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The Role of Artificial Intelligence in Enhancing Heavy Metal Removal Efficiency: A Bibliometric Perspective

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ABSTRACT

The problem of heavy metal pollution in wastewater has prompted the demand for more effective and sustainable treatment systems. In the recent decade, the integration of artificial intelligence (AI) in heavy metal adsorption processes has shown tremendous potential in enhancing efficiency and optimizing operational parameters. This study intends to identify global research trends on the application of AI in optimizing heavy metal adsorption processes by a bibliometric method for the period 2010 to 2024. Data were acquired from Google Scholar and filtered to include indexed papers, then analyzed using VOSviewer and Microsoft Excel software to evaluate annual publishing trends, as well as visualization of keyword co-existence. The findings of the investigation showed an impressive move in publications after 2019. The leading terms detected included “machine learning,” “neural networks,” and “optimization.” Despite demonstrating encouraging trends, research in this subject still confronts hurdles such as inadequate large-scale experimental data, minimal integration of AI with Internet of Things (IoT) systems, and lack of industrial-scale applications. This study shows the need of building hybrid AI-IoT systems, using big data analytics, and adaptive predictive models to increase the effectiveness of heavy metal adsorption systems in the future. These findings are likely to be a key reference for researchers and practitioners in creating smart and sustainable waste processing systems.

Keywords: bibliometric, artificial intelligence, heavy metal, removal

1. INTRODUCTION

Heavy metal contamination in industrial wastewater and the environment constitutes a significant global concern, as contaminants like Pb, Cd, Cr, and Ni are hazardous, persistent, and resistant to natural degradation [1]–[4]. The adsorption process is currently a leading approach due to its efficiency and scalability, although adjustment of experimental parameters (pH, amount of adsorbent, contact time, temperature) demands considerable quantities of time, expense, and resources[5]–[7]. The application of artificial intelligence (AI)—especially machine learning algorithms and metaheuristics—offers a predictive and automated method that can considerably minimize the load of laboratory experimentation and boost the accuracy of process optimization [8], [9].

Since the early 2010s, several research investigations have explored AI models involving Artificial Neural Networks (ANN), Support Vector Machine (SVM), Genetic Algorithm (GA), and Response Surface Methodology (RSM) based on machine learning to correspond the nonlinear relationships between adsorption process parameters and the removal of heavy metals performance [10]–[13]. These models provide quick simulation, identification of important parameters, and construction of prediction models for a wide range of adsorbents, from activated carbon to nanomaterials. The trajectory of AI integration

into adsorption research demonstrates a rapid increase in publications, suggesting that its interest and prospective applications are quickly acknowledged.

Since the literature on AI in heavy metal adsorption optimization is developing, there is no systematic study that maps the evolution of research, collaboration patterns between researchers and institutions, or prevalent issues in this field. As a result, researchers have difficulties identifying major driving countries, reference journals, and methodological holes that need to be filled. Without bibliometric understanding, worldwide research synergy efforts and the selection of new research areas become less targeted and less efficient. Other bibliometric studies have been performed for issues such as AI in air pollution monitoring [14], machine learning in water treatment [15], [16], or optimization of various chemical processes [17], [18]. However, currently there has been no bibliometric study that expressly analyzes the integration of AI in improving heavy metal adsorption—even though this area is expected to improve the effectiveness of environmental remediation technologies. The absence of quantitative mapping makes monitoring technical changes and identifying research gaps still separate and less thorough.

According to a preliminary search on Google Scholar, the number of articles relevant to AI adsorption of heavy metals ascended from less than 10 per year in 2010 to more than 100 in 2022. Research by Kiraz et al, 2019 [19] utilizing ANN-GA for estimating the adsorption capacity of Pb(II), whereas Maamoun et al , 2023 using SVM-RSM for Cr(VI) removal optimization [20]. Nevertheless, citation patterns, international partnerships, and keyword evolution were not previously evaluated bibliometrically.

This research proposes to perform a bibliometric analysis of literature that incorporates artificial intelligence in optimizing heavy metal adsorption processes from 2014 to 2024. The analysis will encompass yearly publication patterns, the most prolific nations and publishers, keyword co-occurrence and grouping, along with overlay and network cooperation visualization. This study aims to offer strategic direction for researchers and policymakers to facilitate further research and enhance collaboration in the advancement of AI-based environmental remediation technologies.

2. METHODS

This research utilizes data from Google Scholar via Publish or Perish (POP) software, combining the keywords "artificial intelligence," "adsorption," "heavy metals," and "optimization." Google Scholar has numerous advantages over other sources like SCOPUS, including extensive and diverse literature coverage, open and free access, more rapid availability of recent papers, and access to global sources. A total of 985 papers were acquired during the period from 2014 to 2024. Subsequently, the acquired data is preserved in the *.ris format. The acquired data is subsequently visualized using bibliometric analysis utilizing VOSviewer software, employing three visualization types: Network visualization, Overlay visualization, and Density visualization. This study additionally analyzes the annual trend in the quantity of studies, keyword frequency, and the publishers with the highest quantity of published documents.

3. RESULTS AND DISCUSSION

3.1 Research Trend

The results of the bibliometric analysis demonstrate a consistently increasing trend in the number of scientific publications related to the use of artificial intelligence (AI) for optimizing the heavy metal adsorption process from 2014 to 2024, as shown in Figure 1. The most notable increase transpired post-2019, coinciding with the growing prevalence of digital technologies in environmental sectors and heightened worldwide consciousness regarding the significance of effective and sustainable waste management.

This trend signifies a transition from traditional experimental methodologies to more predictive, adaptive, and data-driven strategies facilitated by AI integration. This swift progression is inextricably linked to advancements in computing power, the accessibility of open-source software for data modelling and analysis, and the growing availability of experimental data. Conversely, the growing demand for energy efficiency and efficacy in waste management, particularly within the metal industry, significantly propels the use of AI technology. In the context of heavy metal adsorption, AI algorithms such as artificial neural networks (ANN), support vector machines (SVM), random forests, and deep learning approaches continue to be commonly used to model complex interactions between process variables, predict adsorption capacity, and optimize operating parameters without the need for repeated laboratory experiments.

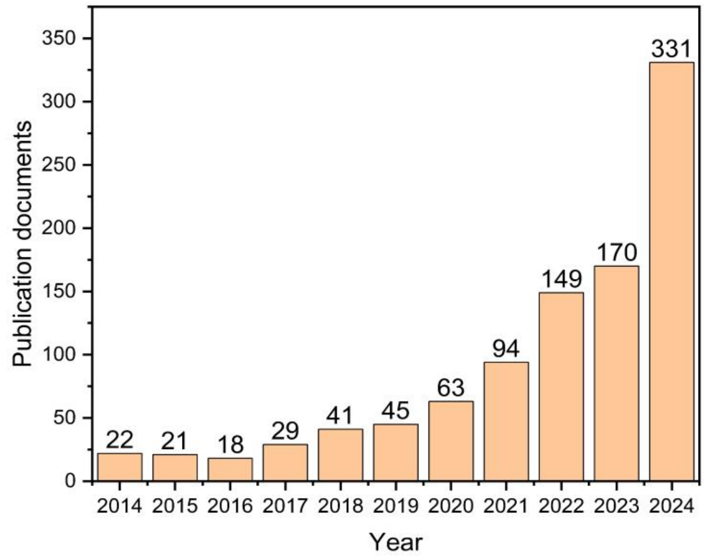

Figure 1. Number of publications related to the use of AI in heavy metal adsorption optimization

In terms of annual distribution, publications connected to this topic had a strong surge from 2021 to 2024. is in line with the increased support for policies and research funding from governments and international institutions, notably those focusing on the Sustainable Development Goals (SDGs), such as Goal 6 (Clean Water and Sanitation) and Goal 9 (Industry, Innovation, and Infrastructure). The COVID-19 epidemic has also indirectly pushed the digitalization of research processes and the deployment of smart technology in the industrial and environmental sectors, particularly in wastewater management. In terms of contributors, countries such as China, and India, occupy the top places in the number of publications. Is not surprising considering that the three countries confront enormous issues in industrial waste management and have strong research communities in the domains of environmental engineering and artificial intelligence. In addition, international research collaborations including institutions from developed and developing nations have also showed a surge, expanding the global knowledge network in this subject. The growing power of China and India has contributed substantially to the creation of literature in this area but also creates important considerations regarding the geographical diversity of research and the potential regional bias in the solutions generated. Therefore, further efforts are needed to promote the participation of other countries, especially from Africa, Southeast Asia, and South America, which similarly confront significant problems in heavy metal waste management but have limited research capacity

In terms of publishers, bibliometric reveals that most of the documents are produced by large publishers that have long been references in the domains of environmental engineering and materials science, It can be obtained from Table 1. Elsevier emerged as the publisher with the highest publication contributions on this issue, especially through journals such as the Journal of Hazardous Materials, Journal of Environmental Chemical Engineering, Journal of Contaminant Hydrology, and Journal of Water Process Engineering. These periodicals contain several articles on the application of AI algorithms in the processes of separation, adsorption, and wastewater treatment. Publications in Elsevier journals often have a high impact factor and broad international coverage, making them the principal avenue for the dissemination of research results with major contributions.

In addition to Elsevier, other publishers such as Wiley Online Library, Springer Nature, Taylor & Francis, and MDPI are also prominent publication channels in this discipline. Wiley Online Library journals such as the Journal of Separation Science, Springer Nature (International Journal of Environmental Science and Technology and Journal of Environmental Health Science and Engineering), and Taylor and Francis (International Journal of Phytoremediation and Soil and Sedimentation Contamination: An International Journal) consistently publish articles with an interdisciplinary approach. Meanwhile, MDPI—although newer than other publishers—has demonstrated a considerable increase in the number of articles on this issue, especially through the journals International Journal of Molecular Science and International Journal of Environmental Research and Public Health. This publisher is noted for its rapid and open-access publication process, thus broadening the reach of knowledge to the global scientific community.

The concentration of publications in these large publishers suggests that these channels play an essential role in promoting the development and diffusion of knowledge in the field of AI-based environmental technology. It also indicates that the quality and significance of these publications make them the key forums for scientific discussion, worldwide collaboration, and the creation of the latest technology solutions in AI-based waste management. However, there are also some obstacles that need attention in the growth of this research. Among these include the absence of validation studies on an industrial scale, the restricted availability of real-world data for algorithm training, and the poor integration between AI and other technological systems such as the Internet of Things (IoT) and big data analytics. In addition, data standards and processes in this discipline are still quite different, making it difficult to repeat and generalize study results. Considering the existing patterns and distribution of publications, the direction of future research has to focus on the creation of hybrid systems that combine AI, IoT, and sensor technologies for real-time and automation-based waste management. In addition, research that assesses the economic feasibility and sustainability of adopting this technology in a real-world situation needs to be supported. A cross-disciplinary collaborative approach between environmental engineering, data science, and public policy is also crucial to accelerate the adoption of smart technology in industrial waste management.

Table 1. Publisher with the largest number of documents

No	Publisher	Number of Documents
1	*Elsevier*	317
2	*Wiley Online Library*	239
3	*Springer*	107
4	*Taylor &Francis*	55
5	*mdpi.com*	26

3.2 Keyword Co-occurrence dan Clustering

Keyword occurrence analysis is one of the primary ways in bibliometric research to discover the main topic, scientific trends, and the most frequently used language in a field of study. In the framework of this study, the analysis was conducted on keywords that appeared in scientific papers linked to the application of Artificial Intelligence (AI) for optimization of heavy metal adsorption processes during the years 2010–2024. The keywords evaluated were taken from author keywords available in document metadata retrieved from indexed databases. The results of the analysis indicated certain keywords, such as adsorption, heavy metals, machine learning, optimization, neural networks, and wastewater treatment, had the highest frequency of occurrence. These keywords indicate the main topics that are most often discussed and explain that research in this field is largely directed at the use of AI techniques to improve the efficiency of the process of separating heavy metals from water media, both in terms of prediction, modeling, and decision-making. The significant prevalence of the keywords neural network and support vector machine demonstrates that the supervised learning approach is still the dominant choice in modeling adsorption systems.

To identify the association between keywords that regularly appear together, a co-occurrence-based clustering analysis was undertaken using VOSviewer software. The visualization results demonstrate the creation of four primary clusters, each reflecting interrelated research sub-domains. The first cluster (red) includes keywords for example algorithm, area, artificial intelligence, artificial intelligence model, artificial intelligence technique, case study, data, field, groundwater, impact, industrial wastewater, integration, machine, machine learning, machine learning model, optimization algorithm, prediction, role, simulation, technique, wastewater treatment.

The second cluster (green) contains keywords such as approach, biomass, catalyst, challenge, comprehensive review, contaminant, critical review, ion exchange, optimization process, organic pollutant, process optimization, production, review, synthesis, technology, waste. The third cluster (blue) with dominant keywords arsenic, artificial intelligent technology, cadmium, chitosan, copper, data mining, detection, determination, iron, lead, optimization study, recent advance, similar technology, training.

The fourth cluster (yellow) highlights aspects with keywords adsorption mechanism, adsorption study, ann, artificial neural network, characterization, chromium, dye, kinetic, modeling, preparation, presence, response surface methodology, rsm, toxic heavy metal.

The cluster structure established reflects an interdisciplinary research direction, merging environmental science, materials technology, and data science. In addition, there are indications that the hybrid approach—which integrates AI with Internet of Things (IoT) technologies, big data, and automatic control—is a burgeoning and attractive topic for further study.

However, the results of the analysis also suggest that there are still significant research gaps, especially in terms of validation of AI algorithms on a pilot or industrial scale, as well as the dearth of studies covering system integration as a whole.

In addition, the diversity of terms used by authors from other areas produces keyword fragmentation that inhibits systematic knowledge synthesis. Therefore, standardization of keyword use in scientific papers is needed to increase the accuracy and usefulness of bibliometric analysis in the future. Overall, the keyword occurrence and clustering analysis provide a thorough view of the conceptual landscape and direction of research progress in the field of AI for heavy metal adsorption optimization. These findings are not only important for charting previous and current patterns but also as a basis for creating a future research program.

In this bibliometric study, visualization is utilized to highlight the structure and dynamics of research. Network visualization displays the relationship between keywords, authors, or institutions through nodes and links and maps the main topic clusters based on the frequency of co-existence and could be seen in Figure 2. Meanwhile, overlay visualization adds a temporal dimension by depicting the growth of trends based on the average publication year, making it easier to detect new subjects. Figure 3 illustrates that subjects related to those connected by greenish to yellow lines are the most commonly investigated topics in the recent 2-3 years. Meanwhile, density visualization illustrates the intensity of term appearance in the literature, showing the most explored research fields. These three visualizations synergistically provide an in-depth insight of the direction and focus of research and assist researchers identify gaps or chances for additional study development. According Figure 4, the density visualization findings suggest that keywords in bright yellow are the focus of research activities or keywords that appear most often and are close to each other. This signifies that the area represents prominent or mainstream themes in the field being analyzed.

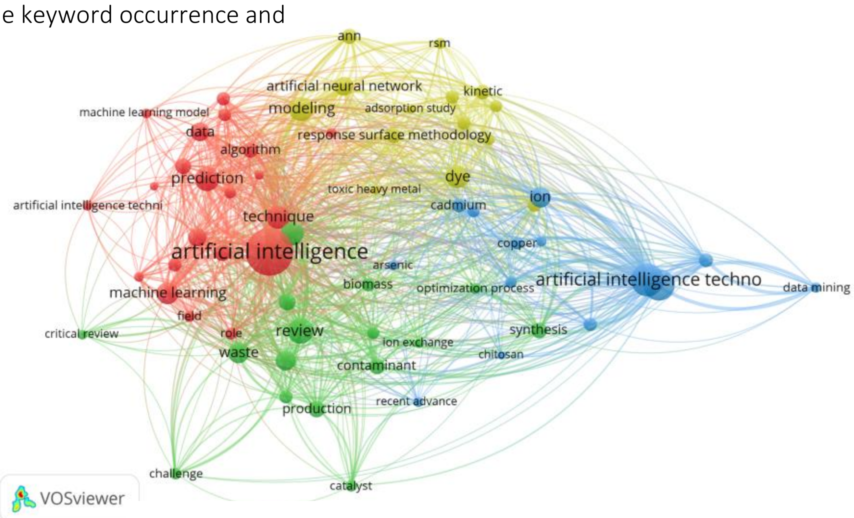

Figure 2. Network Visualization

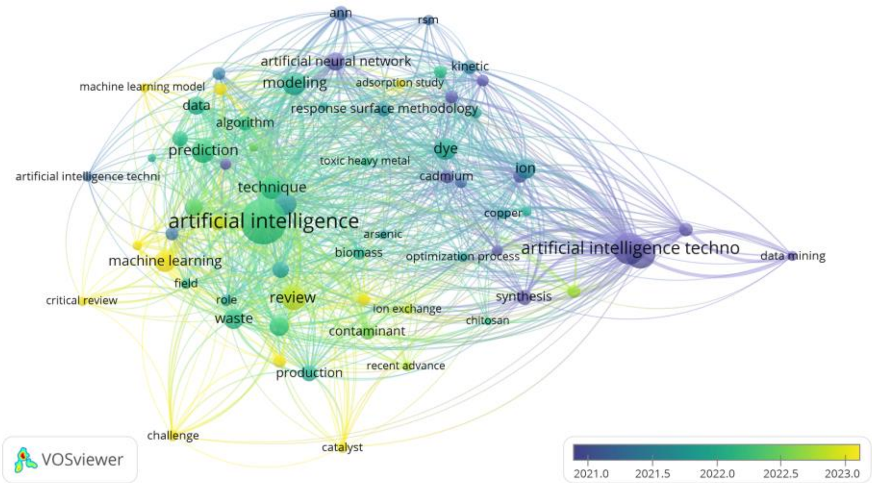

Figure 3. Overlay Visualization

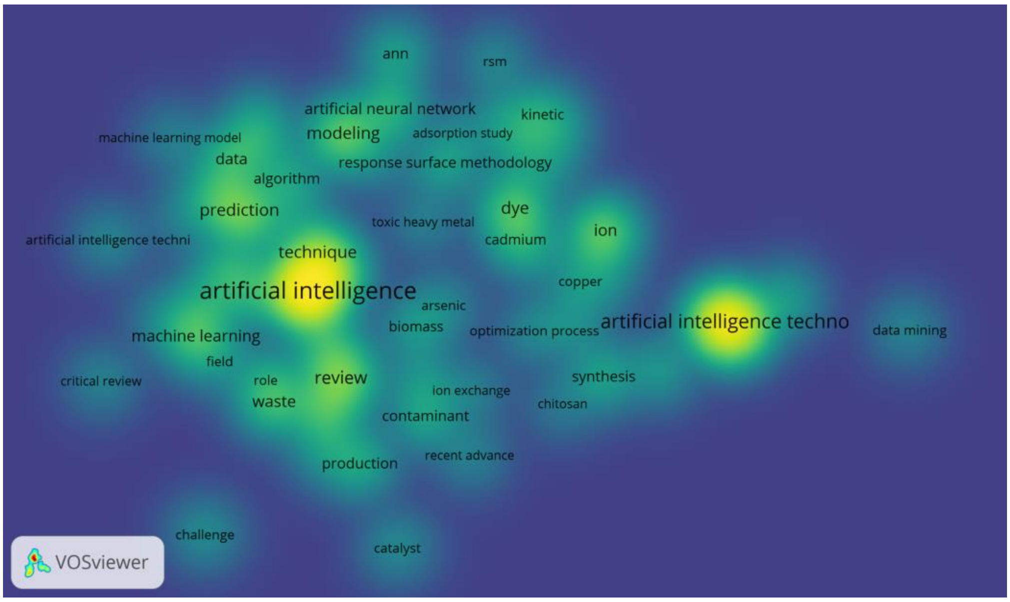

Figure 4. Density Visualization

3.3 Implications and Prospects for Future Research

The trend of using artificial intelligence (AI) in optimizing heavy metal adsorption processes demonstrates great power in enhancing the efficiency, speed, and accuracy of modeling and predicting adsorption processes. Currently, approaches such as machine learning (ML), artificial neural networks (ANN), and genetic algorithms (GA) have been widely employed to improve operational parameters, such as pH, contact time, and the amount of adsorbent[21]–[23]. This strategy promotes the growth of wastewater treatment technologies with a better success rate compared to conventional methods. However, there are significant flaws in the current study trend. Most investigations are currently limited to laboratory scales with small data sets, therefore the created AI models tend to be overfitting and less robust when deployed in real conditions. In addition, interoperability between multiple techniques and model generalization to other types of heavy metals or complicated waste matrices are still hurdles. Research on transfer learning or model adaption across adsorption systems is likewise still relatively minimal.

Several unexplored areas of research include the use of AI to simultaneous multi- heavy metal adsorption systems, real-time data integration for dynamic monitoring, and the creation of big data-based prediction models for future planning in industrial wastewater treatment systems. As a direction for potential growth, it is advised that research merge AI technology with Internet of Things (IoT)-based systems and big data analytics. The combination allows real-time data collection through smart sensors, big data processing to improve forecast accuracy, and the deployment of adaptive learning algorithms to adjust the model to changes in operational conditions. In addition, this technique has an opportunity to build a more automated, efficient, and sustainable heavy metal adsorption technology. In the future, research on this area is likely to focus on the integration of AI with Internet of Things (IoT) technology and big data analytics to construct an adaptable, automated, and real-time data-based wastewater treatment system. A interdisciplinary approach that includes materials science, environmental engineering, and data science will be important to enhancing the accuracy, scalability, and sustainability of heavy metal adsorption systems. Additionally, the development of transfer learning-based machine learning models and dynamic prediction-based systems will expand the use of AI to diverse forms of industrial waste with more complex operational settings. With the application of this technology, it is believed that the management of heavy metal waste in the future can be carried out more efficiently, economically, and ecologically friendly, while boosting the implementation of industrial 4.0-based wastewater treatment.

4. CONCLUSION

This bibliometric review suggests that the implementation of artificial intelligence (AI) in the optimization of heavy metal adsorption processes has witnessed remarkable development in the recent decade. Methods like as machine learning, neural networks, and genetic algorithms have been found to increase the efficiency of predictions and optimization of different adsorption parameters with greater precision than conventional approaches. This development shows the growing global interest in technologically intelligent approaches to solve the issues of heavy metal-based industrial wastewater treatment. However, there are still some limitations that need to be considered, such as the restricted availability of large-scale experimental data, model generalization for varied real-world settings, and the absence of interaction with real-time monitoring systems. These findings show that chances for innovation and cross-field collaboration are still relatively open in the development of artificial intelligence applications for adsorption technology.

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CONFLICT OF INTEREST

No potential conflict of interest was reported by the author(s).

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Moh. Azhar Afandy: Conceptualization, Methodology, Software, Writing - Original Draft, Visualization, Formal analysis, Writing - Review & Editing. **Fikrah Dian Indrawati Sawali**: Writing - Original Draft, Project administration, Software, Formal analysis.

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