Analysis of Nanomaterials used in Environmental Remediation Technologies for the Removal of Metal Ions from Aqueous Media

Análisis de Nanomateriales empleados en tecnologías de Remediación Ambiental para la eliminación de iones metálicos en medios acuosos.

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ABSTRACT

This article presents an analysis of research in the field of nanomaterials applied to environmental remediation processes of metal ions in aqueous media; Through a bibliometric study, trends in the area and development in recent years could be identified. Aspects were analyzed such as articles with the highest number of citations, countries with the highest production, representative institutions in the area, authors, and correlation of keywords. A correlational-descriptive methodology has been used, reviewing publications from 1997 to 2022 in the Scopus database. The trends identified showed a steady growth in research and an increase in collaborative networks between institutions and researchers. In the last 10 years (2012 - 2022), the growth curve has reached a growth rate of 24.75%. Countries like China, India and the United States represent 75% of the total publications. The most representative keywords were bioremediation, heavy metals, and metal removal with more than 600 connections.

Keywords: Bioremediation; Nanomaterials; Metal ions; Environmental remediation; Aqueous media; Bibliometrics.

RESUMEN

Este artículo presenta un análisis de las investigaciones en el campo de los nanomateriales aplicados a procesos de remediación ambiental de iones metálicos en medios acuosos; mediante un estudio bibliométrico, se pudieron identificar tendencias en el área y desarrollo en los últimos años. Se analizaron aspectos como, artículos con mayor número de citaciones, países de mayor producción, instituciones representativas en el área, autores y correlación de palabras clave. Se utilizó una metodología correlacional-descriptiva, revisando publicaciones desde 1997 hasta 2022 en la base de datos Scopus. Las tendencias identificadas mostraron un crecimiento constante de la investigación y un aumento de las redes de colaboración entre instituciones e investigadores. En los últimos 10 años (2012 - 2022), la curva de crecimiento ha alcanzado una tasa de crecimiento del 24,75%. Países como China, India y Estados Unidos representan el 75% del total de publicaciones. Las palabras clave más representativas fueron biorremediación, metales pesados y remoción de metales con más de 600 conexiones.

Palabras Clave: Bioremediación; Nanomateriales; Iones metálicos; Remediación ambiental; Medio acuoso; Bibliometría.

1. INTRODUCTION

In recent decades, global warming has been one of the most critical environmental problems of humanity, but no less important, in recent years society has confronted one of the greatest damages caused by mankind to the planet and life, as is the case of pollution. Among the consequences of this phenomenon, we can find the affectation of water by contamination, which is mostly reflected in the seas, rivers, and other water sources [1].

Wastewater is the result of domestic, industrial, livestock, and agricultural activities, among others, in which water is used for production, treatment, or conversion, including waste liquids, process water, and drainage water [2]. Wastewater contains toxic substances that are harmful to the health of aquatic and terrestrial ecosystems [3]. According to studies conducted by the National Center for Scientific Research in Cuba and the World Bank, approximately 1.8 billion people use water that is contaminated with various microbes and pathogens, exposing them to the risk of waterborne diseases such as typhoid, cholera, dysentery, polio, and others [3].

Wastewater can contain high concentrations of metal ions as well as non-biodegradable materials and organic contaminants. These contaminants have become a major challenge for sustainable industrial wastewater treatment. Elevated levels of metal ions are highly hazardous. Although they occur naturally in the earth's crust as minerals, salts, or other compounds, they cannot be degraded or destroyed naturally or biologically because they do not have specific metabolic functions for living organisms. High concentrations of metals can cause various diseases or pathologies and even death [4].

However, studies and research have been conducted to mitigate the effects of metal ion contamination in water. The use of natural components to synthesize nanomaterials and design environmentally friendly synthetic processes has been widely explored [5]. As global warming and climate change become more pressing concerns, nanotechnology has become an essential aspect of many scientific and engineering fields that address these issues [6].

The use of nanotechnology has grown over the past few decades, and the results can be seen in many emerging industries [1]. One of the areas of success is the synthesis of metallic nanoparticles, useful in electronic and medical applications, using plant extracts as reducing agents [5], [7]. Industrial wastewater treatment, drinking water purification and biomedical engineering are areas where functionalized nanomaterials have found important applications today, with a focus on environmental remediation and drinking water treatment and industrial waste management [6].

According to published studies, green and combined nanotechnology, may be the key to building an environmentally sustainable society in the 21st century [5]. In these modern times, it is necessary to focus on making process technology development environmentally friendly and economically viable [8].

Nanomaterials are environmentally friendly, highly selective, recyclable, and convenient to dispose of, making them an excellent adsorbent for water treatment. In addition, ecologically synthesized nanoparticles are increasingly being investigated, which would further reduce the negative environmental impact and make the application of nanoparticles more cost-effective [3]. Nanostructured materials, such as nanocomposites, functionalized nanomaterials, metal-organic materials, nano catalysts, carbonaceous materials, nano zeolites, nano silica, nano lubricants, and nano coatings, etc., have enormous potential for greenhouse gas sequestration and reduction, biofuel production, wastewater treatment and environmental remediation with a sustainable approach [9].

Despite limited information available, interest in environmentally friendly nanomaterials is growing, as evidenced by the increasing number of research studies in this field and the recent initiative by the government and private sector to commercialize them [10], [11], [5]. The mechanical properties of nanoparticles make them a promising option for wastewater treatment [3]. In addition, it has opened new possibilities in the creation of sustainable tools with great potential to replace conventional tools in their respective fields [9]. The exceptional properties of nanomaterials, such as their unique structure and chemical resistance, as well as their easy availability and precise synthesis protocols, have attracted considerable attention from environmental science researchers in the field of bioremediation [12].

Environmental remediation is a set of techniques or activities aimed at eliminating polluting substances that have been discharged into a physical medium such as water, soil, or air, whether naturally preserved or modified by humans [13]. In addition, environmental remediation aims to reduce pollutants to a level that is safe for health and the environment or to prevent their dispersal in the environment without altering them, in accordance with the provisions of the current legal framework [14]. The solution to a contamination problem is so complex, and the cost of removing contaminants so high, that it is often difficult to carry out remediation. In such cases, the alternative is to take measures to prevent human exposure to the contaminants [15]. The remediation measures and treats technologies to be used depending on the risks identified and the future uses to be assigned to the areas to elect remediated. The term treatment technology refers to any unit operation or series of operations that, through chemical, physical, or biological action, alters the composition of a hazardous substance in such a way as to reduce the toxicity and/or mobility of a contaminant [16].

As a mitigation alternative, technologies have been developed in recent decades to contribute to the oxidation, degradation, transformation, and complete mineralization of these pollutants with less impact on the environment [17].

Bibliometrics is the mathematical and statistical treatment of published scientific information [18]. This bibliometric approach to the analysis of variables has grown over the years, thanks to the accessibility and availability of data analysis software. This has given scientific scope to a large volume of data and has led to high-impact research [19]. One of the most useful methods of bibliometric analysis is citation analysis, which examines a network of published articles to assess the impact and influence of each article in its field [20].

This article analyzes the different types of nanomaterials used in the treatment of metal ions in environmental remediation processes, using a bibliometric approach. In this case, the current status of nanomaterials used in this treatment was reviewed, along with the analysis of the associated variables, examining relevant bibliometric indicators that reflect the current situation of these nanomaterials, to facilitate decision-making in research and innovation in this field.

2. METHODOLOGY

The study of nanomaterials used in environmental remediation processes was developed in four phases. First, in order to know the current status of nanomaterials, a preliminary search for information was carried out using different databases such as PubMed, IEEE Xplore, Science Direct, Scopus, Web of Science, and Google Scholar. Articles related to the study of nanomaterials applied in environmental remediation technologies were reviewed and the variables present in these articles related to the removal of metal ions in aqueous media were analyzed.

The second phase focused on keyword search and analysis. The search terms included all documentation with keywords such as: "environmental remediation", "bioremediation", "heavy metals", "nanoparticles OR nanostructures OR nanomaterials OR, nano*", with searches in sections such as title, abstract, and keywords. The search period started in 1996, when the first documents were found, and lasted until 2022 when 1173 results were obtained. The database used was SCOPUS.

Finally, the impact of bibliometric indicators in the study of nanomaterials used in environmental remediation processes was determined through the evolution of scientific production in the period 1997-2022. The impact of the research was analyzed by country, outstanding authors in the field, analysis of the institutions with the highest production, and the study correlation of keywords obtained from scientific papers. Indicators such as the Impact Factor and the h-index were used; bibliometric indicators for the analysis of journals were also included, such as the SCImago Journal Rank (SJR), which measures the impact, influence, or prestige of a journal based on the average number of citations received by each publication; and CiteScore Metrics, which defines the average number of citations received by the articles of a publication over a given period (3 years from its publication).

In the analysis of articles, it is important to highlight articles with more than 50 citations, called *key articles*. The work of institutions is reflected by the degree of collaboration between authors, institutions, and countries, based on the following equation:

$$C_{Ai} = \frac{\sum_{j=1}^{N} \propto j}{N}; C_{Ii} = \frac{\sum_{j=1}^{N} \beta j}{N}; C_{Ci} = \frac{\sum_{j=1}^{N} \gamma j}{N} \qquad (1)$$

where $\propto j$, βj, and γj are the number of authors, institutions, and countries for each article, respectively. N is the total number of publications, and C_{Ai}, C_{Ii}, and C_{Ci} are the degrees of collaboration in a year i of authors, institutions, and countries, respectively. On the other hand, the author productivity index (PI) was evaluated using equation 2, where N is the number of published articles. If the index is zero (0), it is considered low productivity, a value of 0-1, medium productivity, and a value greater than 1 (greater than 10 papers), high productivity.

$$PI = log\, N \quad (2)$$

Each analysis chapter not only shows the corresponding figures and data of the study but also discusses why these trends are generated and the incidence that they may have on the study of nanomaterials for remediation. Finally, a discussion of recent nanomaterials and technologies used in the treatment of metal ions has been included to help in the decision-making process in terms of research and innovation.

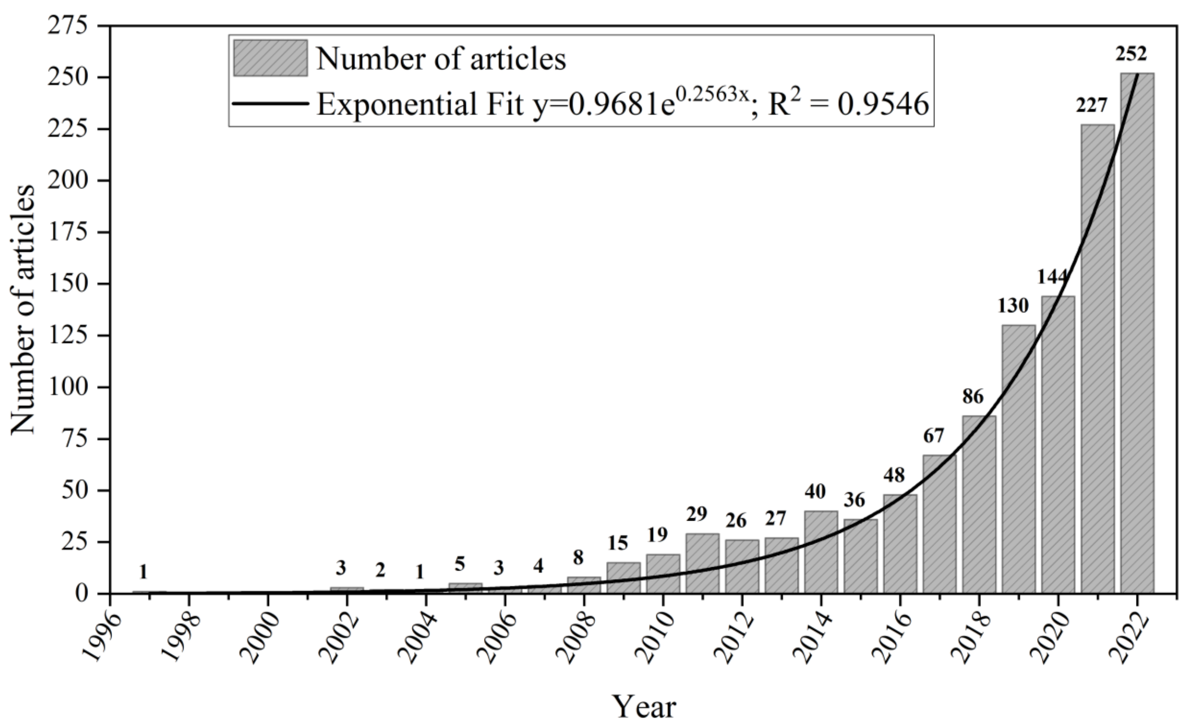
3. RESULTS AND DISCUSSION

3.1 Trends and Publication Analysis

Currently, research in nanotechnology and nanomaterials is driven by scientific progress and innovation. The development of studies on the treatment of metal ions with nanomaterials in environmental remediation processes in the last 25 years is mainly due to 3 relevant factors: firstly, the environmental awareness that society has adopted in recent years; secondly, the growing recognition of environmental problems and, finally, the need for sustainable solutions, which has driven research and development in this field [21]. Next, technological advances have allowed the creation of nanomaterials with unique properties that are particularly useful for environmental remediation, offering a sustainable alternative to remove persistent pollutants such as metal ions [22]. Similarly, the effectiveness that nanomaterials have demonstrated in removing metal ions from various sources, outperforming many traditional methods in terms of efficiency and recoverability, has contributed significantly to the continued development and growth of research in this area [23], [24].

Figure 1 shows the progress of publications in the study of nanomaterials for the treatment of metal ions in environmental remediation processes over the last 25 years. Although research was almost zero around the 1990s, it is observed that the number of publications is higher than ten since 2009, showing an exponential behavior in the last 13 years. The revival of nuclear energy and the need to reduce CO_2 emissions increased research in the first decade of the 21st century [25]. Advances in nuclear technology brought with them an increase in the production of radioactive waste, which prompted the development of alternatives for its treatment [26], [27].

***Figure 1**. Annual growth of publications in the area of nanomaterials for environmental remediation, in the period 1997 – 2022*



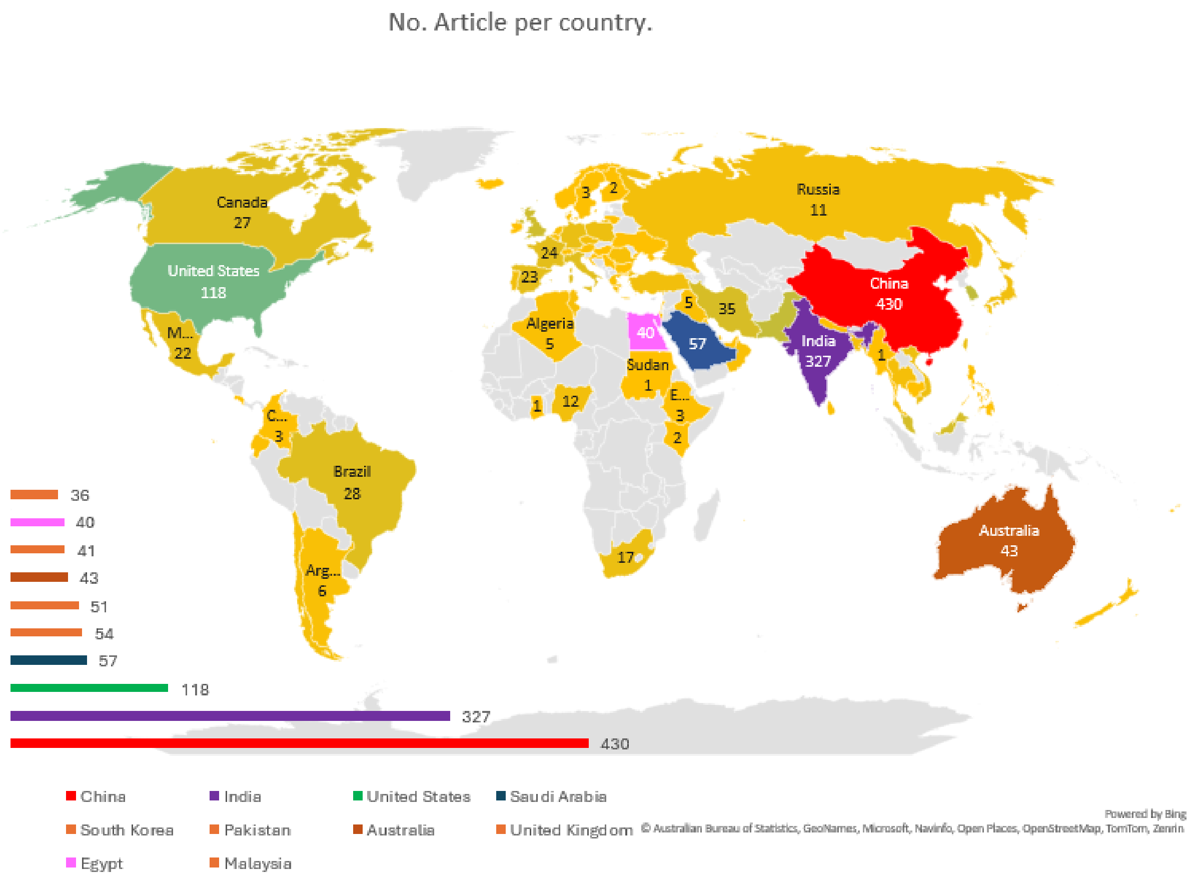
In the last 10 years (2012 - 2022), the growth curve has reached a growth rate of 24.75%, mainly due to the impending need for environmental remediation processes. Pollution by metallic ions has become one of the major environmental problems, posing a serious threat to humans and ecosystems. These metallic ions represent a priority class of pollutants due to their persistence in the environment and their potential to bioaccumulate in biological systems [23].

One of the benefits of nanomaterials is in water treatment. Due to their high specific surface area and adsorption capacity, nanomaterials can effectively remove undesirable metallic ions present in this medium [24]. In terms of research and development, numerous studies and experiments have been conducted in laboratories and pilot plants in the last decade (2012-2022). Among these investigations, green synthesis of metallic nanoparticles has gained popularity due to its efficacy in antimicrobial and anticancer treatment, reduction of metal toxicity, dye degradation, and wastewater treatment [28].

3.2 Leading Countries in the Area

Figure 2 depicts the production of scientific publications by country in the field of nanomaterials used for environmental remediation. Among the countries leading research in nanomaterials for environmental remediation are China, India, and the United States. With a representation of approximately 75% of the total publications in the last 25 years, these three countries contribute studies, publications, and patents at a global level.

Figure 2. *Scientific publications by country in the field of nanomaterials for environmental remediation.*



China has significantly invested in scientific and technological research in recent decades as part of its strategic pursuit of global positioning [29]. Consequently, nanotechnology became a key focus area in China's medium and long-term scientific programs between 2006 and 2020. As evidence of this, in 2012, the country launched a Strategic Pioneer Program on Nanotechnology, with a budget of one billion yuan

(152 million dollars) over five years, led by the Chinese Academy of Sciences (CAS) in Beijing [30]. As a result of this long-term investment, China has become a major player in nanotechnology, ranking first globally in terms of the number of scientific articles and patents, as shown in Table 1.

However, environmental and health needs have also played a fundamental role in scientific advancement. As one of the most populous countries undergoing rapid industrialization, China faces significant challenges in terms of water and soil pollution [29]. This has led to increased research into effective methods of environmental remediation. Additionally, nanomaterials are finding applications in areas such as drug delivery and clinical diagnosis [31], [32]. In addition, China has many research institutions and universities focused on nanotechnology and environmental remediation. For example, Guilin University of Technology and the Key Laboratory of Guangxi for Environmental Pollution Control are working on the application of nanomaterials to remove metal ions [33].

***Table 1**. Top 10 leading countries in the production of scientific publications by country in the area of nanomaterials for environmental remediation.*

		Total		**Articles Key**		
No.	**Countries**	**TA**	**TC**	**AC**	**Citations-AC**	**h-index**
1	China	430	24810	124	19865	79
2	India	327	11398	59	8294	55
3	United States	118	8816	41	7582	44
4	Saudi Arabia	57	2919	12	2230	23
5	South Korea	54	4715	21	4171	28
6	Pakistan	51	2518	10	1980	20
7	Australia	43	2870	16	2230	27
8	United Kingdom	41	3534	13	2985	22
9	Egypt	40	619	2	132	14
10	Malaysia	36	2179	14	1770	22

TA: Total articles; TC: Total citations; AC: Article key.

India ranks second in the world for nanomaterials used to treat metal ions in environmental remediation processes. The country is home to numerous research institutions and universities focused on nanotechnology and environmental remediation. These fields offer solutions to India's growing needs for clean water, food, and low-cost rapid diagnostics. In India, as in many parts of the world, nanomaterials can be used for a wide range of purposes, from water purification to cancer treatment [34], [35].

It is also known that one of the major problems in

India is the pollution of its rivers. The Ganges River is contaminated with five heavy metals: chromium, copper, nickel, lead, and iron [36], [37]. In addition, a study conducted by the Central Water Commission of India found that 42 rivers in India have at least two toxic heavy metals above the permissible limit [38], [39].

Efforts to promote nanotechnology research in India began in the early 2000s. In 2007, the government launched a 5-year program called the "Nano Mission" with broader objectives and increased funding of $250 million. These efforts have yielded good results. India has published more than 23,000 articles in nanoscience in the last 5 years, of which 327 are related to the treatment of metallic ions, as shown in Table 1 [40].

Finally, discoveries through nanoscience have brought socio-economic benefits that contribute significantly to the Sustainable Development Goals (SDGs) in India. The Indian government has placed a high value on the role of science and technology in nation-building. The historical image of India as a country that can achieve modernity and development through engagement with modern science and technology, has supported increased funding for nanotechnology research [41], [42]. The United States is the third leading country in the world, with just over 10% of the total publications on nanomaterials for the treatment of metallic ions in environmental remediation processes. Despite not holding the top position, the United States remains the world leader in terms of the volume of government investment in nanotechnology [43]. As a result, it has numerous research institutions and universities focused on the field, as well as environmental remediation [44], a example to this is the National Nanotechnology Initiative (NNI). The NNI is a government initiative in the United States that provides a long-term vision of the importance of nanoscience, engineering, and technology. This investment is expanding the frontiers of nanoscience, supporting nanotechnology research infrastructure, and advancing education and workforce development efforts. The United States, ranked third among the leading countries, is researching nanomaterials, as are China and India. According to the U.S. Environmental Protection Agency (EPA), scientific methods are being developed to study and evaluate the unique properties of nanomaterials, how they behave during manufacturing, product use, and end-of-life disposal. Significant advances have been made in the synthesis of nanomaterials, which can exhibit exceptional magnetic, electrical, optical, mechanical, and catalytic properties that differ significantly from their bulk counterparts. These properties can be tailored as desired through precise control of size, shape, synthesis conditions, and appropriate functionalization [44].

Despite this progress, there are still limitations and gaps in the research on nanomaterials for the treatment of metallic ions in environmental remediation processes that could affect the position of the United States. For example, it is critical to map the environmental fate of nanomaterials due to the uncertainty surrounding their unique properties and potential uses and effects [24]. Another example is the characterization of nanomaterials, which remains challenging due to their small size and the variety of shapes and structures they can assume [44]. In addition, there is considerable uncertainty in the United States about how nanomaterials behave in the environment. As particle size decreases, as in the case of nanoparticles, the likelihood of misidentification increases, leading to ongoing research in this area [45].

3.3 Leading Journals in the Area

During the last decade, there has been a noticeable interest and need to find sustainable ways to treat metallic ions that are environmentally friendly. This need has led to an increase in publications in the field and, consequently, in the leading journals. Table 2 presents the top 10 leading journals worldwide in the research area of nanomaterials for environmental remediation processes.

Table 2*. Leading journals in the production of publications on nanomaterials in environmental remediation processes.*

	Total		**Relative**					
Journals	**TA**	**TC**	**% TA**	**% TC**	**h-index**	**h-index***	**SJR**	**Publishing Country**
Journal of Hazardous Materials	84	7402	7.16	12.89	44	329	2.57	Netherlands
Chemosphere	72	2698	6.14	4.70	30	288	1.73	United Kingdom

Science of the Total Environment	54	3328	4.60	5.79	29	317	1.95	Netherlands
Journal of Environmental Management	26	1740	2.22	3.03	18	218	1.68	United States
Environmental Pollution	20	1821	1.71	3.17	16	275	2.11	United Kingdom
Environmental Research	16	857	1.36	1.49	13	164	1.64	
Environmental Science and Technology	16	1821	1.36	3.17	14	86	2.91	United States
Ecotoxicology and Environmental Safety	15	649	1.28	1.13	12	161	1.35	
Environmental Science and Pollution Research	15	1006	1.28	1.75	12	154	0.94	Germany
Water Air & Soil Pollution	15	370	1.28	0.64	9	127	0.55	Netherlands

TA: Total articles; TC: Total citation; h-index: topic index; h-index: journal index*

With over 7400 citations, the Journal of Hazardous Materials ranks first among the leading journals, representing approximately 13% of the total citations in the research area. In addition, this journal has the highest number of publications in the Netherlands, as shown in Table 2. This is largely due to its prestige and longevity. According to the ScienceDirect (Elsevier) website, this journal, which was founded in 1975, has published more than 4170 articles and has an impact factor of 13.6 as of mid-October 2023, which confirms its citation frequency. In addition, it has a wide reach and impact on the research of hazardous substances and their environmental consequences. Its high value in SJR (Scimago Journal Rank) demonstrates the importance and relative quality of the journal. Similarly, the journals Chemosphere and Science of the Total Environment, known for their environmental research, are ranked second and third, respectively. Although they have slightly lower SJR scores than the Journal of Hazardous Materials, together they represent more than 10% of the total citations in the research area.

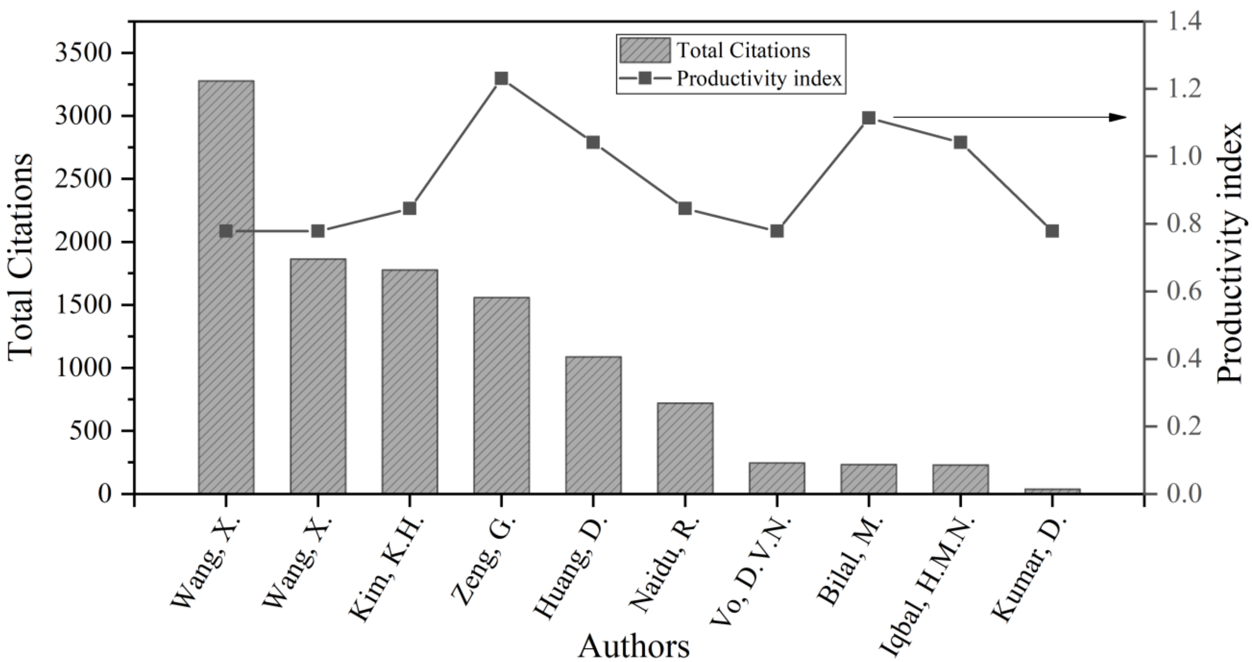
On the other hand, one of the factors that enables robust and well-funded research for the advancement of high-quality publication production is the country of origin [44]. The United States mentioned as the third leading country in terms of publications, ranks first in terms of leading journals. Its solid research infrastructure is due to the country's financial investment and frequent international collaborations, which enable the production of high-quality research and prestigious journals [22], [46]. In second place is the Netherlands, which invests significantly in science and technology, facilitating access to advanced equipment, recruiting leading researchers in the field, and funding important research projects, which is reflected in the high number of leading journals [47].

As for the United Kingdom and Germany, the other two countries with significant participation in leading journals, they stand out for their research in nanomaterials for environmental remediation because of their focus on innovation and sustainability. Germany's economic strength is based on the high performance of its industry and its capacity for innovation, as noted by the well-known German website DW. The United Kingdom, on the other hand, is investing into innovative technologies that are transforming the world of clean energy. The country is investing in sustainable and circular solutions to reduce emissions from buildings and provide reliable renewable energy services, according to the European Commission and the global newspaper BBC [48].

3.4 Authors

One of the fundamental factors in the development of research on nanomaterials used in environmental remediation processes is the authors, as their publications contribute to the advancement of knowledge in the field of study. In addition, findings related to work with nanomaterials confirm, refute, or extend existing theories. Figure 3 shows the top 10 most prominent authors in the field.

***Figure 3**. Top 10 most cited authors on the development of nanomaterials in environmental remediation processes.*



The Productivity Index (PI) allows us to evaluate not only an author's productivity in terms of the quantity of published work but also their impact on the development of research lines. Forty percent of the prominent authors in this research area are affiliated with institutions in China, such as Hunan University and North China Electric Power University. These institutions have been recognized in the field of nanomaterials research for environmental remediation due to their significant contributions and advances in the field. At Hunan University, researchers have explored nanoremediation by analyzing the state of the art of various nanomaterials, such as metals, carbon, polymers, and silica, used for water, soil, and air remediation [49].

On the other hand, at North China Electric Power University, Professor Xiangke Wang, one of the most prominent authors in China, is leading a research team in the development of nanomaterials and technologies that can remove radionuclides from the environment. In addition, they are exploring advanced nanomaterials such as porous organic polymers (POPs), metal-organic frameworks (MOFs), covalent organic frameworks (COFs), and porous aromatic frameworks (PAFs) for this purpose. These research efforts have resulted in several publications, including: *"Advanced photocatalysts for uranium extraction: Elaborate design and future perspectives", "Photochemically Triggered Self-Extraction of Uranium from Aqueous Solution Under Ambient Conditions", "Methyl Position Affect the Fluorescence Performance of HBT Derivatives for the Detection of Hypochlorite Under Alkaline Condition", y "A strategically designed porous magnetic N-doped Fe/Fe 3 C@C matrix and its highly efficient uranium (vi) remediation"* [50], [51], [52]. Table 3 shows the citation indices of prominent authors in the field of nanomaterials for environmental remediation processes

***Table 3**. h-index citations of authors highlighted for their publications in the area of nanomaterials in environmental remediation.*

Authors	Affiliation	h-index author
Zeng, G.	Hunan University	196
Bilal, M.	King Abdulaziz University	75
Huang, D.	Hunan University	112
Iqbal, H.M.N.	Tecnológico de Monterrey	74
Kim, K.H.	Hanyang University	108
Naidu, R.	The University of Newcastle	107
Kumar, D.	Central University of Gujarat	33
Vo, D.V.N.	Dại học Nguyen Tat Thanh	57
Wang, X.	North China Electric Power University	149
Wang, X.	North China Electric Power University (Baoding)	82

Citation metrics, such as the h-index, allow for the measurement of both the productivity and impact of authors' contributions. According to Table 3, the authors with the most influence and relevance in the scientific community in this research area are Zeng, G; Wang, X; Huang, D; and Naidu R.

3.5 Keyword Correlation Analysis

Figure 4 shows an analysis of the research frontiers using keyword frequency and centrality analysis. The resulting keyword co-occurrence map was a merged network with 93859 links across 5 clusters: Cluster 1, red color; Cluster 2, green color; Cluster 3, blue color; Cluster 4, yellow color; and Cluster 5, purple color (colors indicate groups of keywords that are related to each other). The minimum number of repeated keywords is 10, and the total number of keywords is 621. Each node represents one keyword, and the proximity of the nodes indicates the co-occurrence of these keywords.

The most relevant keywords are bioremediation, heavy metals, and metal removal with more than 600 connections. In addition, adsorption, pH, and nanoparticles, among others, are noteworthy. These keywords indicate the main lines of research in the field of nanomaterials for environmental remediation processes.

The analysis of word co-occurrence and descriptors resulted in different groupings, reflecting different approaches, and changing trends in research. Cluster 1 (red) shows relationships in publications related to living organisms, animals, algae, and bacteria, and the processes they perform, such as their functions in the environment, whether as antioxidants or potential bioremediation systems. Within Cluster 2 (green), absorbent, catalytic, and chemical functions in general are found. Cluster 3 (blue) highlights different areas of work for environmental remediation, such as biodegradation, biocompatibility, biomaterials, wastewater processes, as well as regulation, application, and environmental management. Cluster 4 (yellow) relates to research on contaminant entities such as iron, aluminum, chemical compositions, oxide ions, and sediments. Finally, Cluster 5 (purple) focuses on isolation and purification.

***Figure 4**. Co-occurrence map of keywords in publications on nanomaterials used for environmental remediation processes.*

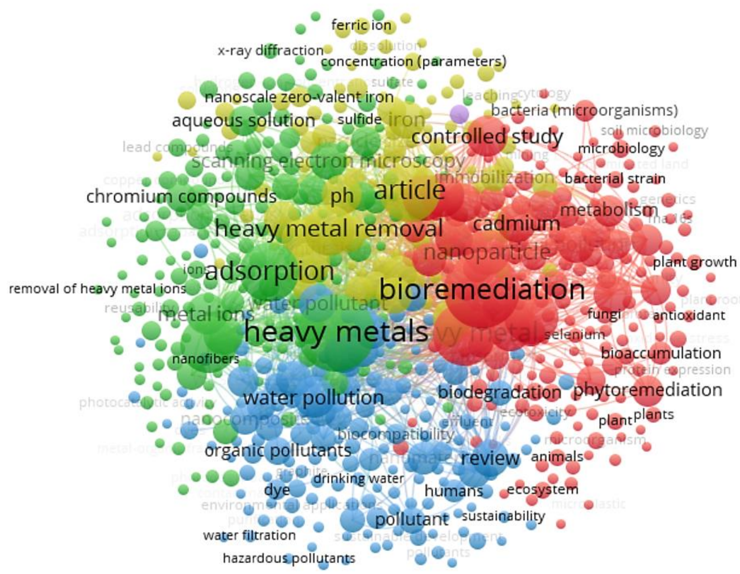
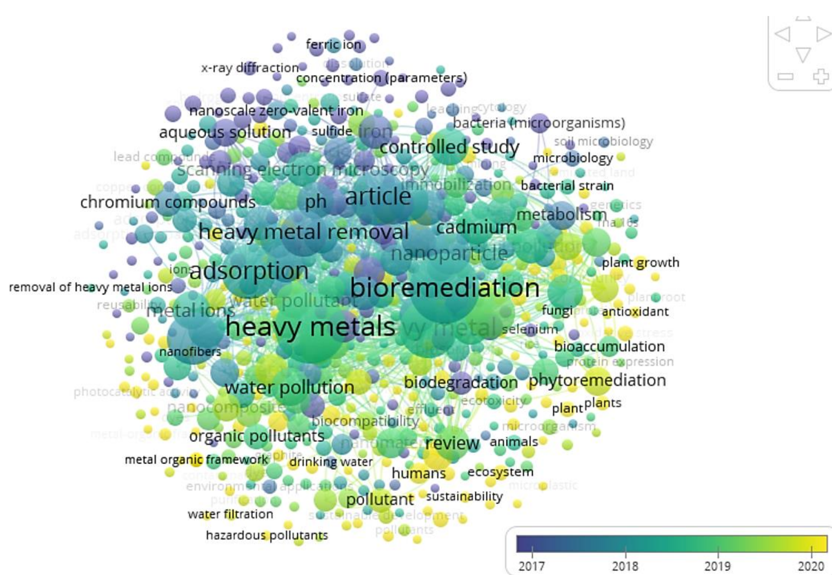


Figure 5 shows the co-occurrence of keywords between 2017 and 2020. Words such as bioremediation and heavy metals have been developed since 2018, while the more recent research lines, focus on thermal stability, photosynthesis, methanogenesis, nanochains, industrialization, retention times, water filtration, antioxidants, sustainability, among others. As shown by some studies carried out in Ecuador, gold mining causes harmful environmental effects, such as the release of metallic ions and inorganic compounds, which are discharged into aquatic systems or onto land surfaces, interacting negatively with various organisms. Faced with this problem, efficient ways to remove mercury, phosphates, sulfates, and nitrates from mining effluents have been evaluated through a phytoremediation process using the microalgae Pleurococcus sp., Chlorella sp. and Scenedesmus sp., strains isolated from the Andes and the Ecuadorian Amazon. [53].

***Figure 5**. Co-occurrence map of keywords in publications about nanomaterials under environmental remediation processes between 2017 and 2020.*



3.6 Top 10 Articles with the Highest Citation

Table 4 presents the top 10 most cited articles in the field of nanomaterials for environmental remediation. This highlights research trends in the area.

Table 4. *Top 10 most cited articles in the area of nanomaterials under environmental remediation processes*

Authors	Title	Year	Source Title	Cited by
Zhao G.; Li J.; Ren X.; Chen C.; Wang X.	Few-layered graphene oxide nanosheets as superior sorbents for heavy metal ion pollution management	2011	Environmental Science and Technology	1527
Fu F.; Dionysiou D.D.; Liu H.	The use of zero-valent iron for groundwater remediation and wastewater treatment: A review	2014	Journal of Hazardous Materials	1236
Singh J.; Dutta T.; Kim K.-H.; Rawat M.; Samddar P.; Kumar P.	'Green' synthesis of metals and their oxide nanoparticles: Applications for environmental remediation	2018	Journal of Nanobiotechnology	1122
Khin M.M.; Nair A.S.; Babu V.J.; Murugan R.; Ramakrishna S.	A review on nanomaterials for environmental remediation	2012	Energy and Environmental Science	1077
Liu J.-F.; Zhao Z.-S.; Jiang G.-B.	Coating Fe3O4 magnetic nanoparticles with humic acid for high efficient removal of heavy metals in water	2008	Environmental Science and Technology	1004
Zou Y.; Wang X.; Khan A.; Wang P.; Liu Y.; Alsaedi A.; Hayat T.; Wang X.	Environmental Remediation and Application of Nanoscale Zero-Valen t Iron and Its Composites for the Removal of Heavy Metal Ions: A Review	2016	Environmental Science and Technology	992
Crane R.A.; Scott T.B.	Nanoscale zero-valent iron: Future prospects for an emerging water treatment technology	2012	Journal of Hazardous Materials	945
Mercier L.; Pinnavaia T.J.	Access in mesoporous materials: Advantages of a uniform pore structure in the design of a heavy metal ion adsorbent for environmental remediation	1997	Advanced Materials	741
Santos D.K.F.; Rufino R.D.; Luna J.M.; Santos V.A.; Sarubbo L.A.	Biosurfactants: Multifunctional biomolecules of the 21st century	2016	International Journal of Molecular Sciences	620

Okesola B.O.; Smith D.K.	Applying low-molecular weight supramolecular gelators in an environmental setting-self-assembled gels as smart materials for pollutant removal	2016	Chemical Society Reviews	592

The analysis of nanomaterials for environmental remediation revealed a total of 1173 documents cited a total of 60,960 times, 16.16% of these citations refer to the top 10 most cited articles. Among these articles are recent advances in the fabrication of new nanoscale materials and processes for the treatment of drinking water and industrial wastewater contaminated with toxic metal ions, radionuclides, organic and inorganic solutes, bacteria and viruses, and air treatment [54]. Some of the investigated topics include graphene oxide nanosheets, which may be suitable materials for the remediation of heavy metal ion contamination if synthesized on a large scale. In addition, recent advances in the use of zero-valent iron (ZVI) for the treatment of toxic contaminants in groundwater and wastewater are highlighted; it has been demonstrated that widely available ZVI materials exhibit appreciable removal efficiencies for various types of contaminants [55], [56], [57].

Similarly, the excellent capability of green synthesis is demonstrated, which is considered an important tool to reduce the destructive effects associated with traditional methods of nanoparticle synthesis commonly used in laboratories and industry [58]. Another highly mentioned topic is the production of biosurfactants, which is considered one of the key technologies for the development of the 21st century. In addition to having a strong positive impact on major global issues, the production of biosurfactants is of great importance for the implementation of sustainable industrial processes, such as the use of renewable resources and green products [59].

3.7 Recent applications of the use of nanomaterials in environmental remediation processes

As a relatively new field, nanotechnology or nanomaterials have long-term effects that are not fully understood. In recent decades, there has been a growing ecological awareness of the effects that different materials can have on ecosystems, as evidenced by the regulations that have emerged regarding their use [60]. According to the EUON (European Union Observatory for Nanomaterials), different nanoforms of a chemical substance can vary their behavior in the environment depending on the nano-specific properties of the material. Therefore, it is recommended to consider the physicochemical properties of nanomaterials when deciding on additional parameters.

Currently, nanomaterials are the subject of constant research due to their various applications in different sectors, from semiconductors to energy, textiles, and construction [61]. In the construction sector, there are technological advances in the application of nanomaterials that improve mechanical properties when used in concrete, soils, and pavements, among others [62]. Among the best-known are colloidal silica, bentonite, and laponite, which have a satisfactory effect in mitigating liquefaction for sandy foundations, and carbon nanotubes, which can increase compressive strength without confinement [63]. The application of these nanomaterials reduces the need for long-term maintenance and repair, which in turn reduces the consumption of natural resources and the generation of waste.

On the other hand, the recent developments in nanotechnology have also brought new opportunities to agriculture; pesticides and fertilizers are two of the many products that have shown great potential when manufactured at the nanometer level, demonstrating high efficiency in the targeted and controlled release of agrochemicals, resulting in greater biological efficacy and overall increased crop yield and productivity [64]. The controlled release of these fertilizers allows for more efficient nutrient uptake by plants and reduces nutrient leaching into groundwater. Therefore, it helps prevent soil and water pollution from excess nutrients.

Similarly, the food industry has embraced nanotechnology as a new way to improve productivity in terms of safety, the use of sustainable packaging materials, and the implementation of flexible and standardized technology, among others. Nanomaterials provide opportunities for large companies to restructure their processing, packaging, and manufacturing schemes [65]. For example, bio-packaging can decompose faster in the environment, reducing the accumulation of plastic waste in oceans and landfills.

4. CONCLUSIONS

We can conclude that the effectiveness of nanomaterials in various environmental remediation processes has been demonstrated, especially in the removal of metal ions. New areas of research have been identified, such as green synthesis and the use of zero-valent iron, to reduce environmental impact. Furthermore, current growth trends in nanomaterials and environmental remediation research show that, although significant progress has been made, there is still a need to reduce environmental damage and to clean up and remediate contaminated sites.

Similarly, the importance of international collaborations and the global contribution to the research field is recognized, as reflected in the growth of publications by country, authors, and journals. However, new challenges are emerging, such as regulation and scalability for the implementation of these techniques on an industrial scale.

The growth rate in the production of scientific articles reached 24.75% in the last 10 years, mainly due to the need for environmental remediation processes. The three main journals are Environmental Science and Technology, Journal of Hazardous Materials and Environmental Pollution. These journals are noted for their continued research in the design and analysis of more efficient, sustainable, and safe nanomaterials. In addition, featured authors include Wang, X, Zeng, G, and Huang, D, who emphasize the importance of assessing long-term environmental impacts.

The countries with the highest scientific output in the research area were China, India, and the United States, accounting for 75% of the total publications. Overall, this study provides a solid foundation and guidance for the development of innovative technologies in the field of nanomaterial-based environmental remediation.

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DECLARATION OF INTEREST

The author(s) declare(s) that there is no conflict of interest

References

[1] E. Dabirian *et al.*, “Nanoparticles application on fuel production from biological resources: A review,” *Fuel*, vol. 331, Jan. 2023, doi: 10.1016/j.fuel.2022.125682.

[2] J. Asitimbay and J. Loor, “‘Diseño de una planta de tratamiento de aguas residuales del centro de acopio de leche COPROCACB, parroquia Quimiag,’” Universidad Nacional de Chimnorazo, Riobamba, Ecuador, 2023.

[3] S. F. Ahmed *et al.*, “Nanomaterials as a sustainable choice for treating wastewater,” *Environ Res*, vol. 214, Nov. 2022, doi: 10.1016/j.envres.2022.113807.

[4] N. A. Pedraza, “Valoración Económica Ambiental por el Mejoramiento de la Calidad del Agua de la Quebrada,” 2022.

[5] Y. Lu and S. Ozcan, “Green nanomaterials: On track for a sustainable future,” *Nano Today*, vol. 10, no. 4, pp. 417–420, Aug. 2015, doi: 10.1016/j.nantod.2015.04.010.

[6] T. M. Tiza, G. Kpur, E. Ogunleye, S. Sharma, S. K. Singh, and D. M. Likassa, “The potency of functionalized nanomaterials for industrial applications,” *Mater Today Proc*, 2023, doi: 10.1016/j.matpr.2023.03.212.

[7] M. Cely-Bautista, G. Castellar-Ortega, J. Jaramillo-Colpas, and I. Romero, “Trends in the development of metallic and bimetallic nanoparticles: a patents landscape analysis.,” *Ingeniería y Competitividad*, vol. 25, no. 3, pp. 1–12, 2023.

[8] A. D. Goswami, D. H. Trivedi, N. L. Jadhav, and D. V. Pinjari, “Sustainable and green synthesis of carbon nanomaterials: A review,” *Journal of Environmental Chemical Engineering*, vol. 9, no. 5. Elsevier Ltd, Oct. 01, 2021. doi: 10.1016/j.jece.2021.106118.

[9] N. Chausali, J. Saxena, and R. Prasad, “Nanotechnology as a sustainable approach for combating the environmental effects of climate change,” vol. 12, no. February, 2023.

[10] N. H. Ly, D. Barceló, Y. Vasseghian, J. Choo, and S.-W. Joo, “Sustainable bioremediation technologies for algal toxins and their ecological significance,” *Environmental Pollution*, vol. 341, p. 122878, 2024, doi: https://doi.org/10.1016/j.envpol.2023.122878.

[11] S. H. Hussein, K. Qurbani, S. K. Ahmed, W. Tawfeeq, and M. Hassan, “Bioremediation of heavy metals in contaminated environments using Comamonas species: A narrative review,” *Bioresour Technol Rep*, vol. 25, p. 101711, 2024, doi: https://doi.org/10.1016/j.biteb.2023.101711.

[12] G. Chellasamy, R. Mary, T. Maharajan, A. Radha, and K. Yun, “Remediation of microplastics using bionanomaterials : A review,” vol. 208, no. September 2021, 2022.

[13] P. Lara, “‘Remediación ambiental en las políticas de reparación integral y los lineamientos del ministerio del ambiente en marco de los derechos de la naturaleza en la constitución del 2008,’” Quito, 2016.

[14] E. M. Angulo, G. O. Castellar, M. B. Mercedes Cely, L. S. Ibáñez, and L. M. Prasca, “Discoloration of wastewater from a paint industry by the microalgae Chlorella sp Decoloración de aguas residuales de una industria de pinturas por la microalga Chlorella sp,” *Rev.MVZ Córdoba*, vol. 22, no. 1, pp. 5706–5717, 2017.

[15] E. E. de J. Sedas and U. Ruiz Saucedo, “La remediación de sitios contaminados,”, SEMARNAT. Dec. 2012.

[16] E. Vidal and L. Regaldo, *Gestión Ambiental: Introducción a sus instrumentos y fundamentos*, UNL. Universidad Nacional del Litoral, 2022. [Online]. Available: www.unl.edu.ar/editorial

[17] J. M. Borja, S. F. Heredia, and M. A. Saez, “Los nanomateriales y sus Aplicaciones en la Remediación Ambiental,” *Polo del Conocimiento*, vol. 5, pp. 338–370, 2020.

[18] M. Gallegos, A. M. Pérez-Acosta, H. Klappenbach, W. L. López, and C. Bregman, “The Bibliometric Studies in the Field of Ibero-American Psychology: A Metabibliometric Review,” *Interdisciplinaria*, vol. 37, no. 2, pp. 95–115, 2020, doi: 10.16888/INTERD.2020.37.2.6.

[19] N. Donthu, G. Kumar Badhotiya, S. Kumar, G. Soni, and N. Pandey, “A retrospective overview of Journal of Enterprise Information Management using bibliometric analysis,” *Journal of Enterprise Information Management*, vol. 35, no. 2, pp. 504–529, 2022, doi: 10.1108/JEIM-09-2020-0375.

[20] H. M. Seriwala, M. S. Khan, W. Shuaib, and S. R. Shah, “Bibliometric analysis of the top 50 cited respiratory articles,” *Expert Rev Respir Med*, vol. 9, no. 6, pp. 817–824, 2015, doi: 10.1586/17476348.2015.1103649.

[21] E. A. Kumah, R. D. Fopa, S. Harati, P. Boadu, F. V. Zohoori, and T. Pak, “Human and environmental impacts of nanoparticles: a scoping review of the current literature,” *BMC Public Health*, vol. 23, no. 1, 2023, doi: 10.1186/s12889-023-15958-4.

[22] M. L. Del Prado-Audelo, I. García Kerdan, L. Escutia-Guadarrama, J. M. Reyna-González, J. J. Magaña, and G. Leyva-Gómez, “Nanoremediation: Nanomaterials and Nanotechnologies for Environmental Cleanup,” *Front Environ Sci*, vol. 9, 2021, doi: 10.3389/fenvs.2021.793765.

[23] A. Inobeme *et al.*, “Recent advances in nanotechnology for remediation of heavy metals,” *Environ Monit Assess*, vol. 195, no. 1, 2023, doi: 10.1007/s10661-022-10614-7.

[24] H. Borji, G. Ayoub, R. Bilbeisi, and L. Malaeb, “How Effective Are Nanomaterials for the Removal of Heavy Metals from Water and Wastewater?,” *Water Air Soil Pollut*, pp. 231–330, 2020.

[25] L. E. Macaskie *et al.*, *Today’s wastes, tomorrow’s materials for environmental protection*, vol. 71–73. 2009. doi: 10.4028/www.scientific.net/AMR.71-73.541.

[26] W.-Q. Shi, L.-Y. Yuan, Z.-J. Li, J.-H. Lan, Y.-L. Zhao, and Z.-F. Chai, “Nanomaterials and nanotechnologies in nuclear energy chemistry,” *Radiochim Acta*, vol. 100, no. 8–9, pp. 727–736, 2012, doi: 10.1524/ract.2012.1961.

[27] L. R. Khanal, J. A. Sundararajan, and Y. Qiang, “Advanced Nanomaterials for Nuclear Energy and Nanotechnology,” *Energy Technology*, vol. 8, no. 3, 2020, doi: 10.1002/ente.201901070.

[28] S. Vijayaram *et al.*, “Applications of Green Synthesized Metal Nanoparticles — a Review,” *Biol Trace Elem Res*, 2023, doi: 10.1007/s12011-023-03645-9.

[29] S. Adabi, A. Yazdanbakhsh, A. Shahsavani, A. Sheikhmohammadi, and M. Hadi, “Removal of heavy metals from the aqueous solution by nanomaterials: a review with analysing and categorizing the studies,” *J Environ Health Sci Eng*, 2023, doi: 10.1007/s40201-023-00863-0.

[30] J. Qiu, “Nanotechnology development in China: Challenges and opportunities,” *Natl Sci Rev*, vol. 3, no. 1, pp. 148–152, 2016, doi: 10.1093/nsr/nww007.

[31] J. Li, X. Li, P. Xie, and P. Liu, “Regulation of drug release performance using mixed doxorubicin-doxorubicin dimer nanoparticles as a pH-triggered drug self-delivery system,” *J Pharm Anal*, vol. 12, no. 1, pp. 122–128, 2022, doi: 10.1016/j.jpha.2021.03.001.

[32] J. Tan, S. Wu, Q. Cai, Y. Wang, and P. Zhang, “Reversible regulation of enzyme-like activity of molybdenum disulfide quantum dots for colorimetric pharmaceutical analysis,” *J Pharm Anal*, vol. 12, no. 1, pp. 113–121, 2022, doi: 10.1016/j.jpha.2021.03.010.

[33] G. Yu *et al.*, “Applications of nanomaterials for heavy metal removal from water and soil: A review,” *Sustainability (Switzerland)*, vol. 13, no. 2, pp. 1–14, 2021, doi: 10.3390/su13020713.

[34] A. Ghosh and Y. Krishnan, “At a long-awaited turning point,” *Nat Nanotechnol*, vol. 9, no. 7, pp. 491–494, 2014, doi: 10.1038/nnano.2014.138.

[35] R. Baby, B. Saifullah, and M. Z. Hussein, “Carbon Nanomaterials for the Treatment of Heavy Metal-Contaminated Water and Environmental Remediation,” *Nanoscale Res Lett*, vol. 14, no. 1, 2019, doi: 10.1186/s11671-019-3167-8.

[36] S. Prasad, R. Saluja, V. Joshi, and J. K. Garg, “Heavy metal pollution in surface water of the Upper Ganga River, India: human health risk assessment,” *Environ Monit Assess*, vol. 192, no. 11, 2020, doi: 10.1007/s10661-020-08701-8.

[37] M. M. Haque *et al.*, “Variability of water quality and metal pollution index in the Ganges River, Bangladesh,” *Environmental Science and Pollution Research*, vol. 27, no. 34, pp. 42582–42599, 2020, doi: 10.1007/s11356-020-10060-3.

[38] A. Botle, S. Salgaonkar, R. Tiwari, S. Ambadekar, and G. R. Barabde, “Brief status of contamination in surface water of rivers of India by heavy metals: a review with pollution indices and health risk assessment,” *Environ Geochem Health*, vol. 45, no. 6, pp. 2779–2801, 2023, doi: 10.1007/s10653-022-01463-x.

[39] P. Kumar *et al.*, “Heavy metal pollution and risks in a highly polluted and populated Indian river–city pair using the systems approach,” *Environmental Science and Pollution Research*, vol. 29, no. 40, pp. 60212–60231, 2022, doi: 10.1007/s11356-022-20034-2.

[40] X. Liu *et al.*, “Trends for nanotechnology development in China, Russia, and India,” *Journal of Nanoparticle Research*, vol. 11, no. 8, pp. 1845–1866, 2009, doi: 10.1007/s11051-009-9698-7.

[41] G. Pandey and P. Jain, “Assessing the nanotechnology on the grounds of costs, benefits, and risks,” *Beni Suef Univ J Basic Appl Sci*, vol. 9, no. 1, 2020, doi: 10.1186/s43088-020-00085-5.

[42] K. Beumer, “Nation-Building and the Governance of Emerging Technologies: the Case of Nanotechnology in India,” *Nanoethics*, vol. 13, no. 1, pp. 5–19, 2019, doi: 10.1007/s11569-018-0327-8.

[43] T. Rambaran and R. Schirhagl, “Nanotechnology from lab to industry - a look at current trends,” *Nanoscale Adv*, vol. 4, no. 18, pp. 3664–3675, 2022, doi: 10.1039/d2na00439a.

[44] N. Baig, I. Kammakakam, W. Falath, and I. Kammakakam, “Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges,” *Mater Adv*, vol. 2, no. 6, pp. 1821–1871, 2021, doi: 10.1039/d0ma00807a.

[45] B. E. Cunningham, E. E. Sharpe, S. M. Brander, W. G. Landis, and S. L. Harper, “Critical gaps in nanoplastics research and their connection to risk assessment,” *Frontiers in Toxicology*, vol. 5, 2023, doi: 10.3389/ftox.2023.1154538.

[46] S. Linley and N. R. Thomson, “Environmental Applications of Nanotechnology: Nano-enabled Remediation Processes in Water, Soil and Air Treatment,” *Water Air Soil Pollut*, vol. 232, no. 2, 2021, doi: 10.1007/s11270-021-04985-9.

[47] N. Shahcheraghi, H. Golchin, Z. Sadri, Y. Tabari, F. Borhanifar, and S. Makani, “Nano-biotechnology, an applicable approach for sustainable future,” *3 Biotech*, vol. 12, no. 3, 2022, doi: 10.1007/s13205-021-03108-9.

[48] R. Vasquez, “Nanotecnología en procesos ambientales y remediación de la contaminación,” *Mundo nano. Revista interdisciplinaria en nanociencias y nanotecnología*, vol. 18, 2015.

[49] M. L. Del Prado-Audelo, I. García Kerdan, L. Escutia-Guadarrama, J. M. Reyna-González, J. J. Magaña, and G. Leyva-Gómez, “Nanoremediation: Nanomaterials and Nanotechnologies for Environmental Cleanup,” *Front Environ Sci*, vol. 9, 2021, doi: 10.3389/fenvs.2021.793765.

[50] T. Chen *et al.*, "Advanced photocatalysts for uranium extraction: Elaborate design and future perspectives," *Coord Chem Rev*, vol. 467, 2022, doi: 10.1016/j.ccr.2022.214615.

[51] Y. Hu, D. Tang, Z. Shen, L. Yao, G. Zhao, and X. Wang, "Photochemically triggered self-extraction of uranium from aqueous solution under ambient conditions," *Appl Catal B*, vol. 322, 2023, doi: 10.1016/j.apcatb.2022.122092.

[52] L. Yu *et al.*, "Methyl position affect the fluorescence performance of HBT derivatives for the detection of hypochlorite under alkaline condition," *Spectrochim Acta A Mol Biomol Spectrosc*, vol. 281, 2022, doi: 10.1016/j.saa.2022.121583.

[53] N. Vela-García, M. C. Guamán-Burneo, and N. P. González-Romero, "Efficient bioremediation from metallurgical effluents through the use of microalgae isolated from the amazonic and highlands of Ecuador | Biorremediación eficiente de efluentes metalúrgicos mediante el uso de microalgas de la amazonía y los andes del Ecua," *Revista Internacional de Contaminacion Ambiental*, vol. 35, no. 4, pp. 917–929, 2019, doi: 10.20937/RICA.2019.35.04.11.

[54] M. M. Khin, A. S. Nair, V. J. Babu, R. Murugan, and S. Ramakrishna, "A review on nanomaterials for environmental remediation," *Energy Environ Sci*, vol. 5, no. 8, pp. 8075–8109, 2012, doi: 10.1039/c2ee21818f.

[55] F. Fu, D. D. Dionysiou, and H. Liu, "The use of zero-valent iron for groundwater remediation and wastewater treatment: A review," *J Hazard Mater*, vol. 267, pp. 194–205, 2014, doi: 10.1016/j.jhazmat.2013.12.062.

[56] Y. Zou *et al.*, "Environmental Remediation and Application of Nanoscale Zero-Valent Iron and Its Composites for the Removal of Heavy Metal Ions: A Review," *Environ Sci Technol*, vol. 50, no. 14, pp. 7290–7304, 2016, doi: 10.1021/acs.est.6b01897.

[57] R. A. Crane and T. B. Scott, "Nanoscale zero-valent iron: Future prospects for an emerging water treatment technology," *J Hazard Mater*, vol. 211–212, pp. 112–125, 2012, doi: 10.1016/j.jhazmat.2011.11.073.

[58] J. Singh, T. Dutta, K.-H. Kim, M. Rawat, P. Samddar, and P. Kumar, "'Green' synthesis of metals and their oxide nanoparticles: Applications for environmental remediation," *J Nanobiotechnology*, vol. 16, no. 1, 2018, doi: 10.1186/s12951-018-0408-4.

[59] D. K. F. Santos, R. D. Rufino, J. M. Luna, V. A. Santos, and L. A. Sarubbo, "Biosurfactants: Multifunctional biomolecules of the 21st century," *Int J Mol Sci*, vol. 17, no. 3, 2016, doi: 10.3390/ijms17030401.

[60] M. Medina, L. Galvan, and R. Reyes, "Las nanopartículas y el medio ambiente," *AutanaBooks S.A.S. Revista de la Universidad Experimental Politécnica Antonio José de Sucre, Vice Rectorado Puerto Ordaz, Venezuela, gestionada en Ecuador por AutanaBooks*, vol. 19, no. 74, 2015.

[61] Y. Chen, "A Review on the Effects of Nanoparticles on Properties of Self-Compacting Concrete," in *IOP Conference Series: Materials Science and Engineering*, 2018. doi: 10.1088/1757-899X/452/2/022134.

[62] S. P. Muñoz-Pérez, Y. M. Gonzales-Pérez, and T. E. Pardo-Muñoz, "The use of Nanomaterials in the construction sector: a literary review• | El uso de los nanomateriales en el sector de la construcción: una revisión literaria," *DYNA (Colombia)*, vol. 89, no. 221, pp. 101–109, 2022, doi: 10.15446/DYNA.V89N221.100210.

[63] L. Bodnarova and T. Jarolim, "Study the effect of carbon nanoparticles in concrete," in *IOP Conference Series: Materials Science and Engineering*, 2018. doi: 10.1088/1757-899X/385/1/012006.

[64] E. Vasquez, "Use of nanomaterials in agriculture and their ecological and environmental implications," *Mundo nano. Revista interdisciplinaria en nanociencias y nanotecnología*, vol. 16, no. 30, 2023.

[65] M. Camacho, J. Vega, and A. Campos, "Use of nanomaterials in biopolymers for food packaging applications," *Revista de la Sociedad Química del Perú*, vol. 77, no. 4, 2011.