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Mapping Research Trend of Heavy Metal Removal Using Nanomaterials (2016-2025): Bibliometric Analysis Based On Scopus Data, Future Perspective And Challenges

Lalu Ahmad Didik Meiliyadi[1]*, Nadia Febriana[2], Dela Yunita Rizki[2], Muhammad Zainur Rahman[3], Jamiluddin[3]

[1]Departement of Physics Education, Faculty of tarbiyah and teacher training, Universitas Islam Negeri Mataram, Jln. Gajah Mada No. 100, Jempong Baru, Mataram

[2]Departement of Physics Education, Faculty of tarbiyah and teacher training, Universitas Islam Negeri Mataram, Jln. Gajah Mada No. 100, Jempong Baru, Mataram

[3]Departement of Social Education Education, Faculty of tarbiyah and teacher training, Universitas Islam Negeri Mataram, Jln. Gajah Mada No. 100, Jempong Baru, Mataram

*email: laludidik@uinmataram.ac.id

Abstract. *Heavy metal pollution in aquatic ecosystems is one of the most pressing global environmental challenges of the 21st century. The use of nanomaterials has emerged as a highly promising remediation solution due to their superior characteristics, such as a massive surface-to-volume ratio and high chemical reactivity. This study aims to map research trends and the knowledge structure related to heavy metal removal using nanomaterials over a ten-year period (2016–2025). Through a bibliometric analysis approach based on Scopus data, a total of 573 English-language experimental articles were extracted and comprehensively evaluated using VOSviewer and Microcal Origin Pro software. The analysis results indicate an exponential growth trajectory in publications, with a stabilization phase at a high productivity level occurring between 2021 and 2024. Demographically, China dominates as the largest contributor of publications (224 documents), while India serves as the main hub of multinational research collaboration networks, and Malaysia has the highest research impact (average citations) per document. Keyword co-occurrence mapping confirms three research focus constellations, including adsorbent materials, environmental toxicology evaluation, and the dynamics of physicochemical mechanisms. Currently, the research landscape is beginning to undergo a paradigm shift from fundamental laboratory-scale studies toward green synthesis technology, economic feasibility, and the management of complex co-contaminants. These findings are expected to serve as a strategic reference for overcoming technical barriers to industrial-scale remediation in the future.*

Keywords: Adsorbance mechanism, Ferrite nanoadsorbents, Heavy Metal Removal, Mapping Research, Scopus Data

INTRODUCTION

Environmental pollution, particularly heavy metal contamination in aquatic ecosystems, has become one of the most pressing global issues of the 21st century (Aziz et al., 2023; Piwowarska et al., 2024; Yu et al., 2025). Various industrial activities such as mining, metal plating, battery manufacturing, and agrochemicals massively release heavy metal ions such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) into the environment (Rajawat et al., 2025; Saxena, 2025; Singh et al., 2025). Unlike organic pollutants, heavy metals are non-biodegradable, toxic even at low concentrations, and tend to bioaccumulate in the food chain, ultimately causing chronic health problems in humans, including nervous system damage and cancer [Add Citation]. Therefore, the removal of heavy metals from wastewater before discharge into the environment is an absolute necessity (Sharma et al., 2023; Zhang et al., 2023).

Over the past few decades, various conventional methods have been applied to remove heavy metals, such as chemical precipitation, ion exchange, coagulation, and reverse osmosis (Priya et al., 2022; Moukadiri et al., 2024). However, these methods often have significant limitations, including high operational costs, low efficiency at very low metal concentrations, and the formation of secondary toxic sludge requiring further treatment (Dagdag et al., 2023; Dutta et al., 2024; Le et al., 2024). In response to these limitations, nanotechnology has emerged as a highly promising solution. Nanomaterials, such as metal oxide nanoparticles, carbon nanotubes (CNTs), graphene, and polymer-based nanocomposites, offer superior characteristics including a very high surface-to-volume ratio, high chemical reactivity, and abundant active sites for the adsorption and reduction of heavy metal ions (Yuvaraj et al., 2023; Tripathy et al., 2024; Pandey et al., 2025; Losetty et al., 2026).

The significance of nanomaterials in water treatment has triggered an exponential surge in scientific publications over the past decade. Hundreds of experimental articles and reviews have been published to explore the synthesis, performance, and mechanisms of nanomaterials in removing heavy metals. However, the sheer volume of this literature presents new challenges; it is extremely difficult for researchers to identify the big picture, track the evolution of the topic, find potential collaborators, and recognize research areas that are becoming saturated or are just emerging (research hotspots) (Haghani, 2023). So far, most existing literature reviews remain conventional and narrative in nature, which are prone to subjective bias and are unable to quantitatively map the structure of knowledge.

To bridge this gap, bibliometric analysis is needed as a systematic, transparent, and measurable method for evaluating academic literature (Meiliyadi et al., 2025a; Meiliyadi et al., 2026). By utilizing the Scopus database one of the world's largest and most reputable scientific literature databases this study aims to map publication trends related to heavy metal removal using nanomaterials (Meiliyadi et al., 2025b; Gilani et al., 2026; Zhong et al., 2026). This analysis will explore performance metrics (such as the most productive authors, institutions, and countries), visualize collaboration networks, and map keyword co-occurrence. Furthermore, this study is designed to identify key challenges (such as nanomaterial toxicity, regeneration, and industrial scalability) and formulate future perspectives that can guide the direction of future research in the field of nanotechnology-based environmental remediation.

METHOD

2.1. Document collection

The literature search and data collection phase of this study utilized Scopus, a comprehensive scientific database with an international reputation (Febriana et al., 2026a; Iwuozor et al., 2026; Nazario-Naveda et al., 2026). The data were accessed on May 3, 2026. In the initial search phase, a specific keyword combination of "nanomaterials, heavy metals, removal" (as shown in Figure 1) was used, which successfully yielded 1,405 documents. To examine the track record and development of studies related to the use of nanomaterials for heavy metal removal, the publication timeframe was narrowed to the last 10 years, specifically from 2016 to 2025.

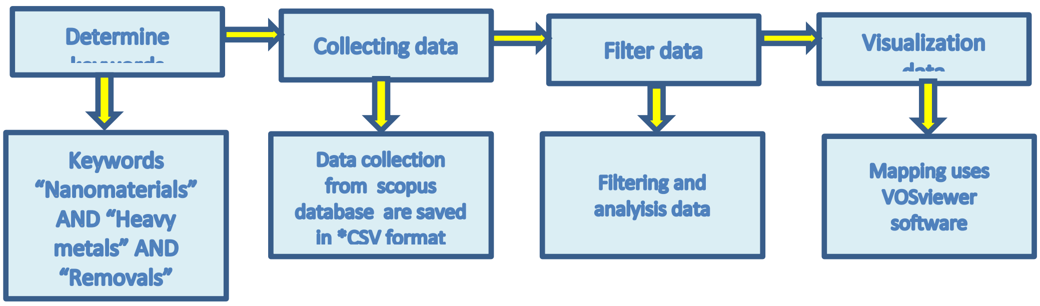

Figure 1. Schematic illustration of document selection and visualization methods

Since this study focuses on the performance and physical characteristics of nanomaterials, the screening process continued by selecting fields of study that directly overlap with this topic. These subject areas include chemistry, environmental science, materials science, chemical engineering, physics and astronomy, engineering, biochemistry, genetics and molecular biology, medicine, and energy. To maintain the quality of the literature and ensure the originality of the evaluated experiments, inclusion criteria were set exclusively for experimental articles published in journals. A strict language filter was also applied, limiting the selection to English-language publications, which ultimately resulted in 573 final documents deemed to meet the study's eligibility criteria.

This set of 573 final documents was subsequently exported for more comprehensive bibliometric analysis. Key parameters evaluated included annual publication patterns, total accumulated citations, and visualizations of co-occurrence networks among keywords. Additional metric evaluations were also conducted to assess the h-index and scientific impact index across the top ten disciplines contributing the highest number of publications (Gallozzo-Cardenas et al., 2026; Meiliyadi et al., 2026; Ran et al., 2026; Rizki et al., 2026). As a supplement, an in-depth study was conducted on the 10 articles with the highest number of citations (based on author name, year of publication, and country of origin), accompanied by the creation of a collaboration network map to track the most productive countries with the strongest research collaboration affiliations.

2.2. Bibliometric analysis

The data preprocessing and standardization stages were performed using the open-source software OpenRefine. This process aimed to normalize terminological variations, specifically by consolidating words with the same semantic meaning but different spellings into a single standardized term. Subsequently, the validated and cleaned dataset was visualized using VOSviewer and Microcal Origin Pro 2019 software. VOSviewer was specifically used to map and visualize bibliometric networks (Chen et al., 2022) from the literature examining the use of ferrite for wastewater treatment. Meanwhile, Microcal Origin Pro 2019 software was used to present graphical representations to illustrate research trends more comprehensively.

RESULT AND DISCUSSION

3.1. Publication trend

This study presents a literature review of articles on the use of nanomaterials for heavy metal removal over a 10-year period, from 2016 to 2025. During this period, research on the use of nanomaterials for heavy metal removal has continued to increase (see Figure 2).

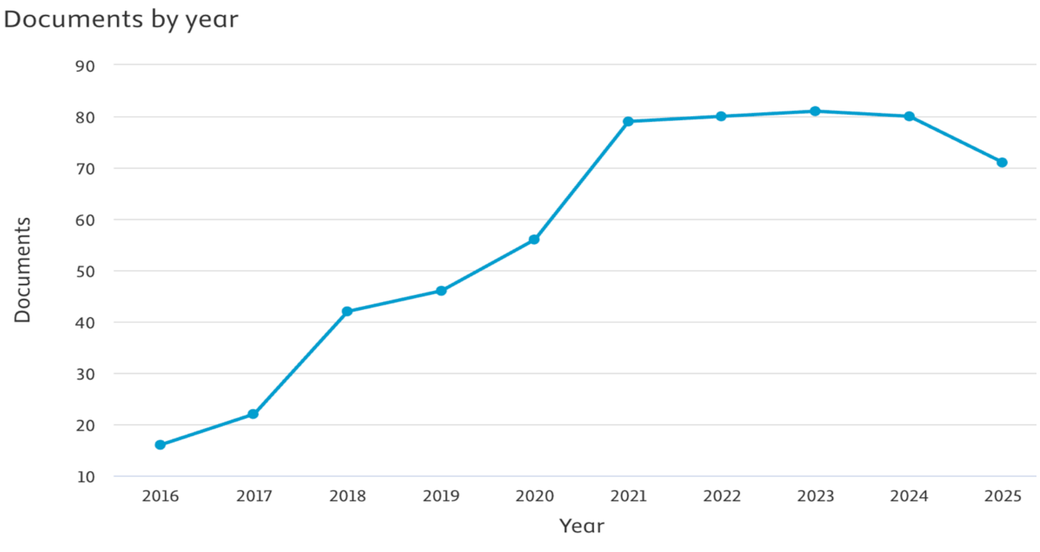

Figure 2. Trends in publications and citations regarding research on the use of nanomaterials for heavy metal removal

Overall, the distribution of the data indicates a positive growth trajectory and a substantial increase in academic attention to this topic, despite fluctuations toward the end of the observation period. Based on a historical review of the presented data, publication trends can be classified into a phase of progressive growth and a phase of stabilization. In the early period (2016–2017), the volume of scientific documents was at a relatively low level, with 16 and 22 publications, respectively. However, entering 2018, there was a significant escalation, with the number of documents nearly doubling to 42 publications. This growth rate continued to accelerate consistently in subsequent years, surpassing 50 publications in 2020 (56 documents), and surging sharply to 79 documents in 2021. The exponential increase during this phase represents rapid advancements in materials innovation and the growing global urgency for environmental remediation technologies.

A stabilization phase at a high publication volume (plateau) was clearly observed between 2021 and 2024. During this four-year period, research productivity demonstrated very high consistency, remaining within a narrow range of 79 to 81 documents per year. The highest peak in productivity for this decade was recorded in 2023 with a total of 81 publications. The consistency in this phase confirms that the discourse on nanomaterials for heavy metal remediation has reached a certain level of research maturity and is recognized as a crucial field of study by the global scientific community.

In 2025, the data indicates a slight reduction in publication volume to 71 documents. This moderate decline can be interpreted in several ways, such as a shift in research focus toward technology commercialization, or the possibility that the compilation of the publication database for the 2025 calendar year had not yet been fully accumulated at the time of data extraction. Despite this minor decline, the accumulation of longitudinal data over this decade provides strong confirmation that the use of nanomaterials remains a vital and relevant pillar in the future development of wastewater treatment technology.

3.2. Co-occurrence of keyword

The bibliometric network visualization created using VOSviewer software is shown in Figure 3. This map illustrates the relationships between interconnected keywords in the scientific literature. The size of each circle represents the frequency of that keyword's occurrence in the research data. The larger the circle, the more dominant the topic. The lines connecting the circles indicate how often these terms co-occur in the same document.

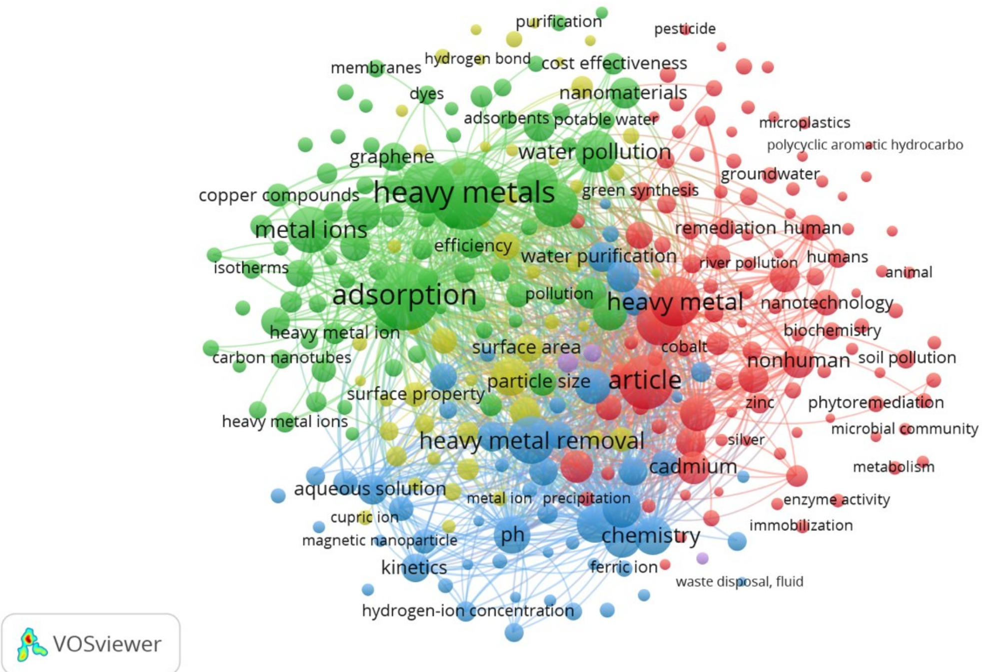

Figure 3. Visualization of keyword co-occurrence networks

Figure 3 depicts a bibliometric mapping based on keyword co-occurrence, aimed at identifying knowledge structures, trends, and the main focus of the research. In this network visualization, the size of the nodes (circles) represents the proportional frequency of keyword occurrence in the literature; the larger the node, the higher the frequency of its use. Meanwhile, the connecting lines (links) indicate the strength of association or the intensity of the relationship between keywords. Color variations indicate the clustering of research thematic areas that share conceptual proximity. Based on the mapping, three to four main clusters were identified that dominate the research discourse.

The keyword network visualization can be grouped according to its color clusters. This grouping helps us understand the division of sub-themes within the research map. The interpretation of the keyword co-occurrence network visualization in the study on the utilization of ferrite nanoadsorbents as heavy metal removers is shown in Table 1.

Table 1. Interpretation of the keyword co-occurrence network visualization in the study on the utilization of nanomaterials for heavy metal removal

Cluster	Main Theme	Research Descriptions
Green	Adsorbent Materials and Key Processes	The green cluster centers on the keywords "heavy metals" and "adsorption." The presence of supporting keywords such as "nanomaterials," "graphene," "carbon nanotubes," as well as "metal ions" and "water pollution" is particularly prominent. This constellation indicates that the most extensive research focus is on the exploration and utilization of various nanoscale materials (such as graphene and carbon nanotubes) as primary adsorbent agents. The close proximity of the nodes within this cluster confirms that adsorption methods are the most extensively studied remediation technology approach for addressing water pollution caused by heavy metals.
Red	Ecological Context and Toxicological Specifications	The red cluster centers on the keyword "article" and is strongly linked to terms representing biological and environmental contexts, such as "human," "nonhuman," "soil pollution," and "river pollution." Additionally, this cluster highlights specific pollutants that are frequently the subject of study, including cadmium, zinc, and cobalt, and connects them to the broader terminology of nanotechnology and remediation. This suggests the existence of a sub-focus of research oriented toward the specific toxicological evaluation of heavy metals, their impact on living organisms and terrestrial and aquatic ecosystems, as well as the broader role of nanotechnology in environmental remediation efforts.
Blue and yellow	Physicochemical Dynamics and Reaction Kinetics	In the lower section of the network, the blue cluster focuses on the terminology of heavy metal removal, chemistry, pH, kinetics, and aqueous solutions. When correlated with the surrounding yellow cluster, which includes surface area, particle size, and efficiency, this mapping indicates an in-depth analytical study of reaction mechanisms. This research area focuses on operational physicochemical parameters—such as the influence of solution acidity (pH) and kinetic

Cluster	Main Theme	Research Descriptions
		rates—as well as the optimization of the physical characteristics of adsorbent materials (surface area and particle size) to achieve maximum heavy metal separation efficiency.

From a holistic perspective, the central position occupied by the major nodes (heavy metals, adsorption, and heavy metal removal)—which act as bridges between clusters—confirms that the core of this research landscape centers on the optimization of advanced material-based adsorption techniques. The high network density between the material cluster (green), toxicology/environmental clusters (red), and physicochemical clusters (blue) demonstrates that the field of heavy metal remediation using nanomaterials is highly interdisciplinary, integrally combining principles of materials science, analytical chemistry, and environmental science.
Unlike network visualizations that focus on thematic clustering, overlay visualizations such as the one shown in Figure 4 are specifically designed to map the evolution of research topics over time. This mapping uses color gradients (spectrum) to represent the average publication year of each keyword. Based on the color bar legend in the lower right corner, the color gradient representing the passage of time starts with dark blue/purple, which represents earlier publications (around mid-2020), moves toward green (around 2021), and reaching a light yellow color representing the focus of recent publications (around 2022 through mid-2022).

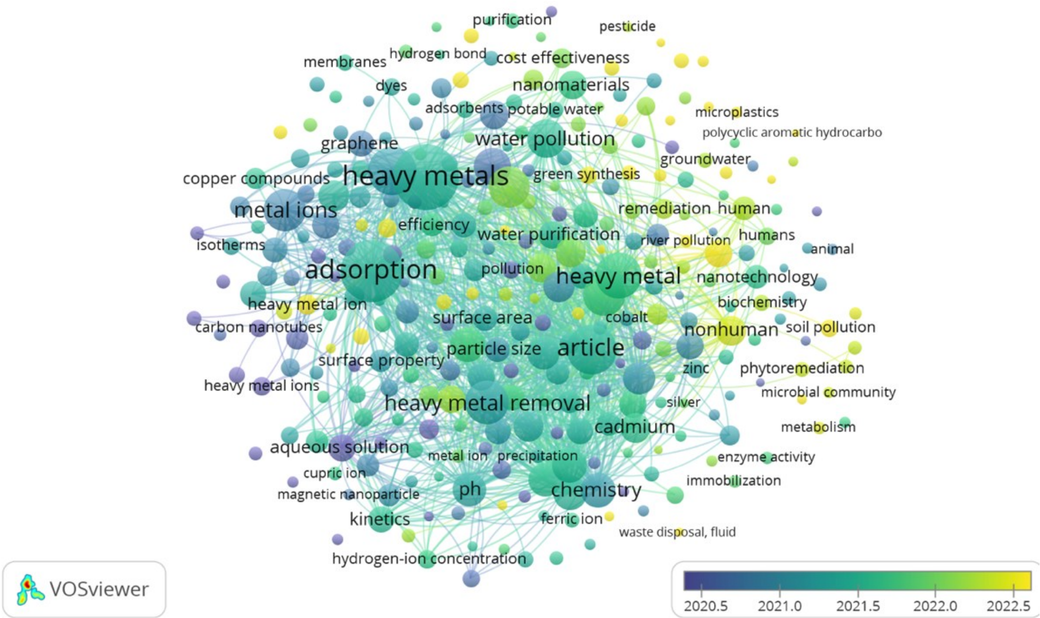

Figure 4. Visualization of keyword co-occurrence overlay

Nodes colored from purple to dark blue indicate research topics that were already extensively explored in the early phase of the analyzed time window. Dominant keywords in this color spectrum include carbon nanotubes, isotherms, kinetics, aqueous solution, and cupric ion. This keyword distribution suggests that during this period, the global research focus tended to revolve around fundamental laboratory-scale studies. Researchers' primary attention was focused on testing conventional adsorbent materials, evaluating thermodynamic equilibrium (isotherms), and modeling the kinetics of metal adsorption reactions in aqueous solutions.

A spectrum of colors ranging from bluish-green (turquoise) to green dominates the central area of the network, marked by the largest nodes. Fundamental keywords such as heavy metals, adsorption, heavy metal removal, chemistry, cadmium, and water purification are found in this phase. The large node size combined with this transitional color indicates a peak in publications (scientific consolidation), during which the main paradigm regarding water remediation techniques based on adsorption processes has become the standard framework and received the highest global research attention.

An evaluation of novelty and future research directions is indicated by the bright yellow nodes. Keywords in this spectrum generally appear in the peripheral areas of the main cluster, encompassing terminology such as microplastics, green synthesis, microbial community, phytoremediation, and cost-effectiveness. The emergence of these topics strongly indicates a paradigm shift (positive divergence) in nanomaterial research. There is a trend toward transitioning from conventional chemical synthesis to more sustainable and ecological approaches (green synthesis, phytoremediation), as well as an expansion of the scope of study to address more complex forms of pollution, such as the interaction of heavy metals with microplastics in real-world environmental matrices.

Holistically, this overlay visualization demonstrates the maturity of the field of heavy metal remediation using nanomaterials. Temporal analysis confirms a logical evolution: beginning with basic physicochemical modeling studies in controlled environments, moving toward the massive optimization of adsorption capacity, and now transforming toward the integration of greener technologies, economic feasibility evaluations, and the management of multi-element co-contaminants in the natural environment. This trend can serve as a strategic reference for researchers in formulating research questions for future studies.

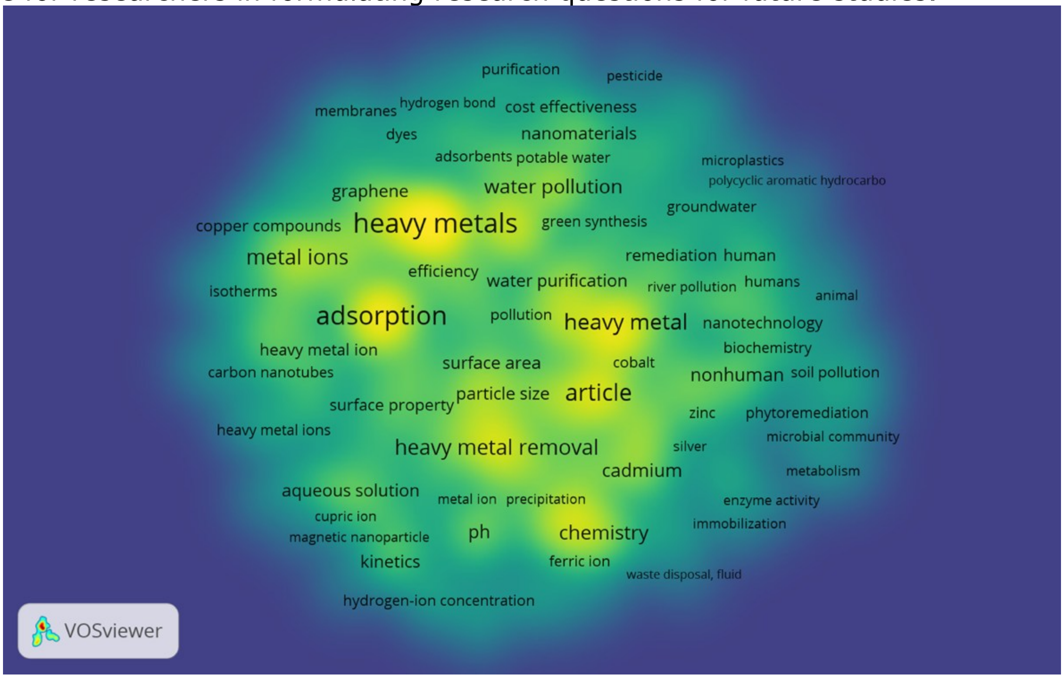

Figure 5. Visualization of keyword co-occurrence density

The visualization of keyword co-occurrence density maps the landscape of scientific literature based on the frequency of keyword occurrences, as shown in Figure 5. The density visualization uses color gradients to indicate the density of research focus. Areas colored light yellow (hotspots) indicate the most dominant and frequently studied topics, while colors transitioning to green and fading into blue indicate topics with lower frequency but remain relevant as supporting elements.

Density mapping specifically serves to identify the level of concentration, depth, and saturation of various topics within a scientific domain. In this visualization, density levels are represented by a thermal spectrum (color gradation) ranging from dark blue (indicating the lowest density), green (medium density), to bright yellow (indicating the highest density or hotspots). The intensity of color in a given area is calculated based on the frequency of keyword occurrence and the weight of their interconnections with other keywords in the surrounding area. This directly reflects the volume of publications and the intensity of researchers' focus on that thematic area.

Analysis of areas with bright yellow hues indicates a very high concentration of research (hotspots) on several central terms. The keywords heavy metals, adsorption, heavy metal removal, and article form the nucleus or core of this research constellation. The absolute density level in this central cluster scientifically indicates that these topics have reached a well-established phase in the scientific field. The high volume of literature in this zone confirms that the use of adsorption methods to remove heavy metals is the most dominant, fundamental, and widely explored research paradigm globally.

Surrounding the main nucleus is a zone ranging from green to yellowish-green, representing research topics with moderate density. Terminology in this transitional area includes chemistry, water purification, graphene, metal ions, cadmium, pH, and nanotechnology. The density at this level indicates that studies on chemical characteristics, the application of nanotechnology (particularly graphene), and the specific identification of contaminants (such as cadmium) constitute substantial supporting subtopics under investigation. These topics serve as operational variables or specific materials that are continuously integrated with the primary research focus in the yellow area.

At the outermost margin of the visualization, the dominance of blue to dark green represents areas with low frequency of occurrence and low conceptual density. There are several significant peripheral keywords, including microplastics, pesticides, cost-effectiveness, phytoremediation, groundwater, and microbial communities. In a bibliometric context, these darker-shaded areas do not indicate irrelevance but rather identify areas that have not yet been extensively explored (research gaps). The low density in these topics indicates that the integration of heavy metal adsorption studies with more complex pollution issues (such as the presence of microplastics and pesticides), economic feasibility analysis (cost-effectiveness), and biological-agent-based remediation (phytoremediation) remains very limited. These peripheral areas represent strategic opportunities for the development of novel research directions in the future.

3.3. Publication source

Table 3 lists the top 10 journals with the most publications on the use of nanomaterials for heavy metal removal. Based on these data, an analysis of publication sources indicates that this topic is of great interest to internationally renowned journals in the fields of environmental science and materials science. This is evidenced by the fact that nearly all journals in this top 10 list are ranked in the highest quartile (Q1).

Table 2. The 10 journals with the most publications on the use of nanomaterials for heavy metal removal

Source	h-index	SJR (2025)	Quartile	Jumlah publikasi	Persentase publikasi (%)
Chemosphere	329	1.896	Q1	33	20,00
Journal of Hazardous Materials	375	3.078	Q1	26	15,76
Science of The Total Environment	399	2.137	Q1	19	11,52
Chemical Enginering Journal	369	2.259	Q1	17	10,30
Journal of Environmental Chemical Engineering	151	1.450	Q1	17	10,30
Environmental Research	217	1.836	Q1	13	7,88
Desalination and Water Treatment	96	0.520	Q2	11	6,67
International Journal of Biological Macromolecules	219	1.285	Q1	10	6,06
Rsc Advances	254	0.859	Q1	10	6,06
ACS Omega	148	0.805	Q1	9	5,45

Based on the quantitative distribution, the journal Chemosphere ranks first as the most dominant publication outlet with a total of 33 articles, representing 20.00% of the total publications in this top ten list. Second place is held by the Journal of Hazardous Materials with 26 publications (15.76%), followed by Science of The Total Environment with 19 publications (11.52%). Cumulatively, the top five journals account for over 67% of the total publications in this table, indicating a concentration of researchers' preferences toward specific publications focused on environmental science and chemical engineering.

From the perspective of quality and academic impact, the data in the table show a very impressive trend. Nine out of the ten listed journals (90%) are classified in Quartile 1 (Q1), which is the highest tier in international journal rankings. Only one journal, namely *Desalination and Water Treatment*, is in the second quartile (Q2). This fact empirically confirms that research on nanomaterials for heavy metal remediation maintains very high standards of novelty and rigorous peer-review processes. Furthermore, an analysis of journal impact metrics shows that the *Journal of Hazardous Materials* has the highest SJR (2025) value of 3.078, making it the journal with the most prestigious scientific influence on this list. On the other hand, Science of The Total Environment is noted for having the highest historical productivity and citation record with an h-index of 399, although it ranks third in terms of the number of publications specifically on this topic.

Comprehensively, the mapping in Table 2 confirms that the scientific discourse on the use of nanomaterials for heavy metal removal is dominated by top-tier journals in the fields of environmental chemical engineering, materials science, and environmental toxicology. The high penetration of publications into these highly cited Q1 journals indicates that this topic is a crucial global issue, highly competitive, and demands comprehensive research outputs with significant impact on the development of water treatment technology.

3.4. Collaboration and productive country/region

Figure 6 shows a visualization map of the collaborative network among the home countries of researchers who published articles on the use of nanomaterials for heavy metal removal. This network visualization illustrates the complex relationships among various countries worldwide, where each circle represents a country's name and the circle's size indicates the volume of activity, influence, or number of publications from that country within the context of the analyzed data. The intersecting curved lines connecting these countries indicate strong interactions or collaborations, with major countries such as India, China, Saudi Arabia, and Egypt emerging as the largest nodes dominating the network, reflecting these countries' research activities in the field of nanomaterials for heavy metal removal.

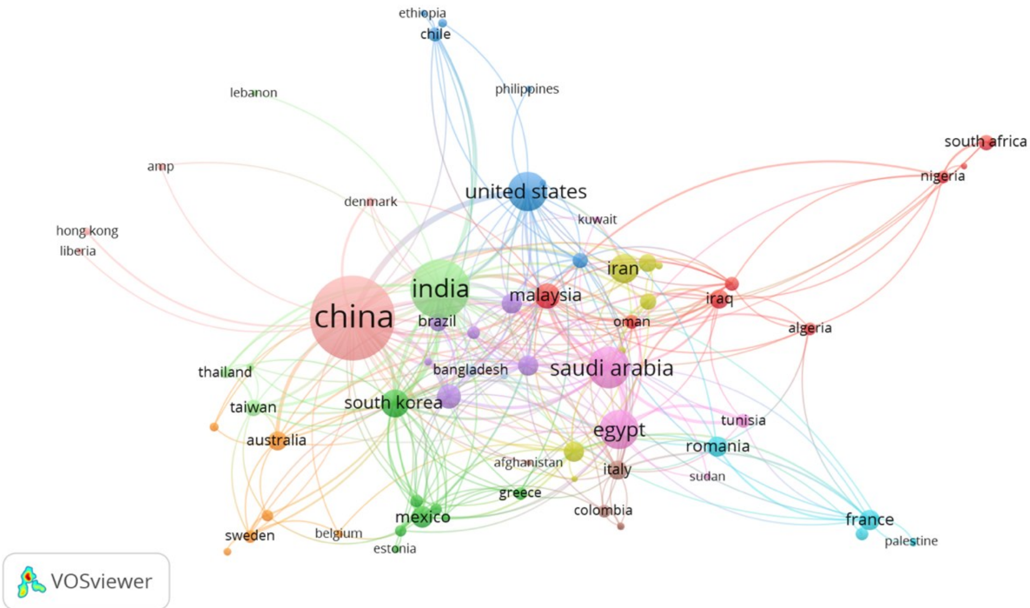

Figure 6. Collaboration network of researchers' home countries publishing articles on the use of nanomaterials for heavy metal removal

Figure 6 depicts the structure of an international research collaboration network. In this bibliometric visualization, each node (circle) represents a country where a researcher is affiliated. The size (diameter) of a node is directly proportional to the number of publications produced by that country; the larger the node, the higher the publication productivity. The connecting lines (links) between nodes visualize collaborative interactions (co-authorship) among researchers from different countries, where the thickness and number of lines indicate the intensity or strength of the collaboration (link strength). Furthermore, color grouping (clustering) indicates the closeness of collaborative relationships, where countries within the same color cluster have a historical tendency to collaborate more closely with one another compared to countries outside that cluster.

Spatially, the network constellation is dominated by four giant nodes acting as the main hubs of global research: China, India, Saudi Arabia, and the United States. This visually confirms the quantitative data in the previous Table 3. The China node (red) appears the largest, representing its absolute dominance in publication volume. However, when viewed in terms of positional centrality and the diversity of connecting lines, the India node (green) and the Saudi Arabia node (purple) appear highly strategic as they are situated right at the network's epicenter. This central position demonstrates that these two countries, particularly India, act as bridges of collaboration that actively connect various clusters of different nations.

Comprehensively, this co-authorship visualization demonstrates that research on the use of nanomaterials for heavy metal removal is not an isolated scientific endeavor, but rather a highly interconnected global research movement. Interestingly, the center of gravity of knowledge in this field is no longer exclusively dominated by developed nations in Western Europe or North America but has shifted significantly toward developing countries and emerging economies in Asia and the Middle East. The high density of collaboration lines between clusters demonstrates a dynamic cross-border exchange of knowledge, research facilities, and funding to address the urgency of the global water pollution crisis.

Table 3. Collaboration and distribution of the most productive countries in research on the use of nanomaterials for heavy metal removal

No	Country	Link Strength	Number of Publications	Number of Citations	Average number of citations per document
1	China	110	224	9,580	42,77
2	India	114	112	6,236	55,68
3	Saudi Arabia	92	54	3,806	70,48
4	Egypt	50	49	1,827	37,29
5	United States	49	48	1,969	41,02
6	Iran	14	27	1,104	40,89
7	South Korea	42	25	1,068	42,72
8	Malaysia	38	21	3,074	146,38
9	Pakistan	33	19	748	39,37
10	Mexico	18	15	341	22,73

Table 3 shows the top ten countries with the highest productivity in research on the use of nanomaterials as heavy metal binding agents. Based on the number of publications, China holds a dominant lead, producing 224 publications and accumulating the highest total of 9,580 citations. India ranks second with 112 publications (exactly half of China's output) and 6,236 total citations. The substantial gap in quantity between the top position and the countries below it indicates the high intensity of investment and research focus in China regarding environmental remediation technology innovation.

Although China dominates in terms of publication volume, the total link strength parameter—which represents the intensity of cross-national research collaboration—shows a different pattern. India is recorded as the country with the strongest collaboration network, with a value of 114, slightly surpassing China, which has a link strength value of 110. This suggests that researchers and institutions from India are highly proactive in establishing multinational research collaborations. Saudi Arabia also demonstrates a good balance between productivity (54 publications) and collaboration (link strength of 92), placing it in a solid third position globally.

The "average citations per document" metric provides an important perspective on the quality, relevance, and impact of the publications produced by each country. In this metric, Malaysia exhibits a highly positive data anomaly. Although ranked eighth with a relatively small number of publications (21 documents), Malaysia holds the absolute highest record for average citations per document, at 146.38. This ratio surpasses Saudi Arabia (70.48) in second place for the impact category, and is more than double that of China (42.77) and India (55.68). This finding crucially confirms that research from Malaysia in this scientific niche possesses such high scientific quality that it serves as a primary reference for global academics.

Demographically, the data reveals a shift in the global center of scientific activity regarding water remediation. Among the ten most productive countries, the Asian region (East Asia, South Asia, Southeast Asia, and the Middle East) dominates this research discourse. The United States (ranked 5th with 48 publications) and Mexico (ranked 10th with 15 publications) are in the minority on this list. The dominance of these developing countries is likely closely correlated with the urgency of addressing industrial pollution and clean water crises, which are more prevalent in countries within these regions.

3.5. Most cited document

Table 4 presents bibliometric data on the ten scientific articles with the highest number of citations that examine the use of nanomaterials as heavy metal removal agents. Overall, the range of citations for these ten articles varies significantly, ranging from 176 to 1,744 citations. The top position is held by the publication by Mitra et al. (2022) from Bangladesh, published in the Journal of King Saud University Science, with a highly exponential citation count (1,744 citations) compared to the other articles. The high citation count for this relatively new article indicates that research on the effects of heavy metals and its innovative therapeutic insights holds extremely high relevance and urgency in current global academic discourse.

Table 4. The 10 articles on the use of nanomaterials for heavy metal removal with the most citations

Number of Citations	Author	Title	Year	Country	Source
1,744	Mitra et al.,	Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity	2022	Bangladesh	Journal of King Saud University Science, 34(3), 101865
524	Vilela et al.,	Graphene-Based Microbots for Toxic Heavy Metal Removal and Recovery from Water	2016	Germany	Nano Letters, 16(4), pp. 2860–2866
414	Li et al.,	Heavy metal removal using nanoscale zero-valent iron (nZVI): Theory and application	2017	China	Journal of Hazardous Materials, 322, pp. 163–171
275	Huang et al.,	Novel insight into adsorption and co-adsorption of heavy metal ions and an organic pollutant by magnetic graphene nanomaterials in water	2019	China	Chemical Engineering Journal, 358, pp. 1399–1409

Number of Citations	Author	Title	Year	Country	Source
242	Qiu et al.,	Constructing Cd0.5Zn0.5S@ZIF-8 nanocomposites through self-assembly strategy to enhance Cr(VI) photocatalytic reduction	2018	China	Journal of Hazardous Materials, 349, pp. 234–241
203	Deng et al.,	PEI modified multiwalled carbon nanotube as a novel additive in PAN nanofiber membrane for enhanced removal of heavy metal ions	2019	China	Chemical Engineering Journal, 375, 122086
193	Lei et al.,	Polyaniline@magnetic chitosan nanomaterials for highly efficient simultaneous adsorption and in-situ chemical reduction of hexavalent chromium: Removal efficacy and mechanisms	2020	China	Science of the Total Environment, 733, 139316
193	Ahsan et al.,	Sustainable synthesis and remarkable adsorption capacity of MOF/graphene oxide and MOF/CNT based hybrid nanocomposites for the removal of Bisphenol A from water	2019	United States	Science of the Total Environment, 673, pp. 306–317
189	Zhang et al.,	Adsorption of heavy metals by L-cysteine intercalated layered double hydroxide: Kinetic, isothermal and mechanistic studies	2020	China	Journal of Colloid and Interface Science, 562, pp. 149–158

Number of Citations	Author	Title	Year	Country	Source
176	Bharath et al.,	Development of adsorption and electrosorption techniques for removal of organic and inorganic pollutants from wastewater using novel magnetite/porous graphene-based nanocomposites	2017	Saudi Arabia	Separation and Purification Technology, 188, pp. 206–218

From the perspective of the geographical distribution of the researchers' institutions or countries of origin, China demonstrates absolute dominance in this list of high-impact publications. Six of the ten most-cited articles originated from China and were published between 2017 and 2020. This reflects the country's massive commitment to research and funding in developing advanced materials technology for environmental remediation, particularly regarding water pollution. The remaining contributions are distributed evenly across various regions, including Bangladesh, Germany, the United States, and Saudi Arabia, each contributing one article to this top-ten list.

Based on temporal analysis and publication sources, these influential articles were published over a six-year span, from 2016 to 2022. This confirms that nanomaterial innovations for water treatment are a continuously evolving field of study that has not stagnated. Furthermore, these articles were published in highly reputable international journals focused on chemical engineering, hazardous materials, and environmental science, such as the *Journal of Hazardous Materials*, *Chemical Engineering Journal*, and *Science of the Total Environment*. When examined in terms of the substance of their titles, the research focus of these articles highlights the diversification of advanced material modifications. Dominant themes include the utilization of nanoscale zero-valent iron (nZVI), graphene-based nanomaterials, carbon nanotubes (CNT), hydrotalcite, and the formation of hybrid nanocomposites (such as the combination of polymers with Magnetic Chitosan or Metal-Organic Frameworks/MOFs). This diversity of materials confirms that global research is focused on optimizing adsorption capacity, magnetic properties for ease of separation, and the efficiency of chemical reduction of toxic heavy metal ions.

3.6. Future Research Directions in the Application of Nanomaterials for Heavy Metal Removal

The use of nanomaterials for heavy metal removal holds great potential, but future research must shift from the laboratory scale to real-world applications. One key focus for the future is testing the performance of nanomaterials in actual industrial wastewater matrices (Amri et al., 2025; Febriana et al., 2026). To date, the majority of research has relied solely on simple, artificially prepared simulation solutions. In reality, actual wastewater has a highly complex composition, containing various interfering ions, natural organic matter, and fluctuating pH levels that can trigger ion competition and drastically reduce the adsorption capacity of nanomaterials (Didik, 2017; Mirayanti et al., 2025, Meiliyadi et al., 2025c).

In addition to operational challenges, aspects of sustainability and economic viability in nanomaterial production are also critical research directions. Conventional synthesis processes often involve high costs and the use of toxic chemicals. Therefore, future research is strongly focused on green synthesis approaches. The use of natural precursors such as plant extracts, microorganisms, or agricultural waste to reduce and stabilize nanoparticles will continue to be explored to lower production costs and minimize negative environmental impacts.

Once applied, the extremely small size of nanomaterials poses new challenges in separation and recovery processes; if left unaddressed, this could turn them into secondary pollutants (Meiliyadi et al., 2024). To address this, researchers will increasingly develop immobilization and separation techniques, such as integrating magnetic properties to facilitate removal via a magnetic field, or embedding nanomaterials into macro-scale support matrices like hydrogels and membranes (Meiliyadi et al., 2023). Concurrently, issues regarding regeneration and reusability must also be resolved. Research needs to identify cost-effective desorption agents capable of releasing heavy metals without damaging the material's structure, enabling nanomaterials to be used across multiple application cycles.

Finally, as the development of smart materials and hybrid nanocomposites with high selectivity for the most toxic metals progresses, environmental safety remains the primary benchmark. The exploration of these new materials must be accompanied by long-term nanotoxicology studies and Life Cycle Assessments (LCA). This is crucial to ensure that any particles that may be released do not harm aquatic ecosystems, as well as to ensure that the carbon footprint during the production of these nanomaterials is commensurate with the ecological benefits they provide.

3.7. Challenges in the Use of Nanomaterials for Heavy Metal Removal

The use of nanomaterials as heavy metal adsorbents has attracted widespread attention in the field of environmental remediation due to their exceptional surface-to-volume ratio and high surface reactivity. Although they promise superior removal efficiency compared to conventional adsorbents, the industrial-scale and field applications of this technology still face a range of comprehensive technical, economic, and environmental challenges.

The first fundamental challenge is closely related to the physical stability of the nanomaterials themselves. Due to their extremely high surface energy, nanoparticles have a strong thermodynamic tendency to aggregate or agglomerate when dispersed in aqueous solutions. This physical phenomenon drastically reduces the active specific surface area and covers adsorption sites, which in turn significantly degrades both the adsorption capacity and rate. Although stabilization efforts can be achieved through surface functionalization or the use of a support matrix (such as polymers or silica), these composite approaches often add to the complexity of the synthesis and may potentially block some active sites.

Another major operational challenge lies in the post-adsorption separation (recovery) process. Given their extremely small size (on the scale of 1–100 nanometers), nanomaterials saturated with heavy metal ions are very difficult to separate from the liquid phase using conventional matrix filtration or sedimentation methods. This separation generally requires energy-intensive ultracentrifugation techniques or modification into nano-magnetic composites so they can be extracted using an external magnetic field. Difficulties in this separation raise serious concerns regarding secondary contamination; if nanoparticles escape into the aquatic environment, the inherent toxicity of some nanomaterials can threaten ecosystems and human health.

Furthermore, the efficacy of nanomaterials under real-world aquatic conditions is often hindered by issues of selectivity and economic viability. Industrial wastewater contains not only heavy metals but also various co-ions (such as calcium, magnesium, and sodium) as well as dissolved organic matter that competitively vie for active sites on the adsorbent surface. From an economic perspective, the upscaling process from laboratory synthesis to industrial manufacturing is often hindered by financial barriers. High precursor costs, expensive chemical reagents, complex synthesis steps, and limitations in the adsorbent regeneration cycle make the current cost-benefit ratio of nanomaterials still challenging to compete with cheaper conventional macroscopic adsorbents.

CONCLUSION

This study has comprehensively demonstrated the evolution and global mapping of the literature on the use of nanomaterials as heavy metal removal agents during the 2016–2025 period. Bibliometric evaluation confirms that the discourse on this topic has reached a well-established level of scientific maturity, characterized by a high volume of publications and dominated by first-quartile (Q1) scientific journals such as Chemosphere and the Journal of Hazardous Materials. A network analysis also reveals that the research center of gravity has shifted toward developing countries in Asia and the Middle East, with China and India acting as the largest hubs for productivity and international collaboration.

Although the application of nanoadsorbents demonstrates exceptional capacity, their practical implementation remains hindered by a number of critical technical and economic challenges. Key obstacles include the difficulty of separating nanomaterials from conventional aqueous matrices—which could potentially trigger secondary contamination—the lack of material selectivity when dealing with co-existing ions in real wastewater, and the high cost-benefit ratio that limits upscaling from the laboratory level to industrial manufacturing. Therefore, future research directions (future perspectives) should focus on sustainable nanocomposite synthesis (green synthesis), the engineering of magnetic particles to facilitate the separation process, the optimization of adsorbent regeneration to improve economic viability, and the expansion of analyses of nanomaterial interactions with multiple contaminants in open ecosystems.

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