measures and data protection policies are necessary due to the growing number of cyber threats, data breaches, and system vulnerabilities in today's increasingly digitalised and interconnected wastewater treatment plants [5]. Wastewater treatment experts, data scientists, and technology suppliers will need to work together closely to overcome these obstacles.

A comprehensive, system-level approach to integrating AI in wastewater treatment could be one strategy, along with capacity-building initiatives and the creation of industry-specific standards and recommendations. If we want to see AI-based solutions used widely in the wastewater treatment sector, we need to solve these problems. 9. Another major obstacle is the adaptability of artificial intelligence systems to various wastewater treatment settings. Location, industrial activities, and population density all have a role in how wastewater behaves in any particular place [17]. Consequently, AI models that were trained using data from one place could not work as effectively when used in another. Adaptable AI solutions tailored to the unique needs of each treatment centre are crucial in finding a solution to this problem. Building standardised protocols for training and evaluating AI models in varied environments or designing modular AI systems that can be fine-tuned with local data are two possible approaches [17,73]. 6. Final Thoughts The primary purpose of this research was to provide a bibliometric review of literature about the use of artificial intelligence in wastewater treatment. The study's objectives were attained by evaluating 368 articles and conference papers filtered from the Scopus database using VOSviewer bibliometric software. Important new information in this area has been revealed by this study. Analyses show that interest in this area has been on the rise over the past five years, with 93 publications reaching a peak in 2023. This points to an increasing interest in and emphasis on using AI methods to solve problems with wastewater management. By utilising co-occurrence and clustering analysis, the article keywords pertaining to AI-related wastewater treatment procedures were investigated. In this area, the most popular search terms are "artificial intelligence," "wastewater treatment," and "machine learning." These terms accurately describe the main focus of research in this discipline. Journal of Environmental Management, Journal of Water Science and Technology, and Journal of Chemosphere are the most important journals in this discipline, according to the study that was conducted using Scopus data. The University of Johannesburg stood out as the most prominent institution, although China, India, and the US all had significant roles in the research. Popular and increasingly used technologies include adsorption, microalgae, and anaerobic digestion. Research on contaminants, such as nutrients and heavy metals, is prevalent. Insights gained from this analysis can help direct future studies, stimulate the creation of useful AI-driven solutions, and lead to greener water management.

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