Indonesian Journal of Limnology
Vol. 05 No. 01, 2024 (49–63)
E-ISSN :2774-2571

Study of Poly(amidoamine) Based Dendrimers as Adsorbents for Heavy Metals Removal Through Bibliometric Analysis

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Received 22 May 2024 Accepted 13 August 2024 Published 30 August 2024

DOI: 10.51264/inajl.v5i1.66

Abstract

Heavy metals have presented various threats to human health and the environment. Consequently, the removal of heavy metals has remained a primary focus for researchers to safeguard water quality. Among the array of available techniques, the adsorption method utilizing dendrimers has garnered the attention of researchers due to its ease of application and impressive results in the removal of heavy metals. Poly(amidoamine) (PAMAM) based dendrimers have been employed in this domain using adsorption techniques since 1999. This manuscript presents a comprehensive bibliometric analysis, coupled with visualization mapping using VOSviewer software, covering research in this field up to the year 2022. The analysis encompasses trends in paper publications across journals, countries, as well as citation and co-citation patterns among authors and countries. A total of 96 articles were shortlisted based on a defined selection criterion. The majority of articles were published between 2019 and 2022, with 2019 standing out as the peak year for publications. The total published articles garnered a total citation count of 4490, with the most cited article in the list receiving a total of 270 citations. A total of 61 journals are associated with the published articles, with the "Journal of Hazardous Materials" emerging as the leading journal both in terms of article count (8) and total citation count (915). Yuzhong Niu is identified as the author with the highest number of associated articles (15) and the highest citation count (698). China ranks at the top of the list of countries with published articles on this topic.

Keywords: Adsorbent, Bibliometric Analysis, Heavy Metal, PAMAM.

1. Introduction

The rising global population is driving an escalating demand for pure and uncontaminated water. Water stands as a fundamental requirement for human survival on our planet, serving not only as a vital element for drinking but also as an essential resource for various everyday applications and needs. Consequently, access to clean water has become an indispensable necessity. Water contamination arises from the introduction of harmful chemicals and microorganisms into water bodies, leading to a gradual deterioration of water quality and the potential for it to become hazardous to both human health and the environment. Additionally, water can naturally contain elements that are unsuitable for various applications, such as the presence of naturally occurring chemicals like arsenic, radon, uranium and others. Water contamination is a consequence of diverse sources and human activities, including the use of pesticides and fertilizers, improper sewage disposal, and the release of industrial waste, among others. Primary pollutants in water encompass suspended solids (Iber et al. 2023), microorganisms (Gerba and Goyal 1985; Harrison 2014), organic materials (Cui *et al.* 2022; Mukhopadhyay *et al.* 2022) and heavy metals (Pandey and Sharma 2014). The presence of these contaminants can result in a range of issues, from health-related diseases to disruptions in the ecosystem and even phenomena like ocean acidification.

Among these contaminants, heavy metals represent one of the most hazardous categories. The term "heavy metal" is assigned to metals with comparatively high density that can be toxic even in small quantities. Heavy metals are hazardous due to their enduring presence, toxicity, tendency to accumulate within organisms, and resistance to degradation. Heavy metals exhibit toxic effects (Pandey and Sharma 2014) even when present in low concentrations, and such levels can be lethal to living organisms. Both human-made activities and natural geochemical processes contribute to heavy metal contamination in ecosystems (Li *et al.* 2007; Singh Sankhla *et al.*, 2016). There is a diverse array of heavy metals found in water, with primary examples including mercury, cadmium, chromium, selenium, arsenic, silver, gold, gadolinium, nickel, copper, zinc, and lead, among others.

Heavy metals pose a significant hazard to aquatic life (Demarco *et al.*, 2023) and human beings even at low concentrations. They can induce stress in aquatic organisms at minimal levels and, at higher concentrations, hinder the growth of aquatic animals like fish. Zinc pollution, for instance, can cause structural changes in the lungs and heart (Li *et al.*, 2019; Skidmore 1964). Mercury poisoning is known to damage the brain and central nervous system, lead to complications in pregnancy resulting in abortions and congenital deformities, among other adverse effects (Zheng *et al.*, 2019). Exposure to lead (Pb) can affect the developing fetus and infants, impair the synthesis of hemoglobin, impact the kidneys, gastrointestinal tract, joints and reproductive system, as well as cause acute or chronic damage to the nervous system (Lee *et al.*, 2019). Similarly, other heavy metals also exhibit toxicity and can give rise to various issues for humans, animals, and the environment. Hence, it is imperative to treat water and remove such contaminants before its use.

In recent years, the removal of heavy metals from wastewater has become a focal point for researchers. The primary approaches for heavy metal removal fall into three main categories: physical, chemical, and biological. These techniques encompass microbial systems, electrochemical processes, chemical precipitation, coagulation, photocatalytic degradation, ion-exchange adsorption, membrane filtration, and bioremediation (Demarco *et al.*, 2023), to name a few.

Among the various available techniques, the adsorption process stands out as a simple and efficient method for removing heavy metals. This method has been noted for its low operating costs, high removal capacity, ease of implementation and simple treatment. Sequestration of heavy metals through adsorption can be accomplished using following major adsorbents:

1.1. Industrial waste (Ahmed and Ahmaruzzaman 2016; Bhatnagar et al., 2006): A diverse range of industrial waste materials can be used for this purpose. For e.g. sludge, blast furnace slag & flue dust, fly ash, lignin, red mud.

1.2. Carbon based adsorbents (Yang *et al.*, 2019; Yu *et al.*, 2015): Carbon-based nano-porous adsorbents, particularly activated carbons, carbon nanotubes and graphene find widespread use in heavy metal removal applications due to their exceptionally large surface areas.

1.3. Chitosan-based adsorbents (Ngah and Fatinathan 2008; Wan Ngah *et al.*, 2011): Chitosan is a natural adsorbent polymer known for its affinity towards heavy metals, attributed to its amino ($–NH_2$) and hydroxyl (–OH) groups.

1.4. Mineral adsorbents (Gu et al., 2019; Zhang et al., 2021): Mineral adsorbents like zeolite, silica and clay are recognized as excellent options for water purification due to their cost-effectiveness in terms of operational expenses.

1.5. Magnetic adsorbents (Khan *et al.*, 2020; Tamjidi *et al.*, 2019): Magnetic adsorbents are a distinct type of material matrix that incorporates iron particles, typically magnetic nanoparticles like Fe_3O_4. The foundational material can vary and may include carbon, chitosan, polymers, starch, or biomass.

1.6. Dendrimer based adsorbents (Shahbazi *et al.*, 2011): Silica based dendrimers (Shahbazi *et al.*, 2011), carbon nanotubes (Iannazzo *et al.*, 2017), PAMAM dendrimer and Its conjugates, are all noteworthy compounds when it comes to their use as adsorbents.

The use of dendrimers as adsorbents to address environmental challenges, such as the removal of heavy metals from wastewater, has garnered significant interest due to their distinctive physical and chemical characteristics which set them apart from traditional adsorbents and make them highly advantageous in various fields (Wazir *et al.,* 2020). To be considered an excellent adsorbent for efficiently removing a substantial number of pollutants in a short timeframe, certain attributes are crucial. These include a large surface area, rapid adsorption rates and short adsorption equilibrium times (Guo *et al.,* 2019). Within the dendrimer structure, numerous empty cavities are present, which can effectively trap or encapsulate pollutants, enhancing their adsorption capabilities (Sajid *et al.,* 2018).

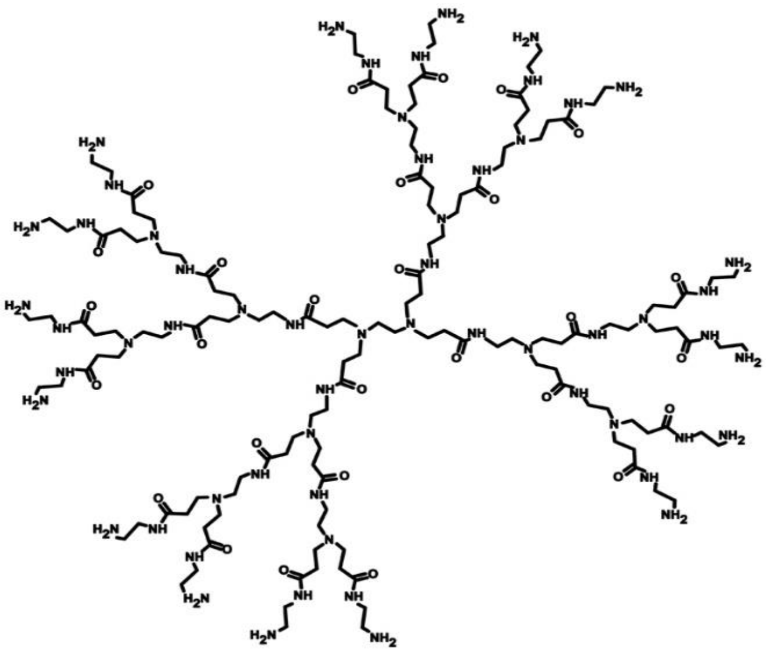

Figure 1. Generation 2 PAMAM dendrimer (Ref. ("PAMAM Dendrimers" n.d.))

Dendrimer-based adsorbents have showcased significant potential, with PAMAM dendrimers (Figure 1) emerging as the most prominent for water purification applications. In 1985, Tomalia et al. pioneered the synthesis of the classic dendritic macromolecule known as PAMAM (Tomalia et al., 1985; Tomalia et al., 1990). Nowadays, scientists across various disciplines are dedicated to the preparation, modification, and application of dendritic compounds. PAMAM has emerged as one of the most extensively researched dendrimers due to its cost-effectiveness, low toxicity and ease of fabrication. In 1999, Diallo and colleagues were the first to report the utilization of PAMAM dendrimers for removing copper ions from water (Diallo et al., 1999). PAMAM dendrimers find utility as adsorbents for a range of substances, including organic molecules (Cui *et al.,* 2022; Sajid *et al.,* 2018), heavy metals (Sajid *et al.,* 2018; Vunain *et al.,* 2016) and dyes (Wan Ngah *et al.,* 2011; Zhan *et al.,* 2023). They have gained considerable recognition for their role in purification as effective adsorbents and their application in detecting and quantifying toxic pollutants as sensors.

PAMAM dendrimers are renowned for their versatility in offering a wide range of end groups and easy surface modification, making them well-suited for environmental remediation purposes (Guo *et al.,* 2022). While these polymers have proven effective in removing diverse pollutants such as metal ions, radionuclides, dyes, drugs, and pesticides, their retrieval from the aqueous phase poses a significant challenge. Hence, one of the most effective approaches involves growing or immobilizing dendrimers onto various solid supports. Magnetite nanoparticles show up as particularly attractive support materials due to their cost-effectiveness, biocompatibility, simple preparation, low environmental impact and magnetic properties. On the other hand, carbonaceous materials like graphene oxide and carbon nanotubes have also been employed as supports for the growth or immobilization of dendrimers, enhancing the adsorption properties of hybrid materials based on PAMAM.

The utilization of magnetic support offers the advantage of reusability for PAMAM dendrimers. The most common supports for immobilizing PAMAM include magnetite nanoparticles with a silica shell coating, carbon nanotubes (CNT), graphene oxide (GO), and silica (SiO_2). Non-magnetic hybrid materials are effective at sequestering pollutants, but they often exhibit limited absorbent recovery. These non-magnetic supports primarily consist of carbonaceous materials (such as graphene oxide (Xiao *et al.*, 2016), carbon nanotubes (Hayati *et al.*, 2016) and silica supports (Niu *et al.*, 2014; Wu *et al.*, 2022). Additionally, other modifications have been reported, including the synthesis of modified PAMAM using polymers like poly(styrene-codivinylbenzene) (Guo *et al.*, 2021) adsorbents with phosphorus functional groups and poly(styrene-divinylbenzene-glycidylmethacrylate) compounds (Cao *et al.*, 2013). These modifications broaden the range of applications for PAMAM dendrimers in pollutant removal and environmental remediation.

Bibliometric analysis involves the statistical evaluation of published scientific literature, encompassing articles, books and book chapters. This method is widely utilized to investigate various facets of scientific research, making it a powerful tool for quantifying the impact and influence of publications within the scientific community. With this perspective in mind, the current research endeavours to conduct a bibliometric analysis focused on PAMAM as adsorbents for heavy metals. PAMAM can be utilized either as dendrimers with active sites or in modified forms (Guo *et al.*, 2022; Yasir *et al.*, 2023). By comprehensively reviewing the available research literature, this study aims to provide valuable insights into the progress and potential of using PAMAM adsorbents for the removal of heavy metals.

2. Data Source, Data Selection, Data Processing and Methodology

The data for this study has been sourced from research articles published in journals indexed by Dimensions, recognized as one of the most advanced scientific research databases. This particular research platform was selected for its accessibility as a freely available resource. The search criteria involved using keywords such as "Adsorbent" in conjunction with "PAMAM" and "Polyamidoamine." Data collection for this study encompassed all years and the filtering process focused on identifying these keywords within the "title" and "abstract" fields of the publications. Initially, a total of 183 relevant search results were identified pertaining to the topic. Subsequently, a more refined selection process was executed wherein review articles were excluded and only those articles were selected that investigated the utilization of PAMAM as an adsorbent for heavy metals up to the year 2022. This refined search yielded a final count of 96 articles, which constitute the subset of research articles employed for conducting the bibliometric analysis.

Various data like citation no., h-index, quartile (Q rank) and impact factors were projected here from the data source taken by dimensions software, Scimago journal & Country rank (SJR) and Journal’s website for accessing the research articles. VOSviewer is a software application designed to create and display bibliometric networks in a visual format (van Eck and Waltman, 2010). The same software is utilized in the present study to construct visual representations, such as author networks, country affiliations, citation network, publication patterns and journal categorizations.

3. Results and Discussion

3.1. Annually Publication trend

A total of 96 publications were identified under the search restrictions. The synthesis of PAMAM dendrimers began in 1985 and their utilization in heavy metal sequestration commenced in 1999 when D.A. Tomalia et. al. demonstrated the capture of Cu^{+2} ions from water. Following this, researchers exhibited interest in advancing PAMAM and its modified derivatives for removing heavy metals (Figure 2). The growth in research activities noticeably accelerated starting from 2012. However, during the period from 1999 to 2012, specifically in the years 2000-2004, 2006 and 2008, there were intervals where no publications were recorded. The publication trend reached its zenith in 2019. Subsequently, there was a slight decline in research activity in the subsequent years, likely influenced by the onset of the pandemic in 2020.

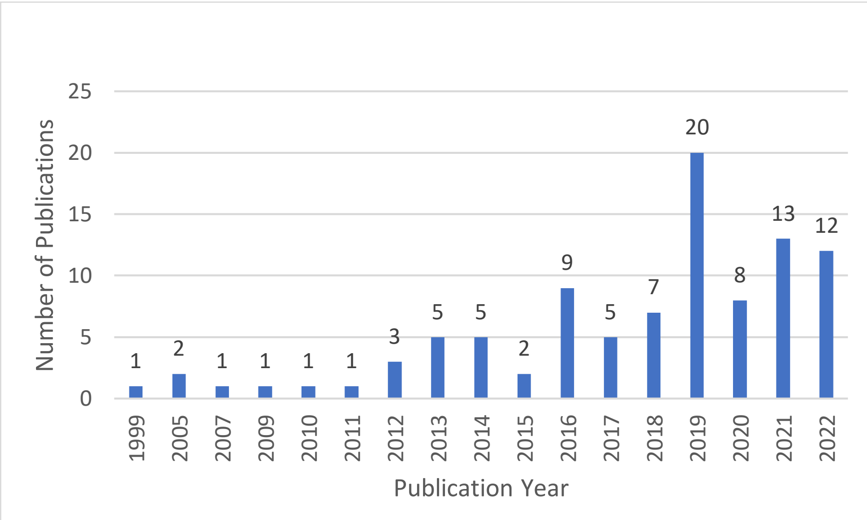

Figure 2. Publication Trend Across the Years

An alternative approach was employed to examine the publication trend. Accordingly, the entire publication period has been divided into four distinct groups, as illustrated in Table 1 and Figure 3. The segmented analysis reveals that a significant portion, amounting to 56% of the total publications, has been observed in the most recent years, falling within Group 4, spanning from 2019 to 2022, where a total of 56 articles were published. Groups 2 and 3 also exhibit a notable level of publication activity, accounting for 15% and 24% of the overall publications, respectively. As pollution and population levels are rising day by day, the need for clean water is increasing. Consequently, research in this field has garnered escalating attention, as indicated by the upward trend in paper publications over the years.

Table 1. Groupwise Publication and Metrics

Groups (Year Range)	Number of Publications	% Of Publications
Gr1 (1999-2010)	5	5.3%
Gr2 (2011-2014)	14	15%
Gr3 (2015-2018)	23	24%
Gr4 (2019-2022)	53	56%

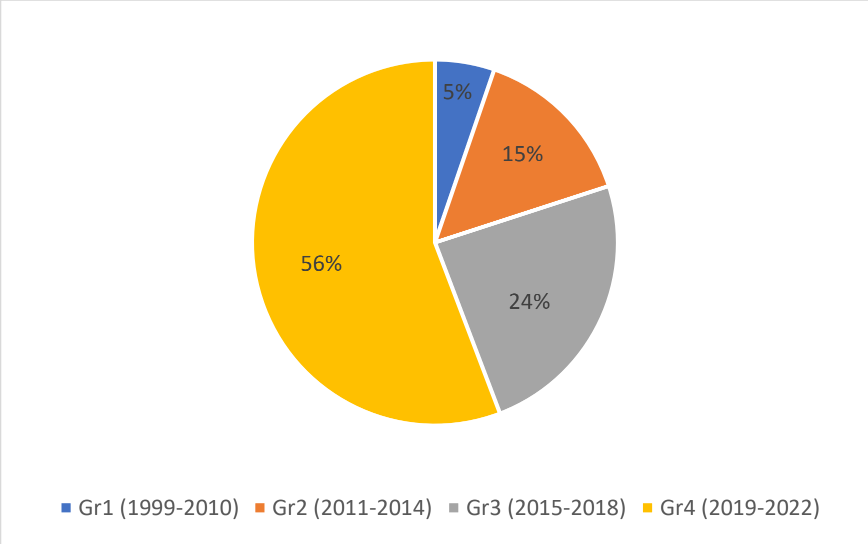

Figure 3. Graphical Representation of Publications in Different Group of Years

3.2. Trend analysis among journals

The publications retrieved in this study were distributed across 61 different journals. In Table 2, the top 6 most productive journals, each of which had at least 3 articles published, were highlighted along with specific metrics such as Impact Factor, Q rank, and H-index . The Journal of Hazardous Materials emerged as the most prolific journal for cited research articles, with a total of 8 publications. In 2022, it held an impressive Impact Factor (IF) of 13.6. Following closely were the Chemical Engineering Journal, Journal of Molecular Liquids and Journal of the Taiwan Institute of Chemical Engineers, each with 5 publications. These journals all exhibited high impact factors, exceeding 5, underscoring the significance of the subject matter under investigation. Together, these top 6 journals accounted for 30% of the total relevant publications.

Table 2. Top 6 Journals and Metrics

Sr. No.	Journal title	Total Publications (TP)	TP (%)	Cumulative (%)	IF (2022)	Q Rank	H index
1.	Journal of Hazardous Materials	8	8.3	8.3	13.6	Q1	329
2.	Chemical Engineering Journal	5	5.2	13.5	15.1	Q1	280
3.	Journal of Molecular Liquids	5	5.2	18.7	6	Q1	150
4.	Journal of the Taiwan Institute of Chemical Engineers	5	5.2	23.9	5.7	Q1	103
5.	Environmental Science and Technology	3	3.1	27.1	11.4	Q1	456
6.	Journal of Environmental Chemical Engineering	3	3.1	30.2	7.7	Q1	107

3.3. Citation and Co-Citation Analysis of Published Articles

The total number of citations recorded for all the titles included in the analysis amounted to 4490. On average, each paper received a citation percentage of 47%. Out of the total articles, 27 garnered more than 50 citations and 15 articles received more than 100 citations, as detailed in Table 3. This trend in citations underscores the significance of these articles within the research community.

Table 3. Top 10 Most Cited Article Titles

Sr. No.	Title	Journal Title	Publication Year	Authors	Times cited
1	Dendrimer Enhanced Ultrafiltration. 1. Recovery of Cu(II) from Aqueous Solutions Using PAMAM Dendrimers with Ethylene Diamine Core and Terminal NH2 Groups	Environmental Science and Technology	2005	Mamadou S. Diallo et. al.	270
2	Poly(amidoamine) Dendrimers: A New Class of High Capacity Chelating Agents for Cu(II) Ions	Environmental Science and Technology	1999	Mamadou S. Diallo et. al.	189
3	Heavy metal adsorption using PAMAM/CNT nanocomposite from aqueous solution in batch and continuous fixed bed systems	Chemical Engineering Journal	2018	Bagher Hayati et. al.	185
4	Synthesis of silica gel supported salicylaldehyde modified PAMAM dendrimers for the effective removal of Hg(II) from aqueous solution	Journal of Hazardous Materials	2014	Yuzhong Niu et. al.	181
5	Intensively competitive adsorption for heavy metal ions by PAMAM-SBA-15 and EDTA-PAMAM-SBA-15 inorganic-organic hybrid materials	Microporous and Mesoporous Materials	2007	Yijun Jiang et. al.	179
6	Adsorption of Pb(II) from aqueous solution by silica-gel supported hyperbranched polyamidoamine dendrimers	Journal of Hazardous Materials	2012	Yuzhong Niu et. al.	163
7	Preparation of Graphene-Oxide/Polyamidoamine Dendrimers and Their Adsorption Properties toward Some Heavy Metal Ions	Journal of Chemical & Engineering Data	2014	Fan Zhang et.al.	146
8	Super high removal capacities of heavy metals (Pb^{2+} and Cu^{2+}) using CNT dendrimer	Journal of Hazardous Materials	2017	Bagher Hayati et. al.	144
9	Poly(amidoamine) modified graphene oxide as an efficient adsorbent for heavy metal ions	Polymer Chemistry	2013	Yang Yuan et. al.	143
10	Removal of Copper from Contaminated Soil by Use of Poly(amidoamine) Dendrimers	Environmental Science and Technology	2005	Yinhui Xu, Dongye Zhao	128

The most cited article in the list, co-authored by Mamadou S. Diallo et al., received a total of 270 citations. This particular article, published in 2005, stands among the initial publications related to the use of PAMAM dendrimers for heavy metal removal (Diallo *et al.*, 2005). The second article on the list, also authored by Mamadou S. Diallo et al., garnered 189 citations and is considered the first article ever published on the removal of heavy metals using PAMAM dendrimers (Diallo *et al.*, 1999). Both of these pivotal articles focus on the removal of Cu(II) ions using PAMAM dendrimers with different terminal groups. These two articles not only mark the early contributions to the field but also serve as central reference points for researchers exploring the application of these dendrimers, not only for copper ions but also for other heavy metals.

Additionally, a citation analysis was conducted using VOSviewer software, focusing on documents with a minimum of 100 citations each. This analysis yielded a total of 8 clusters. Figure 4 visually presents the largest cluster, which encompasses 12 interconnected items.

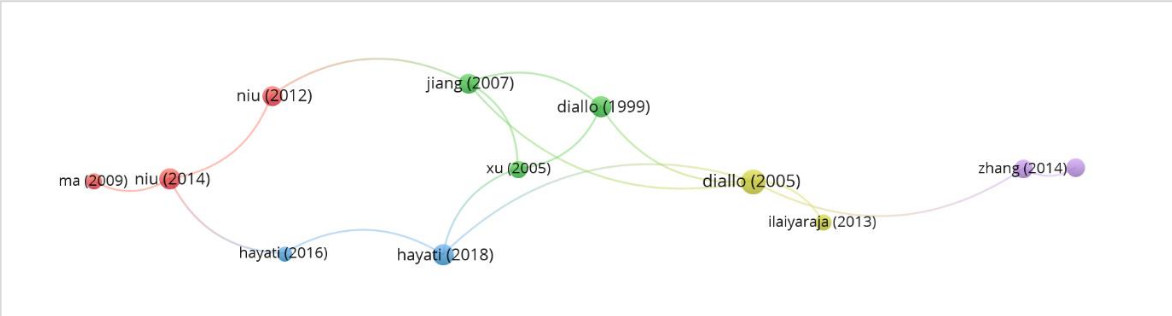

Figure 4. Citation Cluster of Most Cited Articles (Largest cluster with maximum interconnections)

A subsequent co-citation analysis was performed on the selected relevant articles. Co-citation, as a bibliometric analysis, identifies the frequency with which two publications are cited together, implying a potential relationship or similarity between them. The strength of the co-citation link between publications is represented by the thickness of the connecting lines. Figure 5 provides a visual representation of this co-citation network, adhering to a criterion that sources must have a minimum of 20 citations to be included to identify significant connections.

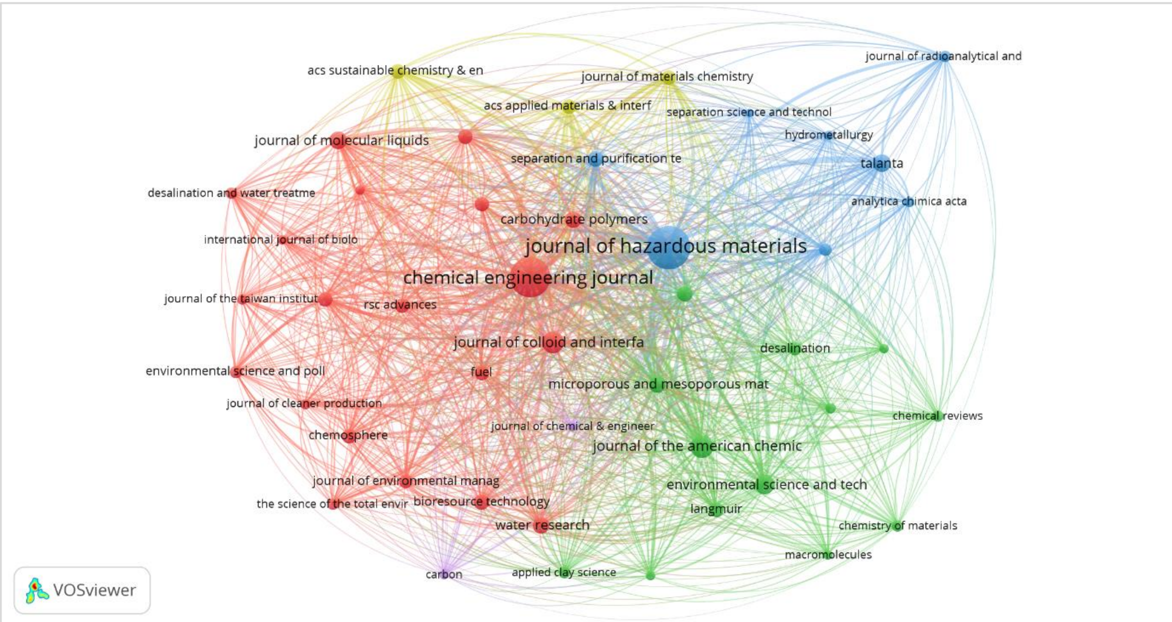

Figure 5. Co-citation Among Publications

3.4. Journals' Citation analysis

The citation analysis of journals sheds light on their significance, determined by the total number of citations received for the articles they have published. Table 4 presents the top ten journals, ranked based on the cumulative number of citations garnered by all relevant articles they have published. The journal with the most citations tends to be the one with the most published articles in the relevant field. The significance of the subject matter can be gauged by examining the last three journals listed, which demonstrate that even a single highly cited article can position a journal among the top-ranked ones. Figure 6 visually depicts the most dominant interconnected cluster of the frequently cited articles using a minimum document criteria of 2.

Table 4. Top 10 Highest Cited Journals

Sr. No.	Journal Title	No. of Articles	citations
1	Journal of hazardous materials	8	915
2	Environmental science and technology	3	587
3	Chemical engineering journal	5	456
4	Microporous and mesoporous materials	2	194
5	Journal of molecular liquids	5	177
6	Journal of the taiwan institute of chemical engineers	5	171
7	Journal of chemical & engineering data	2	166
8	Polymer chemistry	1	143
9	Bioresource technology	1	125
10	Journal of materials chemistry A	1	124

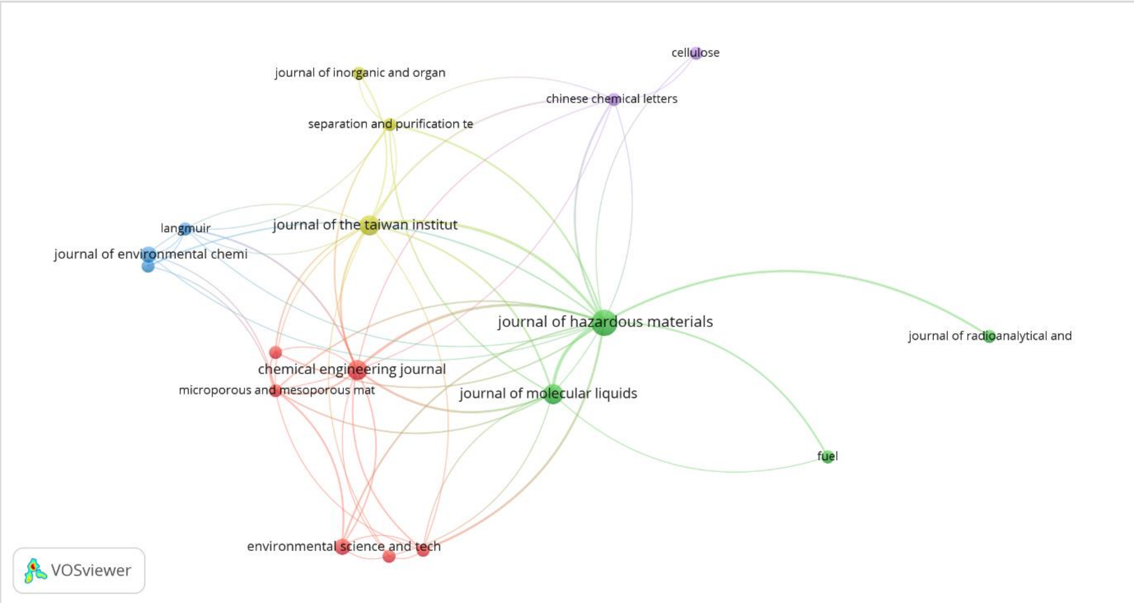

Figure 6. Citation cluster of Journals

3.5. Author analysis: Citation, Co-authorship, Co-citation

In the articles analyzed for this study, a total of 373 authors made contributions. The highest number of contributions was documented by Yuzhong Niu, who co-authored 15 articles and received a total of 698 citations. Rongjun Qu co-authored 12 articles, which garnered the highest number of citations, totaling 718. Table 5 presents a list of authors who have been associated with 5 or more publications, along with the number of publications and the respective citation counts. Additionally, Figure 7 offers a visual representation of the co-authorship patterns within the most interconnected cluster of authors, with a minimum authorship criterion set at 3 for inclusion.

Table 5. List of Authors with Higher Number of Documents

Sr. No.	Author	Number of Articles	Citations
1	Yuzhong Niu	15	698
2	Rongjun Qu	12	718
3	Changmei Sun	9	572
4	Ying Zhang	8	391
5	Wenlong Xu	8	247
6	Hou Chen	6	444
7	Chunnuan Ji	6	355
8	Iiping Luan	6	216
9	Bagher Hayati	5	459
10	Bentian Tang	5	205
11	Ping Yin	5	204

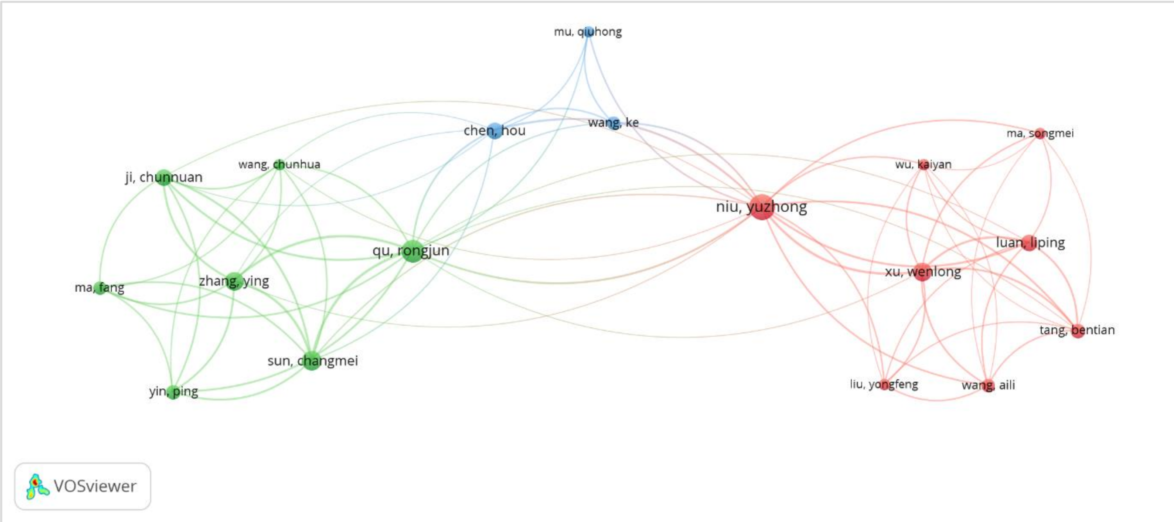

Figure 7. Visualization of Co-authorship Among Authors
(Largest set of interconnected clusters)

The co-citation analysis reveals how often authors are cited together, indicating a degree of association or similarity in their work. In this context, Yuzhong Niu and Rongjun Qu, who have the highest number of publications at 15 and 12, respectively, are also frequently co-cited by other authors. Figure 8 visually presents the co-citation map among authors, with a minimum citation threshold of 30 for inclusion. This map helps to identify the prominent connections and relationships among authors' work based on their co-citation patterns.

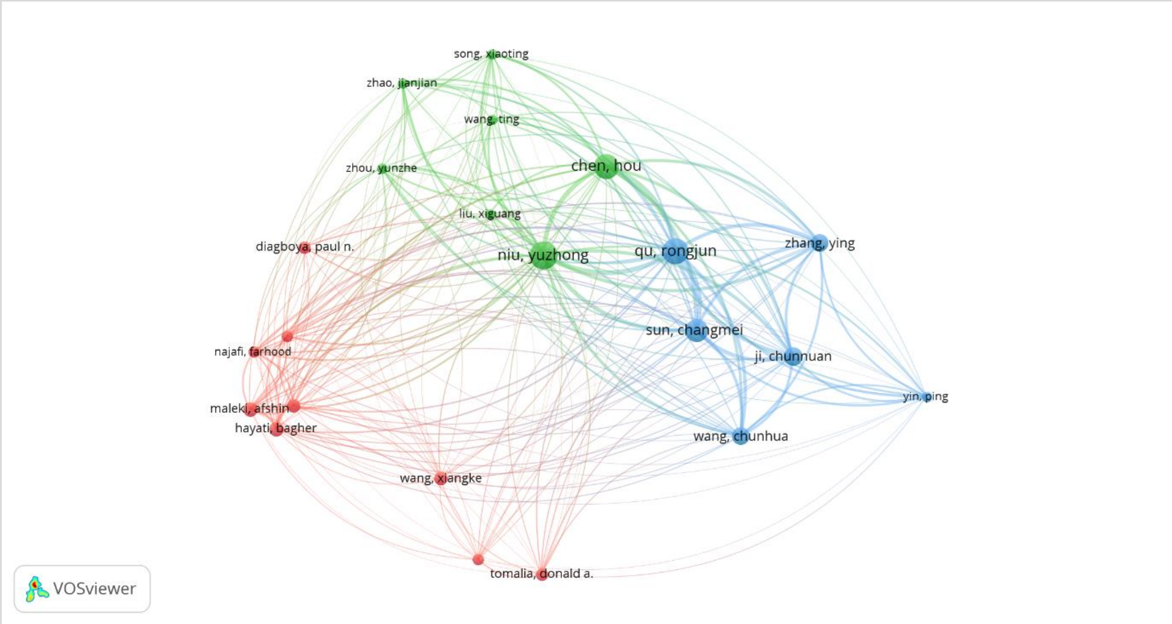

Figure 8. Co-citation Among Authors

3.6. *Country wise analysis: published articles, Citation*

A country-wise analysis showcases contributions from 21 distinct countries. The top five most productive countries are highlighted in Table 6. China leads the chart with the highest number of articles published and the maximum total citations 2132. Iran holds the second spot with 12 published articles, which have received 860 citations collectively. India ranks third, having published 8 articles that have been cited 424 times. Egypt and the United States are both positioned at fourth, each with 5 articles; however, while Egypt's articles have gathered 82 citations, the United States' articles have been cited 596 times. Notably, these figures indicate that just 5 articles received 596 citations, underscoring the significance of their contributions to the field. Figure 9 visually presents a network illustrating the citation relationships among countries, maintaining a minimum criterion of 3 documents per country. This visual representation allows for a quick overview of the interconnectedness and influence of each country in the domain under study.

Table 6. List of top 5 countries

Sr. No.	Country	Number of Articles	citations	Year (No. of article)
1	China	51	2132	2022(7), 2021(8), 2020(4), 2019(10), 2018(3), 2016(4), 2015(2), 2014(5), 2013(3), 2012(2), 2011(1), 2009(1), 2007(1)
2	Iran	12	860	2020(2), 2019(1), 2018(4), 2017(1), 2016(3), 2012(1)
3	India	8	424	2022(2), 2019(1), 2018(1), 2017(3), 2013(1)
4	Egypt	5	82	2022(3), 2019(2)
5	United States	5	596	2022(1), 2019(1), 2005(2), 1999(1)

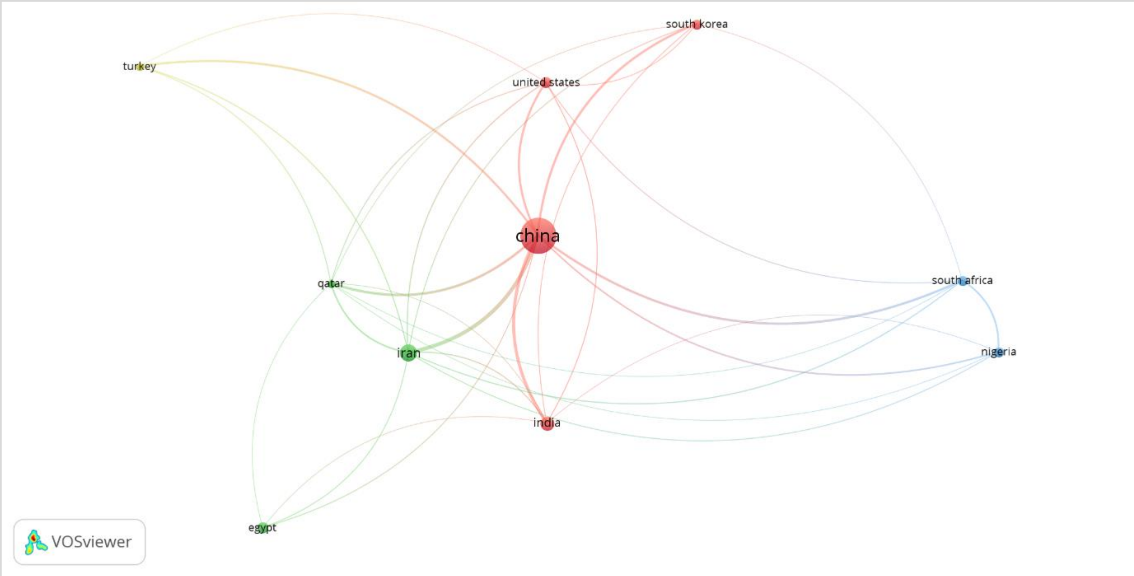

Figure 9. Network Visualization of Citations Among Countries

4. Conclusion

A total of 96 articles were selected for analysis, spanning from the first relevant publication in 1999 to the year 2022. These articles were thoroughly examined in various dimensions, including publication trends across different years, journals and countries, as well as citation and co-citation analyses among authors and journals. The primary objective of this bibliometric study was to analyze the role of PAMAM in sequestering heavy metals using VOSviewer application's mapping capabilities to highlight the trends.

The systematic analysis conducted in this study underscores the significance of PAMAM derivatives as effective adsorbents for removing heavy metals from various systems. This is exemplified by the substantial number of published articles and the citations they have received. It is evident that this area of research has gained substantial interest in recent years, with over 50% of the publications falling within the 2019-2022 timeframe. The most highly cited article in this field was one of the pioneering works associated with the utilization of PAMAM as a chelating agent for heavy metals, authored by Diallo et al. in 2005. This underscores the foundational importance of this research and its enduring impact on the field of heavy metal sequestration.

In conclusion, this bibliometric analysis offers valuable insights into the present landscape of research pertaining to the removal of heavy metals using PAMAM dendrimers as adsorbents. It underscores the importance of further investigations to address gaps in understanding of the diverse applications of these dendrimers in heavy metal removal. This includes exploring their effectiveness in removing various other types of heavy metals, synthesizing novel PAMAM derivatives, and assessing their efficiency in heavy metal sequestration, along with focusing on easy removal methods for these adsorbents. Additionally, fostering collaboration among researchers from different countries is imperative for comprehensive exploration of the potential applications of PAMAM dendrimers in this field. Such international cooperation can facilitate the exchange of knowledge and ideas, ultimately advancing understanding and capabilities in addressing the crucial issue of heavy metal pollution.

5. Acknowledgement

I would like to express my sincere gratitude to my family for support and encouragement throughout the writing process.

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