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Review

Catalytic Nanomaterials for Soil and Groundwater Remediation: Global Research Trends (2010–2024)

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Abstract

This study presents a comprehensive bibliometric analysis of 217 publications on nanomaterials for soil and groundwater remediation, sourced from the Scopus database, covering the period from 2010 to 2024. The findings highlight significant contributions from various countries, with India identified as the leading contributor, followed by China and the United States. This reflects robust international collaboration in addressing environmental contamination. The analysis also identifies influential journals in this field, particularly "Science of the Total Environment" and "Environmental Science and Technology", which are recognized for their high citation impact and play a crucial role in disseminating research findings and advancing knowledge in nanomaterials for environmental remediation. A keyword co-occurrence analysis reveals six distinct clusters that emphasize critical research themes. The first cluster focuses on environmental toxicity, underscoring the risks posed by contaminants, particularly heavy metals and emerging pollutants such as PFAS, highlighting the need for advanced monitoring strategies. The second cluster showcases innovative nanoremediation technologies, particularly zero-valent iron (nZVI) and carbon nanotubes (CNTs), which are noted for their effectiveness in pollutant removal despite challenges like surface passivation and high production costs. The third cluster addresses heavy metals and phytoremediation, advocating integrated strategies that enhance crop resilience while managing soil contamination. The fourth cluster explores photocatalysis and advanced oxidation processes, demonstrating how nanomaterials can enhance pollutant degradation through light-activated catalytic methods. The fifth cluster emphasizes adsorption mechanisms for specific contaminants, such as arsenic and pharmaceuticals, suggesting targeted remediation strategies. Finally, the sixth cluster highlights the potential of nanomaterials in agriculture, focusing on their role in improving soil fertility and supporting plant growth. Overall, while nanomaterials demonstrate significant potential for effective environmental remediation, they also pose risks that necessitate careful consideration and further research. Future studies should prioritize optimizing these materials for practical applications, addressing both environmental health and agricultural productivity.

Keywords: bibliometric analysis; groundwater remediation; nanomaterials; research trends; Scopus database; soil remediation; VOSviewer; water treatment

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1. Introduction

Soil and groundwater contamination, particularly in industrialized and urban areas, is a pervasive and critical environmental challenge that affects ecosystems and human health worldwide [1,2]. Urbanization and industrialization have led to significant increases in the release of various pollutants, including heavy metals [3], hydrocarbons [4], chlorinated solvents [5], and persistent organic pollutants [2,6,7]. These contaminants can infiltrate soil and groundwater through multiple pathways, such as industrial discharges, agricultural runoff, and improper waste disposal, leading to concentrations that pose severe risks to public health and ecological integrity [2,7,8]. The degradation of these vital resources not only threatens ecosystems but also compromises the quality of drinking water and agricultural productivity, thereby posing substantial risks to public health and economic stability [8].

Soil pollution, characterized by the presence of harmful contaminants and hazardous substances, is a growing concern worldwide [9]. These pollutants can disrupt essential soil functions, compromise food safety, and alter the natural balance of ecosystems. The Food and Agriculture Organization of the United Nations estimates that 25% of global soils are highly degraded, with an additional 44% significantly affected, highlighting the urgency of addressing this critical issue [9]. This degradation underscores the need for innovative and sustainable remediation strategies to restore soil health and functionality. The intricate relationship between soil and groundwater underscores the importance of addressing contamination holistically. Contaminated soil can act as a reservoir for pollutants, allowing harmful substances to leach into groundwater and affecting drinking water supplies and agricultural lands [7,8]. Conversely, groundwater can transport contaminants to surface soils, exacerbating pollution in terrestrial ecosystems [7]. This interconnectedness necessitates integrated remediation strategies that address contamination in both mediums, as treating one without considering the other may result in incomplete remediation and persistent environmental hazards. Selecting a proper remediation technology depends on contaminant characteristics and contaminated site characteristics such as physical, chemical, and biological properties [9,10].

Remediation techniques can be broadly categorized into two main approaches: ex situ and in situ remediation [2]. Ex situ remediation (land farming, bioreactors, windrows, biopile, etc.) involves the removal of contaminated materials from their original location for treatment, either on-site or at designated facilities [2,11]. While this method can effectively eliminate contaminants, it often comes with high operational costs, logistical challenges, and the potential generation of secondary waste, making it less feasible for large-scale or resource-constrained projects [12]. For instance, the remediation cost associated with the removal and replacement of contaminated soil can reach approximately $3 million per hectare [13], a substantial burden for many communities, particularly in developing countries striving to implement effective environmental policies [8]. In contrast, in situ remediation techniques treat contamination directly at the site, minimizing ecological disruption and the costs associated with material transport [9]. Common in situ methods include bioremediation, solidification, chemical oxidation, permeable reactive barrier, phytoremediation, biosparging, bioslurping, and bioventing [2]. These techniques are often preferred due to their lower costs and reduced ecological impact; however, they can also present limitations, such as lower remediation potential and uncertainties regarding their effectiveness in various contexts [14].

Recently, nanotechnology has emerged as a promising approach in the field of environmental remediation, leveraging the unique properties of nanoparticles (NPs) to enhance the effectiveness of treatment strategies [15,16]. Nanomaterials, such as nanoscale zerovalent iron (nZVI) [17], metal oxides [18], and carbon-based nanoparticles [18], exhibit unique physicochemical properties, including high surface area and reactivity [17]. These characteristics enable NPs to interact with contaminants more effectively than traditional remediation agents [15]. For instance, nZVI can catalyze the reduction in various organic and inorganic pollutants, facilitating their transformation into less harmful compounds [8]. Nanoremediation technologies involve the use of reactive NPs for conversion and detoxification of contaminants [8,17]. Additionally, the small size of NPs allows them to penetrate fine soil pores and remain suspended in groundwater, thereby reaching contaminants that are difficult to access with conventional methods [15,19].

Despite these advantages, concerns regarding the environmental impacts and potential toxicity of NPs persist [20]. Understanding their behavior in environmental matrices—how they transport, degrade, and interact with soil microbiota—is crucial for ensuring safe and effective remediation practices [21]. As a result, there is a growing need for comprehensive assessments of the environmental and human health risks associated with nanoremediation technologies. The global market for environmental remediation technologies is substantial, reflecting the increasing urgency of addressing contamination issues effectively [9,22]. The European Environment Agency (EEA) estimated that 3 million areas in the European Economic Area were potentially contaminated sites [23]. Similarly, the US Environmental Protection Agency (EPA) prioritized the cleanup of more than 900 sites in the US alone [24]. Given the rapid advancements in the use of nanotechnology for soil and groundwater remediation, a thorough bibliometric analysis is essential to map the evolution of research trends in this field from 2010 to 2024.

Bibliometric analysis offers a systematic and quantitative approach to examining published literature, revealing insights into research productivity, collaboration patterns, and thematic developments [25–27]. By analyzing publication trends, citation dynamics, and keyword co-occurrence, this study aims to identify key contributors and emerging focus areas within the domain of nanomaterials for soil and groundwater remediation. This approach provides a broad overview of the research landscape. This bibliometric analysis will employ statistical techniques to evaluate articles, review articles, conference papers, book chapters, and citations, uncovering patterns in research productivity across individuals, institutions, and countries. Ultimately, this analysis aims to enhance our understanding of the complex relationship between soil and groundwater contamination and the strategies for remediation. By highlighting significant advancements, challenges, and future directions in the application of nanomaterials, the findings will contribute to the development of more effective and sustainable methods for mitigating soil and groundwater contamination.

2. Results and Discussion

2.1. Publication Trends of Nanomaterials in Soil and Groundwater Remediation Articles

Figure 1 illustrates the publication trends and total citations for research on nanomaterials in soil and groundwater remediation from 2010 to 2024. This visual representation provides critical insights into the evolution and impact of research in this domain.

In 2010, the field began with 1 publication, which attracted 41 citations, indicating the nascent stage of research into the application of nanomaterials for environmental remediation. As the years progressed, a notable shift occurred; in 2011, the number of publications surged to 12, resulting in 166 citations. This increase signifies a growing interest and expanding activity within the field, indicating an early recognition of the potential benefits that nanomaterials could offer. However, the following year, 2012, witnessed a stark decline in research output, dropping to just 2 articles, which collectively attracted only 36 citations. This dip may suggest a temporary reduction in focus or funding, reflecting the natural ebb and flow of research priorities. Fortunately, 2013 marked a resurgence in the field, as 7 publications emerged, amassing 742 citations. This spike underscores the increasing acknowledgment of the significance of nanomaterials in remediation efforts, indicating a renewed enthusiasm among researchers. Continuing this upward trend, 2014 saw a slight increase in output with 8 articles, which accumulated 425 citations. This sustained interest in the subject matter reinforced the notion that nanomaterials were gaining traction as viable solutions for environmental challenges. However, in 2015, the number of publications dipped again to 6, resulting in 203 citations. This fluctuation in output highlights the ongoing engagement with research on nanomaterials, even amidst varying levels of publication activity.

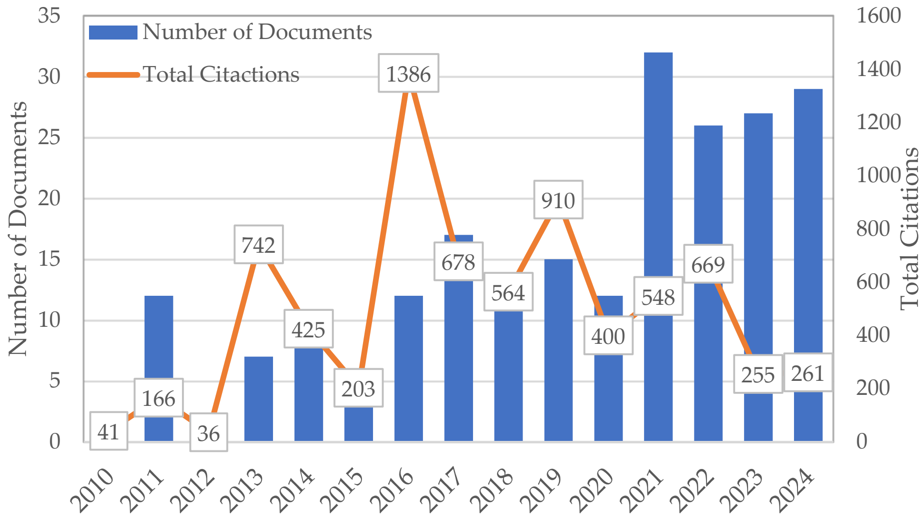

Figure 1. Trends in publications and citations for nanomaterials in soil and groundwater remediation, as determined by the Scopus database until 2024 (n = 217).

The peak of research activity occurred in 2016, where 12 publications were released, generating an impressive 1386 citations. This peak year illustrates both the volume and the substantial impact of research during this period, showcasing the growing recognition of the importance of nanomaterials in remediation efforts. Nevertheless, the subsequent years demonstrated variability. In 2017, there was an increase to 17 publications, which resulted in 678 citations, while 2018 saw a decrease back to 12 articles with 564 citations. These fluctuations may reflect not only the dynamic nature of research interests but also the increasingly competitive landscape of scientific publishing.

From 2019 to 2024, a trend of stabilization in output emerged. In 2024, there were 29 publications, yielding 261 citations. While this indicates a significant volume of research output, it also highlights the challenge of citation accumulation for newer articles. The "citation lag" phenomenon is crucial to consider here; it emphasizes that recent publications may not achieve the same citation levels as older articles simply because they have had less time to be cited. This phenomenon reveals a methodological limitation in interpreting citation data, particularly for recent years [28].

Overall, the analysis presents a complex narrative regarding publication trends in nanomaterials for soil and groundwater remediation. The data indicate a growing body of research, particularly from 2010 to 2016, followed by fluctuating output and citation dynamics in subsequent years. This variability suggests that while interest in the subject persists, external factors such as competition for research funding and publication opportunities may influence the consistency of output. The differences in citation counts for recent publications underscore the necessity for further investigation into the factors affecting the recognition of newer research. Future studies could focus on the dissemination strategies employed by researchers to enhance visibility and citation potential, which is critical for ensuring the practical impact of findings in environmental science.

In summary, Figure 1 highlights a clear upward trend in research volume from 2010 to 2024, emphasizing the growing importance of nanomaterials in environmental remediation. However, the observed citation patterns warrant careful consideration, as they may not accurately reflect the quality of research due to the inherent dynamics of citation accumulation. This analysis advocates for continued research efforts and effective communication strategies to maximize the academic and practical significance of findings in this vital area.

Figure 2 illustrates the distribution of research publications across various scientific disciplines concerning nanomaterials for groundwater and soil remediation. This categorization highlights the multifaceted nature of research in this area and underscores the importance of interdisciplinary approaches to address environmental challenges. "Environmental Science" emerges as the leading category, comprising 23.5% of total publications. This significant share reflects the central role of environmental science in understanding contamination issues, particularly those related to nanomaterials. Research in this discipline is crucial for developing effective management and remediation strategies, aiming to mitigate the ecological impacts of nanomaterials on ecosystems. The emphasis on environmental science indicates the urgency of addressing the challenges posed by contaminants and the need for innovative solutions [2].

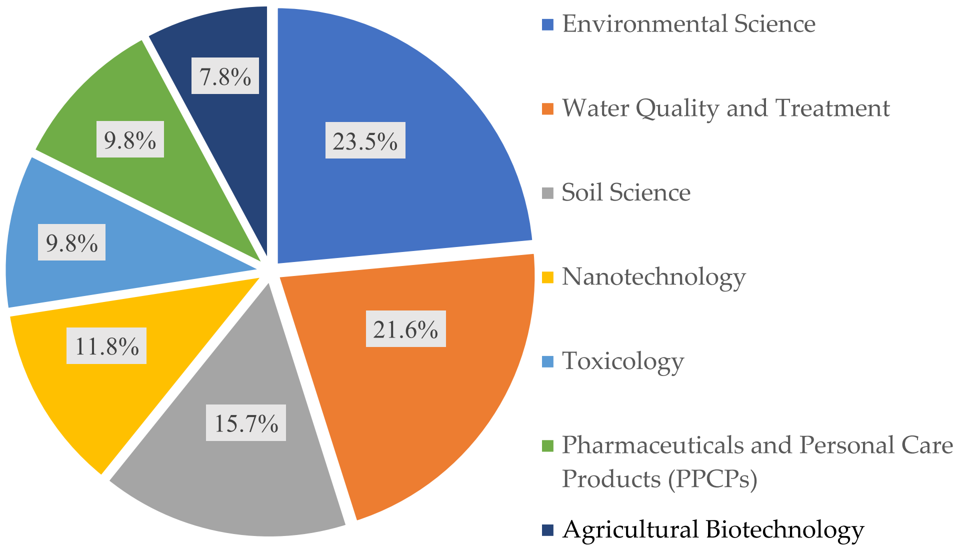

Figure 2. Categorization of documents related to nanomaterials on groundwater and soil remediation.

"Water Quality and Treatment" accounts for 15.7% of the publications, underscoring the importance of ensuring safe and clean water resources. This field focuses on the application of nanomaterials in water treatment processes, which is vital for removing pollutants and enhancing water quality. The contributions from this discipline are essential for creating effective treatment solutions that can help manage waterborne contaminants [29].

"Soil Science" represents 11.8% of the research, highlighting the significance of understanding how nanomaterials interact with soil properties and processes. This discipline is critical for assessing the implications of nanomaterials on soil health and fertility, as well as their potential for remediation of contaminated soils. The insights gained from soil science are vital for developing strategies that leverage nanomaterials for effective soil remediation [17]. "Toxicology" comprises 21.6% of the publications, emphasizing the need to investigate the potential health impacts of nanomaterials. Understanding the toxicological effects is essential for evaluating risks associated with exposure to nanomaterials in various environmental contexts. This research is crucial for informing safety regulations and public health policies [8].

"Pharmaceuticals and Personal Care Products (PPCPs)" contribute 9.8% to the total publications, reflecting the relevance of nanomaterials in addressing contaminants from these sources. Research in this area focuses on the detection, degradation, and remediation of PPCPs in environmental matrices, which is vital for maintaining ecosystem health [30]. "Agricultural Biotechnology" accounts for 7.8% of the publications, emphasizing the implications of nanomaterials in agricultural practices. This field explores the use of nanomaterials in enhancing crop productivity and soil remediation, highlighting the potential benefits and risks associated with their application in agriculture [8].

Overall, Figure 2 illustrates a diverse array of research disciplines contributing to the understanding and application of nanomaterials for groundwater and soil remediation. The varied distribution of publications underscores the complexity of this field and the importance of interdisciplinary collaboration. Each discipline plays a unique role in addressing the multifaceted challenges posed by environmental contaminants, emphasizing the need for integrated approaches to develop comprehensive solutions for effective remediation and management strategies.

2.2. Leading Journals for Articles of Nanomaterials in Soil and Groundwater Remediation

Table 1 provides a detailed overview of the top 12 journals that publish articles related to nanomaterials in soil and groundwater remediation. Table 1 includes significant metrics such as TLS, number of documents published, total citations, h-index, SCImago Journal Rank (SJR), and quartile ranking (Q). The data highlights the prominence of certain journals in disseminating critical research findings in this evolving field.

Table 1. The top 12 leading journals by TLS for nanomaterials in soil and groundwater remediation.

Source Journal	TLS	Number of Documents	Total Citations	H-Index	SJR	Q
Science of the Total Environment	243	9	343	399	2.137	1
Environmental Science and Technology	202	4	437	504	3.69	1
Journal of Contaminant Hydrology	198	6	169	115	1.091	1
Environmental Science and Pollution Research	153	6	493	212	1.004	1
Chemosphere	149	9	453	329	1.896	1
Journal of Nanoparticle Research	149	3	304	149	0.469	2
Environmental Science: Nano	145	5	222	119	1.201	1
Environmental Pollution	136	7	130	328	2.205	1
Nanomaterials	42	4	97	151	0.811	1
Ecotoxicology and Environmental Safety	38	4	41	197	1.553	1
Journal of Environmental Management	22	3	61	268	1.994	1
Environmental Chemistry Letters	4	4	427	144	3.929	1

The journal "Science of the Total Environment" leads the list with a TLS of 243, publishing 9 articles that have collectively garnered 343 citations. Its h-index of 399 indicates that many of its articles are frequently cited, underscoring its influence in environmental research. Following closely is "Environmental Science and Technology", which has published 4 articles that achieved a total of 437 citations, resulting in a TLS of 202. This journal's high h-index of 504 signifies its strong impact in the field. The "Journal of Contaminant Hydrology" ranks third with a TLS of 198. It has published 6 articles that received 169 citations, reflecting a focused but significant contribution to the understanding of contaminant behavior in hydrological contexts.

"Environmental Science and Pollution Research" and "Chemosphere" also stand out, with TLS values of 153 and 149, respectively. Both journals have published multiple articles, with "Chemosphere" achieving a higher citation count of 453, indicating its substantial role in environmental science discourse. Other notable publications include "Journal of Nanoparticle Research" and "Environmental Science: Nano", both of which, despite lower TLS values, contribute valuable insights into the nanomaterial's domain. The h-index and SJR metrics across these journals illustrate their standing within the scientific community, with the majority residing in the first quartile (Q1), indicating their high impact and relevance in the field of nanomaterials research for soil and groundwater remediation. In summary, Table 1 emphasizes the concentration of influential research in high-impact journals, which plays a crucial role in advancing the understanding of nanomaterials in environmental remediation efforts.

To analyze the network of international collaborations in nanomaterials research concerning soil and groundwater remediation, a network diagram was created using VOSviewer (version 1.6.18, Leiden University, Leiden, The Netherlands, 2022), as illustrated in Figure 3. Each journal is represented as a node, and the connections (edges) between them signify collaborative relationships or thematic overlaps in published research. The size of each node reflects the number of publications related to nanomaterials, with larger nodes indicating journals that have made substantial contributions to the field [27].

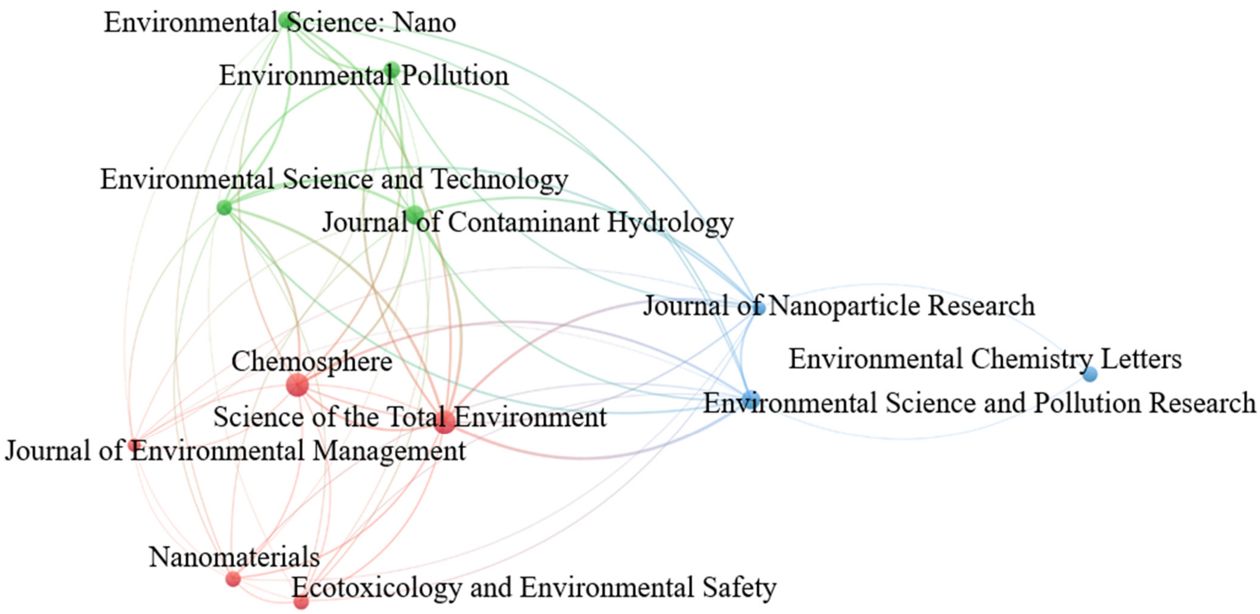

Figure 3. Co-occurrence map of journals published that have more than 3 publications related to nanomaterials in soil and groundwater remediation.

Prominent journals such as "Environmental Science and Technology" and "Chemosphere" stand out, highlighting their importance in the literature on nanomaterials. The lines connecting the nodes represent the strength of relationships between journals, with thicker lines indicating stronger collaborations or thematic similarities in research topics. For instance, "Environmental Science and Technology" exhibits strong connections with multiple other journals, suggesting that it plays a central role in disseminating research findings in this area.

The clustered arrangement of the nodes indicates that certain journals may focus on specific themes within nanomaterials research. Journals like "Journal of Contaminant Hydrology" and "Science of the Total Environment" likely cover similar environmental impacts of nanomaterials, showcasing a shared research focus. Moreover, the presence of diverse journals interconnected on the map highlights the interdisciplinary nature of this field of research. It encompasses environmental science, chemistry, and nanotechnology, suggesting a collaborative approach to addressing complex environmental challenges.

Figure 3 can serve as a valuable guide for researchers seeking potential collaborators and relevant publication venues. It emphasizes the importance of considering thematic connections when selecting journals, as closely linked publications may cater to similar audiences and research interests.

Overall, this co-occurrence map provides essential insights into the dynamics of research in nanomaterials related to soil and groundwater remediation. It illustrates the collaborative landscape of high-impact journals and underscores the critical role they play in advancing knowledge and fostering interdisciplinary research in this vital area.

Figure 4 presents a comprehensive overview of the publication statistics concerning nanomaterials in soil and groundwater remediation. This analysis highlights the contributions of several key journals that have significantly shaped the discourse in this field. The journals included in the analysis are "Chemosphere", "Science of the Total Environment", "Environmental Science and Pollution Research", "Journal of Contaminant Hydrology", "Environmental Science: Nano", and "Environmental Pollution".

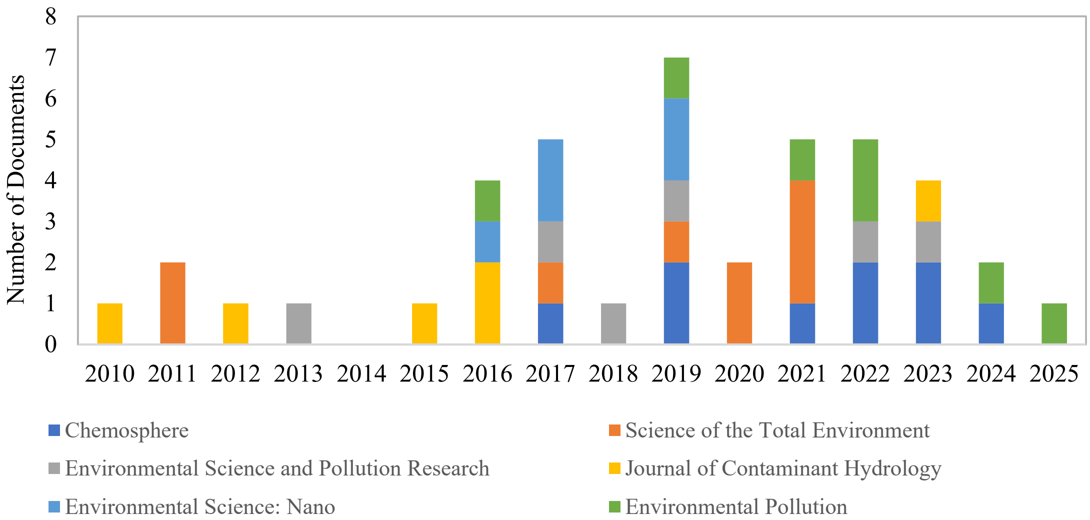

Figure 4. Publication statistics on nanomaterials in soil and groundwater remediation.

The overall trends indicate that both "Chemosphere" and "Science of the Total Environment" are the leading journals in this field, with each having published a total of 9 articles during the analyzed period. This significant output reflects a strong commitment from both journals to advancing research in this critical area, underscoring their importance within the environmental literature. Following closely, "Environmental Pollution" has published 7 articles, demonstrating a focused interest in pollution-related issues, including the implications of nanomaterials. The consistent output from this journal highlights its relevance in addressing environmental challenges.

In addition to these leading journals, "Environmental Science and Pollution Research" and "Journal of Contaminant Hydrology" each contributed 6 articles. Their outputs indicate an active engagement with the topic of nanomaterials, although they did not lead in publication counts. Meanwhile, "Environmental Science: Nano" published 5 articles, suggesting a growing interest in the applications of nanotechnology within environmental contexts, albeit with a lower output compared to the top-tier journals.

Examining the yearly trends reveals more nuanced insights into publication activity. The year 2016 marked a peak for "Chemosphere", which published 2 articles, signaling a potential increase in research interest during that period. Similarly, 2018 saw a notable surge for both “Chemosphere” and “Environmental Pollution”, each contributing 2 articles. This indicates that 2018 was a significant year for advancements in research related to nanomaterials. In 2021, “Environmental Pollution” experienced another spike in activity, publishing 2 articles, reflecting heightened interest in pollution-related research at that time. However, the years from 2022 to 2024 show a decline in publication activity across most journals, suggesting a potential stabilization or shift in research focus.

In conclusion, the analysis of publication counts from 2010 to 2024 illustrates a competitive landscape among these key journals. Both “Chemosphere” and “Science of the Total Environment” emerge as leading sources of research on nanomaterials, while “Environmental Pollution”, “Environmental Science and Pollution Research”, and “Journal of Contaminant Hydrology” also make meaningful contributions to the discourse. The fluctuation in publication counts over the years reflect varying trends in research interest and urgency, highlighting the evolving nature of environmental research related to nanomaterials in soil and groundwater remediation. Collectively, these trends underscore the commitment of the academic community to address the challenges posed by nanomaterials in environmental contexts.

2.3. Country Distribution of Nanomaterials Research in Soil and Groundwater Remediation

The bibliometric analysis presented in Table 2 offers a comprehensive overview of the leading countries involved in research on nanomaterials for soil and groundwater remediation. The data includes key metrics such as TLS, the number of publications, and total citations for each nation.

Table 2. Leading 10 nations through publishing on the nanomaterials research in groundwater and soil remediations from 2010 to 2024 (ranked by TLS).

Country	TLS	Number of Publications	Total Citations
India	6281	85	1533
China	5646	56	1669
United States	5460	53	1676
South Korea	3100	16	1425
Australia	2406	12	702
Saudi Arabia	2403	10	246
Pakistan	2246	11	374
Canada	1605	8	336
Spain	1548	10	298
Mexico	755	10	218

India stands out as the top contributor, boasting a TLS of 6281, 85 publications, and 1533 citations. This impressive output highlights India’s robust research capabilities and a growing focus on addressing soil and groundwater contamination challenges, underscoring the nation’s commitment to environmental remediation technologies. The high TLS indicates strong collaborative networks, suggesting that Indian research is influential in this field. China ranks second, with a TLS of 5646, 56 publications, and 1669 citations. This reflects China’s significant investment in environmental research and its proactive approach to tackling pollution issues. The notable number of citations indicates that Chinese research is impactful on a global scale, reinforcing its position as a key player in nanomaterials research.

One of the primary reasons for this engagement is the pressing environmental challenges faced by many countries. Rapid industrialization, agricultural runoff, and urbanization have led to severe soil and groundwater contamination issues, particularly in nations like India and China [31]. As these countries grapple with the consequences of their growth, there is an urgent need to find effective solutions to mitigate pollution. This urgency drives governments and researchers to explore innovative technologies, such as nanomaterials, which offer promising approaches for environmental remediation [31].

The United States follows closely in third place, contributing a TLS of 5460, 53 publications, and 1676 citations. The U.S. has a longstanding history of leadership in nanotechnology and environmental science, as evidenced by its publication output and citation impact. This strong presence suggests a well-established academic infrastructure and considerable funding dedicated to research in these areas. South Korea, with a TLS of 3100 and 16 publications, has also made significant contributions, accumulating 1425 citations. This indicates South Korea's commitment to developing technologies for environmental remediation, despite its relatively lower publication count compared to leading nations. Australia's contributions, with 12 publications and a TLS of 2406, reflect its focus on sustainable environmental practices, supported by its research institutions. Meanwhile, Saudi Arabia's involvement, with 10 publications and a TLS of 2403, signifies its growing interest in addressing soil and groundwater challenges within the framework of its environmental policies.

Pakistan, with a TLS of 2246 and 11 publications, alongside Canada, which has 1605 TLS and 8 publications, shows that both countries are gradually increasing their participation in nanomaterials research. Their citation counts indicate that their findings are gaining recognition within the international scientific community. Spain and Mexico, each contributing 10 publications, demonstrate a commitment to environmental research, with citation counts of 298 and 218, respectively. Their involvement reflects a broader engagement across Europe and Latin America in addressing environmental challenges through innovative solutions.

Overall, the interest of these countries in nanomaterials research for soil and groundwater remediation is driven by a combination of environmental necessity, public health considerations, economic incentives, collaborative opportunities, regulatory pressures, and the scientific promise of nanotechnology. As global awareness of environmental issues continues to grow, these factors will likely sustain and enhance the commitment of nations to pursue innovative research in this vital field.

Figure 5 presents a network visualization that illustrates the primary nations engaged in nanomaterials research for groundwater and soil remediation. The analysis reveals a total of 11 countries, each represented by nodes of varying sizes and connecting lines of different thicknesses. The size of each node corresponds to the level of engagement in this research area, with larger nodes indicating a more prominent role and influence within the network. Among the countries represented, India and China emerge as central players, characterized by their larger nodes and thicker connecting lines. This positioning signifies their substantial contributions and the strong collaborative networks they have established in the field of nanomaterials research. The close connectivity between these two countries suggests a robust exchange of knowledge and resources, reinforcing their leadership roles in addressing environmental challenges associated with soil and groundwater.

The United States, while slightly smaller than India and China, also occupies a critical position in the network, reflecting its historical strength in nanotechnology and environmental science. The connections to other countries, such as Canada and Australia, further illustrate the collaborative nature of the research landscape, indicating active partnerships that enhance the dissemination of knowledge and technological advancements. South Korea and Saudi Arabia are also notable contributors, represented by medium-sized nodes that indicate a significant but comparatively lower level of engagement than the leading nations. Their connections within the network suggest that they are part of important collaborative efforts, although they may not yet have the same level of influence. The inclusion of countries like Spain, Mexico, and Pakistan highlights the global dimension of this research area. These nations, while having smaller nodes, still play a role in the network, contributing to the diversity of perspectives and approaches in nanomaterials research. Their participation underscores the importance of international collaboration in addressing complex environmental issues.

Figure 5. A network visualization displaying the primary nations taking part in the nanomaterials research in groundwater and soil remediation.

Overall, this network visualization provides valuable insights into the global research landscape surrounding nanomaterials for groundwater and soil remediation. By highlighting the major contributors and their interconnections, it emphasizes the collaborative dynamics that are essential for advancing understanding and management strategies in this vital area of environmental science. Recognizing these relationships is crucial for identifying key players and fostering future collaborations aimed at tackling the challenges associated with environmental remediation.

To highlight the primary universities engaged in nanomaterials research for soil and groundwater remediation, a comprehensive network visualization was constructed, as illustrated in Figure 6. This figure maps the affiliations of key institutions based on their involvement in relevant research publications.

Table 3 presents a detailed analysis of the top eight universities according to author affiliations, showcasing their respective departments, locations, total citation metrics, and publication counts.

Among these leading institutions, the "Guangdong Provincial Academy of Environmental Science" in Guangzhou, China, emerges prominently with a total of 104 total citations derived from two publications. This indicates its foundational role in advancing research in this critical area. Similarly, the "Guangdong Provincial Research Center for Environment Control and Remediation Materials at Jinan University", also in Guangzhou, records equivalent performance with two documents and 104 citations, reflecting its significant contributions to environmental remediation studies. The "National Institute of

Technology" in Srinagar, India, has produced two publications with 32 citations, indicating a growing presence in this field. Notably, "Carnegie Mellon University" in Pittsburgh, USA, with its Department of Civil Engineering, has also contributed two documents, but with a higher citation count of 26, underscoring the impact of its research output.

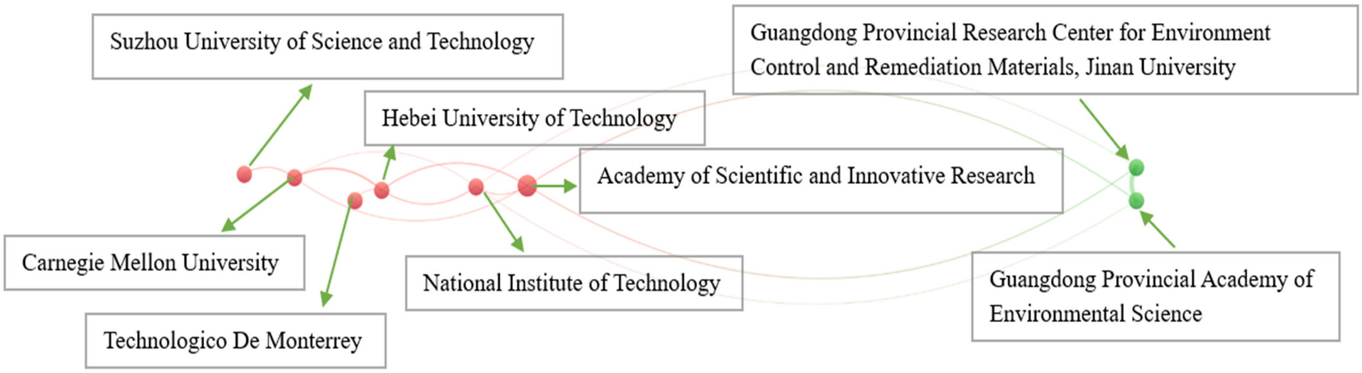

Figure 6. A network visualization displaying the primary universities taking part in the nanomaterials research in soil and groundwater remediation.

Table 3. Top 8 universities according to authors' affiliation.

Affiliation	Department	Country	TLS	NO. of Documents	Total Citations
Guangdong Provincial Academy of Environmental Science	____*	Guangzhou, China	104	2	6
Guangdong Provincial Research Center for Environment Control and Remediation Materials, Jinan University	College of Life Science and Technology	Guangzhou, China	104	2	6
National Institute of Technology	____	Srinagar, India	32	2	3
Carnegie Mellon University	Department of Civil Engineering	Pittsburgh, PA, USA	26	2	19
Jiangsu Key Laboratory of Environmental Functional Materials, Suzhou University of Science and Technology	School of Chemistry Biology and Material Engineering	Suzhou, China	25	3	51
Academy of Scientific and Innovative Research (ACSIR)	____	Ghaziabad, India	13	2	26
Tianjin Key Laboratory of Clean Energy and Pollution Control, Hebei University of Technology	School of Energy and Environmental Engineering	Tianjin, China	6	2	0
Technologico De Monterrey	School of Engineering and Sciences	Monterrey, Mexico	2	2	200

* The department in not mentioned in the analysis.

Additionally, "Jiangsu Key Laboratory of Environmental Functional Materials at Suzhou University of Science and Technology" published three papers, accumulating 25 citations, which showcases its active engagement in this domain. The "Academy of Scientific and Innovative Research (ACSIR)" in Uttar Pradesh, India, has generated two publications with 13 citations, while "Tianjin Key Laboratory of Clean Energy and Pollution Control at Hebei University of Technology" has two documents but no citations, suggesting challenges in research dissemination or impact. Lastly, "Tecnologico De Monterrey" in Monterrey, Mexico, stands out with a striking citation count of 200 from only two publications, indicating a significant influence despite a relatively low output.

Overall, these institutions collectively reflect a rich tapestry of contributions to the study of nanomaterials in environmental remediation. The disparity in publication counts and citation metrics among these universities suggest varying research focuses and levels of impact, emphasizing the collaborative nature of advancements in this vital scientific field.

2.4. Co-Citation Network of Authors in Nanomaterials Research for Soil and Groundwater Remediation

Co-citation analysis serves as a pivotal bibliometric tool to elucidate the relationships between authors within a specific research domain [32]. This method identifies authors who are frequently cited together, revealing thematic connections that underpin the literature on nanomaterials in soil and groundwater remediation. Understanding these relationships can provide valuable insights into the collaborative nature of research in this field. Table 4 presents the most prolific authors in the field of nanomaterials research for soil and groundwater remediation. It includes key metrics such as TLS, total citations, and the number of publications for each author.

Table 4. Most prolific authors: publication metrics.

Most Prolific Author	TLS	Total Citation	No. of Publications
Su, C.	490	91	5
Wang, D.	490	74	3
Huangfu, X.	424	51	3
Xu, N.	424	51	3
Hussain, C.M.	103	0	3
Palit, S.	103	0	4

Table 4 highlights the researchers with the highest publication counts. Leading the table is Su, C., who has a TLS of 490 and five publications, accompanied by a total of 91 citations. This significant output not only showcases Su's active engagement in the field but also indicates the impact of their work on the academic community. Wang, D. also has a TLS of 490, with three publications and 74 citations, highlighting their notable contribution to the body of literature. The identical TLS between Su and Wang suggests that both authors have established strong connections within the research network, indicating their collaborative influence in the field of nanomaterials. Following them are Huangfu, X. and Xu, N., each with a TLS of 424 and three publications, alongside 51 citations. This level of citation indicates a moderate recognition of their contributions, suggesting that their research is relevant. Hussain, C.M. and Palit, S. also contributed three and four publications, respectively, but have not yet garnered any citations, as indicated by their TLS of 103. This might suggest that their work is emerging, reflecting the varying stages of research impact among these authors. Overall, Table 4 illustrates a concentrated effort among these researchers to advance knowledge in the domain of nanomaterials for environmental applications. The diversity in publication counts and citation metrics underscores the collaborative nature of the research environment, highlighting both established and emerging scholars who are collectively driving innovation in soil and groundwater remediation.

Table 5 focuses on the authors who have garnered the highest citation totals in the research area of nanomaterials for soil and groundwater remediation. It displays their TLS, total citations, and number of publications.

Table 5. Most cited authors: citation metrics.

Most Cited Author	TLS	Total Citation	No. of Publications
Stefaniuk, M.	656	805	1
Babajide, O.O.	642	396	1
Koel, B.E.	536	393	2
Zhang, W.X.	463	389	1
Duarte, A.C.	401	317	2
Waite, T.D.	219	301	1

Table 5 highlights authors who have received the highest citation totals in this research domain. Stefaniuk, M. stands out with a remarkable total of 805 citations, demonstrating a substantial impact on the field despite having only one publication. This suggests that their work has been highly influential and widely recognized within the academic community. Following Stefaniuk is Babajide, O.O., who has accumulated 396 citations from a single publication. This indicates that Babajide's work is also significant and has resonated with researchers in the field. Similarly, Koel, B.E. has achieved 393 citations from two publications, highlighting the effectiveness of their contributions to literature. Other notable authors include Zhang, W.X., with 389 citations from one publication, and Duarte, A.C., who has garnered 317 citations from two publications. Both authors have made relevant contributions, further emphasizing the importance of their research in the area of nanomaterials. Lastly, Waite, T.D. has achieved 301 citations from a single publication.

The diversity in the number of publications among these highly cited authors, coupled with their citation totals, underscores the varying degrees of impact and recognition achieved in the scholarly community. Overall, Table 5 illustrates the significant contributions of these authors to the research landscape of nanomaterials for soil and groundwater remediation, highlighting the importance of both quality and quantity in academic research.

2.5. Top Cited Publications in Nanomaterials Research Related to Soil and Groundwater Remediation

Citation analysis is a crucial approach for understanding the intellectual connections among scholarly publications, especially when one work references another. This method allows researchers to pinpoint significant articles within a specific academic discipline and to analyze trends and patterns in citations [33]. In this study, we conducted a citation analysis of papers focusing on nanomaterials in the context of soil and groundwater remediation.

Table 6 presents the top 30 publications ranked by citation counts, with the ranking determined by their adherence to the criteria of the Scopus database. This analysis offers important insights into the most impactful and influential works in this field. These key publications represent vital progress in our understanding of how nanomaterials can be utilized to remediate contaminated soil and groundwater, addressing their mechanisms of action, effectiveness, and environmental implications.

Nanomaterials have emerged as a transformative approach in addressing soil and groundwater contamination, presenting innovative solutions for remediation. These materials, which include nZVI, carbon nanotubes (CNTs), metal oxides, and various nanocomposites, possess unique attributes such as elevated surface area and reactivity. These properties make them exceptionally effective in the removal of pollutants. However, the implementation of nanotechnology in environmental remediation necessitates careful consideration of synthesis methodologies, potential ecological impacts, and sustained performance.

In particular, nZVI has garnered attention for its heightened reactivity and ability to transform contaminants into less harmful forms. While much of the existing literature focuses on adsorption and redox processes, it is crucial to highlight its catalytic potential in degrading hazardous chlorinated compounds, such as polychlorinated biphenyls (PCBs) and various herbicides. The catalytic activity of nZVI is primarily attributed to its capacity to facilitate electron transfer reactions. For example, it can break carbon-chlorine bonds through catalytic reductive dechlorination, resulting in the formation of less chlorinated species or complete dechlorination into benign products like ethylene or methane [34].

Several investigations underscore the efficacy of nanomaterials in the remediation of diverse contaminants. Studies such as Stefaniuk et al. [35] emphasize the cost-effectiveness and adaptability of nZVI, while Yan et al. [36] and Galdames et al. [17] highlight its potential in addressing a spectrum of subsurface contaminants. Conversely, Bae et al. [37] address the challenges associated with the surface passivation of nZVI, underscoring the necessity for inventive strategies to uphold its reactivity. CNTs are also garnering attention for their distinctive adsorption characteristics, rendering them appropriate for remediating both organic and inorganic pollutants. Metal oxides and their modified configurations, as elucidated by Siddiqui et al. [38], demonstrate promise as efficacious adsorbents for arsenic removal, effectively tackling challenges related to toxicity and separation.

To alleviate the ecological apprehensions linked to conventional nanomaterial synthesis, researchers are exploring environmentally conscious green synthesis methodologies. Hao et al. [39] exemplify the utilization of green tea extract for synthesizing iron nanoparticles, thereby proffering a cost-efficient and sustainable approach for eliminating hexavalent chromium. Dutta et al. [40] accentuate the imperative of sustainable practices in nanomaterial development, underscoring the potential of bio-inspired synthesis using waste materials and natural precursors. These green synthesis techniques not only curtail ecological impact but also augment the stability and performance of nanomaterials in remediation applications.

Comprehending the transport and fate of nanomaterials within the environment is paramount for evaluating their prospective risks and optimizing their application. Yin et al. [41] explore the co-transport of graphene oxide and heavy metal ions in porous media, unveiling intricate interactions influenced by surface characteristics. Rahmatpour et al. [42] scrutinize the transport of silver nanoparticles in calcareous soils, underscoring the significance of soil texture and flow conditions in influencing their behavior. Garner et al. [43] address the ecological hazards linked to engineered nanomaterials, emphasizing the necessity for further research into their fate and toxicity across diverse environments.

Despite the encouraging potential of nanomaterials in environmental remediation, several challenges persist. These encompass the necessity for standardized reporting of toxicological data, the advancement of cost-efficient production methods, and the optimization of nanomaterial transport and mixing in subsurface environments. Zhang et al. [44] underscore the challenges pertaining to nanomaterial mixing and transport in subsurface environments, emphasizing the exigency for enhancements in mixing techniques. Moreover, Al-Salim et al. [45] accentuate the imperative of comprehending both the toxicity of nanomaterials to non-target organisms and their prospective exposure pathways.

Future research endeavors should concentrate on surmounting these challenges and fostering the integration of nanotechnology with other remediation methodologies to formulate sustainable and efficacious solutions for soil and groundwater contamination. The utilization of stabilized nanomaterials, such as polymer-coated nZVI, and the advancement of advanced filtration systems that selectively eliminate detrimental contaminants are also auspicious avenues for prospective research.

Table 6. The top 30 most cited articles.

First Author	Year	Document Title	Journal	Citations	Ref.
Stefaniuk, M.	2016	"Review on nano zerovalent iron (nZVI): From synthesis to environmental applications"	Chemical Engineering Journal	805	[35]
Tijani, J.O.	2016	"Pharmaceuticals, endocrine disruptors, personal care products, nanomaterials and perfluorinated pollutants: a review"	Environmental Chemistry Letters	396	[30]
Yan, W.	2013	"Iron nanoparticles for environmental clean-up: Recent developments and future outlook"	Environmental Sciences: Processes and Impacts	389	[36]
Bae, S.	2018	"Advances in Surface Passivation of Nanoscale Zerovalent Iron: A Critical Review"	Environmental Science and Technology	301	[37]
Garner, K.L.	2014	"Emerging patterns for engineered nanomaterials in the environment: A review of fate and toxicity studies"	Journal of Nanoparticle Research	293	[43]
Siddiqui, S.I.	2017	"Iron oxide and its modified forms as an adsorbent for arsenic removal: A comprehensive recent advancement"	Process Safety and Environmental Protection	291	[38]
Sarma, G.K.	2019	"Nanomaterials as versatile adsorbents for heavy metal ions in water: a review"	Environmental Science and Pollution Research	243	[46]
Mohmood, I.	2013	"Nanoscale materials and their use in water contaminants removal-a review"	Environmental Science and Pollution Research	235	[47]
Hussain, A.	2022	"In situ, Ex situ, and nano-remediation strategies to treat polluted soil, water, and air–A review"	Chemosphere	193	[2]
Galdames, A.	2020	"Zero-valent iron nanoparticles for soil and groundwater remediation"	International Journal of Environmental Research and Public Health	153	[17]
Shaji, E.	2024	"Fluoride contamination in groundwater: A global review of the status, processes, challenges, and remedial measures"	Geoscience Frontiers	145	[48]
Song, B.	2019	"Using nanomaterials to facilitate the phytoremediation of contaminated soil"	Critical Reviews in Environmental Science and Technology	145	[49]
Zhang, T.	2019	"In situ remediation of subsurface contamination: Opportunities and challenges for nanotechnology and advanced materials"	Environmental Science: Nano	119	[44]
Babaee, Y.	2018	"Removal of arsenic (III) and arsenic (V) from aqueous solutions through adsorption by Fe/Cu nanoparticles"	Journal of Chemical Technology and Biotechnology	115	[50]
Alazaiza, M.Y.	2021	"Recent advances of nanoremediation technologies for soil and groundwater remediation: A review"	Water (Switzerland)	101	[8]
Thomé, A.	2015	"Review of nanotechnology for soil and groundwater remediation: Brazilian perspectives"	Water, Air, and Soil Pollution	100	[51]
Al-Salim, N.	2011	"Quantum dot transport in soil, plants, and insects"	Science of the Total Environment	92	[45]
Taghipour, S.	2019	"Engineering nanomaterials for water and wastewater treatment: Review of classifications, properties and applications"	New Journal of Chemistry	92	[29]

Table 6. *Cont.*

First Author	Year	Document Title	Journal	Citations	Ref.
Rathnayake, S.	2014	"Multitechnique investigation of the ph dependence of phosphate induced transformations of ZnO nanoparticles"	Environmental Science and Technology	89	[52]
Thakur, A.K.	2020	"A review on design, material selection, mechanism, and modelling of permeable reactive barrier for community-scale groundwater treatment"	Environmental Technology and Innovation	87	[53]
Raza, A.	2022	"Recent advances in carbonaceous sustainable nanomaterials for wastewater treatments"	Sustainable Materials and Technologies	83	[54]
Gomes, A.R.	2017	"Review of the ecotoxicological effects of emerging contaminants to soil biota"	Journal of Environmental Science and Health–Part A Toxic/Hazardous Substances and Environmental Engineering	82	[55]
Marcon, L.	2021	"In situ nanoremediation of soils and groundwater from the nanoparticle's standpoint: A review"	Science of the Total Environment	78	[9]
Dutta, V.	2022	"Bio-inspired synthesis of carbon-based nanomaterials and their potential environmental applications: A state-of-the-art review"	Inorganics	77	[40]
Rahmatpour, S.	2018	"Transport of silver nanoparticles in intact columns of calcareous soils: The role of flow conditions and soil texture"	Geoderma	65	[42]
Mura, S.	2013	"Advanced of nanotechnology in agro-environmental studies"	Italian Journal of Agronomy	65	[56]
Boregowda, N.	2022	"Recent advances in nanoremediation: Carving sustainable solution to clean-up polluted agriculture soils"	Environmental Pollution	63	[57]
Yin, X.	2019	"Co-transport of graphene oxide and heavy metal ions in surface-modified porous media"	Chemosphere	63	[41]
Bossa, N.	2017	"Cellulose nanocrystal zero-valent iron nanocomposites for groundwater remediation"	Environmental Science: Nano	62	[58]
Hao, R.	2021	"Green synthesis of iron nanoparticles using green tea and its removal of hexavalent chromium"	Nanomaterials	60	[39]

A significant publication in the field of nanomaterials for soil and groundwater remediation is the 2016 study by Stefaniuk, M., titled "Review on nano zerovalent iron (nZVI): From synthesis to environmental applications", published in the "Chemical Engineering Journal". This impactful paper has garnered 805 citations. This review focuses on nZVI, a widely utilized nanoparticle known for its effectiveness in removing contaminants in environmental remediation. While it discusses various nanoparticles, including zeolites and metal oxides, nZVI is highlighted for its cost efficiency and superior performance. Stefaniuk outlines both traditional and innovative methods for synthesizing nZVI, such as chemical reduction and green synthesis. These advancements are crucial for enhancing the application of nZVI in various environmental contexts. The review also addresses the complexities involved in modifying nZVI to enhance its stability and reactivity [35].

The 2016 study by Tijani, J.O., titled "Pharmaceuticals, endocrine disruptors, personal care products, nanomaterials and perfluorinated pollutants: a review", published in "Environmental Chemistry Letters", is a highly cited work with 396 citations. This review examines the environmental risks posed by emerging micropollutants, including pharmaceuticals, endocrine disruptors, and perfluorinated substances. The paper highlights how these micropollutants enter the environment through human activities, being detected in surface water, groundwater, and drinking water at concentrations ranging from nanograms to micrograms per liter. The study emphasizes the need for increased public awareness and strong governmental policies to tackle these pollutants. It advocates for proactive measures, such as improved wastewater treatment technologies and enhanced monitoring efforts [30].

In a related vein, Yan et al. (2013) [36] delve into the chemistry and reactivity of nZVI, discussing methods to improve its stability and transport in porous media. Their work highlights the engineering challenges that need to be addressed to enhance the practical application of nZVI for environmental cleanup [43]. This exploration of nZVI's capabilities is vital for developing effective remediation strategies [36]. Bae et al. (2017) [37] further contribute to this discourse by exploring issues related to nZVI, particularly surface passivation and its detrimental effects on reactivity. Oxidation processes can lead to the formation of various iron-bearing phases, which ultimately compromise the material's effectiveness in degrading contaminants. Bae explores the factors influencing this corrosion process, including the composition of nZVI, the types of aqueous species, reaction time, and environmental conditions. Interestingly, the presence of different iron oxidation states on nZVI surfaces may create unique reactive microenvironments that facilitate the adsorption and transformation of pollutants. The review aims to clarify the nature of passivation processes and byproducts formed in various environments, employing advanced techniques like electron microscopy and X-ray spectroscopy for identification. Additionally, it delves into the mechanisms of species in both oxic and anoxic conditions and examines how synthesis methods, along with the presence of inorganic and organic materials, affect passivation byproducts. Furthermore, Bae discusses potential depassivation strategies to enhance nZVI's reactivity, thereby improving its effectiveness in contaminant degradation [37].

Garner et al. (2014) [43] offer a broader perspective on the environmental risks associated with engineered nanomaterials (ENMs). Their review synthesizes findings on the fate and transport of ENMs in various ecosystems, emphasizing the need for standardized toxicological data to assess risks effectively. In aquatic environments, ENMs demonstrate greater stability in freshwater and stormwater compared to seawater, suggesting a higher potential for transport in these settings. The behavior of ENMs in soil is influenced by factors such as aggregate size and soil chemistry, with certain materials like silver and nZVI raising toxicity concerns for aquatic organisms. Garner notes that while the overall risk from most ENMs appears low at current environmental concentrations, direct applications or accidental releases may have significant localized effects. This foundational understanding is critical for ensuring the safe application of nanomaterials in environmental contexts [43].

In the 2017 study titled "Iron oxide and its modified forms as an adsorbent for arsenic removal: A comprehensive recent advancement", Siddiqui, S.I. addresses the critical issue of arsenic contamination, which poses severe health risks globally. Arsenic, found in dissolved forms in groundwater, has led to widespread health crises. The study highlights that arsenic exists in water as oxyacids in two oxidation states: As(III) and As(V), with As(III) being the more toxic form. While various techniques are employed for arsenic removal, many are ineffective against As(III). Among these, adsorption has emerged as the preferred method for removing both forms of arsenic, with nanomaterials demonstrating superior efficacy. However, some nanomaterials present challenges, including toxicity, difficulty in separating post-adsorption, and inefficacy under water constraints. Siddiqui emphasizes the advantages of iron oxides and their modified forms as adsorbents, which address these challenges effectively [38].

Sarma et al. (2019) further explore the effectiveness of various nanomaterials in adsorbing heavy metals, detailing various types of nanomaterials such as clay-nanocomposites, metal oxides, carbon nanotubes, and polymeric nanocomposites, and their applicability for removing a range of heavy metals such as arsenic, cadmium, cobalt, chromium, copper, mercury, manganese, nickel, lead, tin, uranium, vanadium, and zinc from water [46]. This research contributes to the growing body of literature demonstrating the utility of nanomaterials in environmental remediation [46]. Mohmood et al. (2013) [47] discuss the applications of nanoscale materials in water purification, emphasizing their advantages and potential toxicity. Their study raises critical concerns regarding the safe application of engineered nanomaterials in water treatment [47].

Hussain et al. [2] extends this discussion in "In-situ, Ex-situ, and nano-remediation strategies to treat polluted soil, water, and air". The review discusses the role of nanostructured materials, such as titanium dioxide (TiO_2), dendrimers, iron-based nanoparticles, silica, carbon nanomaterials, graphene, nanotubes, and polymers, in mitigating environmental hazards. Hussain explores the roles of various nanostructured materials in innovative remediation methodologies, including in situ techniques like bioventing, bioslurping, biosparging, phytoremediation, and permeable reactive barriers, as well as ex situ methods such as biopiles, windows, bioreactors, and land farming. The study emphasizes the adaptability of nanoparticles for effective pollutant treatment, underscoring their small size and high surface area-to-volume ratio as critical advantages in various remediation contexts. The review highlights how the choice of nanomaterials and remediation methods depends on the specific properties of the contaminants and the characteristics of the pollution site [2].

Galdames investigates the effectiveness of ZVI as a remediation agent for environmental contaminants. The study highlights the advantages of nZVI, particularly its high specific surface area, enhancing reactivity and efficiency in remediation processes. Galdames discusses the gap between laboratory findings and field applications. The review summarizes various nZVI systems and their remediation capacities. To address these challenges, the development of stabilized nZVI—particularly polymer-coated nZVI—has been proposed. These coatings improve the colloidal properties and mobility of the nanoparticles, making them more versatile for use in different contaminated sites. Among the coatings discussed, carboxymethyl cellulose (CMC) is highlighted for its excellent mobility and biodegradability, making it an environmentally friendly option. The study suggests that using biodegradable and natural polymer coatings can enhance the performance of nZVI while ensuring minimal environmental impact [17].

In the 2024 study titled "Fluoride contamination in groundwater: A global review of the status, processes, challenges, and remedial measures", Shaji, E. explores the critical issue of fluoride pollution in groundwater, emphasizing its toxic effects on human health. The primary sources of fluoride in drinking water are geogenic, along with contributions from agricultural products, dental products, and over-fluoridated water. Despite the existence of efficient fluoride removal techniques, including filters utilizing next-generation nanomaterials, no single method has emerged as a robust solution for practical fluoride removal from drinking water. The review advocates for the development of advanced filtration systems that can selectively remove harmful fluoride while retaining essential minerals [48].

Song et al. (2019) [49] examined the role of nanomaterials in phytoremediation, noting their potential to enhance plant growth and increase the uptake of pollutants. The review highlights the role of nanotechnology in enhancing the efficiency of phytoremediation. Nanomaterials can contribute to phytoremediation in several ways: they can directly remove contaminants, promote plant growth, and enhance the phytoavailability of pollutants. Among the various strategies for phytoremediation, phyto extraction is noted as the most effective, allowing plants to absorb and concentrate contaminants from the soil. The study focuses on nZVI. Additionally, fullerene nanoparticles are mentioned for their ability to increase the availability of pollutants to plants. While the use of nanomaterials in phytoremediation shows promise, the review notes that this approach is still in its exploratory phase [49].

In the 2019 study, Zhang, T. outline the complexities of using nanotechnology for in situ remediation, discussing significant challenges related to the mixing and transport of nanomaterials in subsurface environments. Zhang discusses various nanomaterials that could enhance remediation efforts, including multifunctional nanocomposites that enable synergistic contaminant sequestration and degradation, selective adsorbents, catalysts, and nano-tracers for delineating subsurface contaminants. Additionally, stimuli-responsive nanomaterials can facilitate the slow release of reagents, improving remediation effectiveness. However, the study notes significant challenges related to the mixing and transport of nanomaterials in subsurface environments, particularly in laminar flow conditions. Enhancements in mixing techniques are needed to overcome these transport limitations, as well as strategies to generate reactive nanomaterials in situ for treating contamination, especially in low hydraulic conductivity zones [44].

Babaee et al. (2018) [50] investigate the effectiveness of iron/copper nanoparticles in removing arsenic from water, demonstrating their significant potential for practical applications in arsenic remediation. The study focused on the application of these nanoparticles in treating synthetic arsenic-laden solutions. The Fe/Cu nanoparticles demonstrated significant effectiveness in arsenic removal, achieving maximum sorption capacities of 19.68 mg/g for As(III) and 21.32 mg/g for As(V) at a pH of 7. The adsorption data fit well with the Langmuir isotherm model, indicating that adsorption occurs on a surface with a finite number of identical sites. The kinetics of sorption followed pseudo-second-order kinetics, suggesting that the rate of adsorption is influenced by the availability of active sites. Furthermore, the presence of coexisting carbonate, sulfate, and phosphate ions did not significantly affect the arsenic removal efficiency at the concentrations tested. The study found that removal efficiency was enhanced in acidic environments, while arsenic desorption could occur under basic conditions. This study contributes to the growing recognition of bimetallic nanoparticles in environmental cleanup efforts [50].

In "Recent Advances of Nanoremediation Technologies for Soil and Groundwater Remediation", Alazaiza explores the significant role of nanotechnology in addressing contamination. The review discusses various types of nanomaterials, including nZVI, carbon nanotubes (CNTs), and metallic and magnetic nanoparticles (MNPs), highlighting their applications in environmental cleanup. The use of metal and MNPs is advantageous due to their ease of magnetic separation and effective metal-ion adsorption capabilities. Additionally, the review addresses the environmental risks associated with the application of nanomaterials in soil remediation. It emphasizes that modified nZVI can exhibit reduced toxicity towards soil bacteria compared to unmodified versions, suggesting that coating or modifying these nanoparticles may mitigate their ecological impacts. The combination of nanoremediation with other remediation technologies is presented as a promising approach, as it can enhance the sustainability and effectiveness of the cleanup process [8].

Thomé et al. (2015) [51] examined the nascent field of soil remediation in Brazil. The review provides a bibliographic overview of nanotechnology applications in remediation efforts, assessing the potential for further research in Brazil. It begins by comparing the number of identified contaminated sites in the USA and Europe, setting the context for Brazil's challenges. The paper explains fundamental concepts related to nanomaterials, including their classification, synthesis, and characterization, along with the types of contaminants that have been effectively addressed using this technology. Thomé discusses the chemical interactions between contaminants and nanoparticles, as well as the challenges associated with the delivery and migration of NPs in porous media [51].

In the 2011 study by Al-Salim, the author investigates the environmental risk assessment of nanomaterials, specifically focusing on quantum dots (QDs). The study highlights the necessity of understanding both the toxicity of these nanomaterials to non-target organisms and their potential exposure pathways. The research examines the transport and fate of QDs, which are nanoparticles with an average size of 6.5 nm, across various environmental compartments. The study utilized breakthrough curves from experiments involving CdTe/mercaptopropionic acid QDs applied to soil columns from an organic apple orchard. The results indicated that preferential flow occurred through the soil's macropores, but only 60% of the QDs were recovered in the effluent after several pore volumes. This suggests that approximately 40% of the QDs were filtered and retained by the soil, possibly through unknown exchange, adsorption, or sequestration mechanisms. Additionally, the study explored the uptake of QDs by plants, specifically ryegrass, onion, and chrysanthemum [45].

In the 2019 review by Taghipour, the author discusses the rapid advancements in nanotechnology, which have led to the development of engineered nanomaterials (NMs) that offer innovative solutions for contaminant removal in water treatment. The review categorizes various nanomaterials and examines their properties and pollutant removal mechanisms. A novel categorization of these materials is presented, including carbonaceous nanostructures, nanoparticles, and nanocomposites. Among the various NMs, graphene and its derivatives, such as graphene oxide and reduced graphene oxide, were highlighted for their excellent environmental compatibility, large surface area, and high purity. These characteristics contribute to their remarkable adsorption capacity by trapping electrons and preventing their recombination. Metal oxides, known for their unique electronic structure and high porosity, are primarily utilized as catalysts in photocatalytic reactions due to their stability and efficient light absorption. The review also discusses the discovery of oxyacids, which have shown higher photoactivity and surface areas than traditional metal oxides, often at a lower cost. This has led to the development of binary or ternary composites combining metals, metal oxides, and oxy-acids, enhancing the surface area and reducing the band gap for improved contaminant cleanup [29].

In the 2014 study by Rathnayake, the author emphasizes the importance of understanding the ecological and human health risks associated with zinc oxide manufactured nanomaterials (ZnO MNMs) released into the environment. The study investigates the transformation of 30 nm ZnO MNMs in the presence of varying concentrations of phosphate, examining the effects of time and pH using multiple analytical techniques. The composition of phosphorus species was found to be pH dependent. At pH 6, 82% of the phosphorus was present as hopeite-like phosphate, while this proportion dropped to only 15% at pH 8. These results underscore the influence of environmental variables, particularly pH, on the reactions between ZnO MNMs and phosphate, suggesting that such interactions can lead to structurally and morphologically heterogeneous end products [52].

In the 2022 review by Raza titled "Recent Advances in Carbonaceous Sustainable Nanomaterials for Wastewater Treatments", the review focuses on various carbonaceous nanomaterials, such as activated carbon, multi-walled and single-walled carbon nanotubes, and carbon quantum dots, emphasizing their roles as effective adsorbents in wastewater treatment and purification. It also discusses the significant contributions of graphene (GR) and graphene oxide (GO) derivatives, along with other carbon-based nanomaterials like graphitic carbon nitrides and carbon sponges/aerogels. These materials have shown promise in addressing wastewater treatment and remediation. The review encompasses various developed technologies and methodologies, as well as surface modifications of carbonaceous nanomaterials aimed at pollutant removal, including ionic metals in aqueous environments [54].

In the 2017 review by Gomes, the author discusses the growing concern surrounding emerging contaminants, which include pesticides and their metabolites, pharmaceuticals, personal care products, lifestyle compounds, food additives, industrial products, and nanomaterials. The review highlights the limited data available on the toxicity and potential bioaccumulation of these contaminants in soil biota. When data do exist, they often pertain only to select representatives of major chemical groups and a restricted number of species, typically following non-standard testing protocols. This scarcity of information complicates the assessment of predicted no effect concentrations (PNEC) and hinders the establishment of regulatory limits for their environmental release [55].

In the 2021 review by Marcon, this review focuses on recent advancements in the application of engineered NPs for in situ remediation of soil and groundwater. Key areas of emphasis include the successful applications of nanomaterials for environmental cleanup, the potential safety implications arising from the need for high reactivity toward pollutants while maintaining low reactivity toward biota, and the challenges faced in transport and evolution within environmental matrices. The review also discusses scientific and regulatory challenges associated with the use of nanomaterials. Promising nanomaterials highlighted in the review include nanoscale zero-valent iron, nano-oxides, and carbonaceous materials [9].

In the 2022 review by Dutta, the author discusses the increasing global challenge of providing safe drinking water and clean water. Despite ongoing critical issues, the implementation of ecologically sustainable nanomaterials (NMs) with unique characteristics—such as high efficiency, selectivity, earth abundance, renewability, low-cost manufacturing, and stability—has become a priority. The review highlights the promise of carbon nanoparticles (NPs) in energy and environmental sectors. The review focuses on research surrounding these carbon-based NPs, particularly in their application for water treatment and purification, especially concerning industrial and pharmaceutical waste. Enhanced carbonaceous NMs, novel nano-sorbents, and methods for treating wastewater, drinking water, and groundwater, as well as removing ionic metals from aqueous environments, are examined. The review also discusses the latest advancements and challenges related to environmentally friendly carbon and graphene quantum dot NMs. It emphasizes the urgent need for organic compounds and heavy hydrocarbons to meet the growing demand for carbon-based nanostructures in emerging fields such as sensors, biomedicine, supercapacitors, and gas storage. Carbon-based NPs may offer advantages over other types of NPs regarding infrastructure, resource use, and safety concerns. The review suggests that using carbon nanotubes (CNTs), carbon quantum dots (CQDs), graphene quantum dots (GQDs), and graphene-based NPs could be more effective than traditional treatment methods [40].

In the 2018 study by Rahmatpour, the author investigates the potential contamination of groundwater and soils by manufactured nanomaterials, specifically focusing on silver nanoparticles (AgNPs). The study examines the transport and retention of polyvinylpyrrolidone (PVP) stabilized AgNPs (with a diameter of 40 nm) under both saturated and unsaturated conditions in intact columns of two types of calcareous soils: sandy loam (TR) and loam (ZR). To provide a comparison, similar experiments were conducted using quartz sand as a reference medium. A pulse of AgNP suspension with an initial concentration (C0) of 50 mg/L was injected into the columns for three pore volumes, while the transport of bromide (Br) as a non-reactive inert tracer was also monitored. The results indicated high mobility of AgNPs through the sand columns due to unfavorable conditions for nanoparticle deposition on the quartz surfaces. In contrast, nearly all AgNPs introduced into the columns of both calcareous soils were retained, with less than 1% of the total injected mass leaching out. The retention profiles were hyperexponential, with maximum concentrations of 100–130 mg/kg occurring near the inlet of the columns. Notably, the ZR soil exhibited slightly stronger retention and higher maximum concentrations of AgNPs compared to the TR soil, likely due to its smaller grain size [42].

In the 2013 paper by Mura titled "Advanced of Nanotechnology in Agro-Environmental Studies". The paper reviews recent applications of nanotechnology in agro-environmental studies, focusing on the fate of nanomaterials in water and soil, their advantages, and potential toxicological effects. The findings suggest that nanomaterials can enhance environmental quality and aid in the detection and remediation of pollution. However, only a limited number of these materials have shown potential toxic effects, which are explored in detail. The intelligent use of nanotechnology can enhance environmental quality, contribute to the development of detection techniques for biological and chemical toxins, remediate contaminants, and foster green industrial processes that minimize energy consumption. Mura notes that while some nanomaterials pose hazards and potential toxic effects, not all exhibit toxicity. For instance, certain materials like carbon black and titanium dioxide (TiO_2) have been used for an extended period and demonstrate low toxicity [56].

Boregowda et al. (2022) [57] emphasized the ecological harms associated with excessive use of chemical fertilizers and pesticides. The review emphasizes the potential of engineered nanomaterials as effective solutions for the remediation of contaminated soils. Nanomaterial-enabled technologies can help prevent the uncontrolled release of harmful substances into the environment and are equipped to address soil and groundwater pollutants. Boregowda discusses recent advancements in agricultural nanobiotechnology and the tools developed to tackle soil pollution [57].

In the 2019 study by Yin, the author explores the transport of heavy metal ions in porous media with varying surface characteristics. The research focuses on the effects of graphene oxide (GO) on the co-transport and remobilization of lead (Pb^{2+}) and cadmium (Cd^{2+}) in different coated sand media, including humic acid (HA), smectite, kaolinite, and ferrihydrite. Laboratory packed-column experiments were conducted to evaluate these interactions. Scanning electron microscopy and energy dispersive X-ray analysis revealed significant differences in the surface morphology of the coated sands, with approximately 56.7% to 89.9% of the surface covered by the coatings. The major elemental components identified were carbon (C), oxygen (O), silicon (Si), aluminum (Al), and iron (Fe). The findings indicated that GO exhibited high mobility in HA, kaolinite, and smectite-coated sand but showed considerable retention in ferrihydrite-coated sand. Interestingly, while GO reduced the transport of Pb^{2+} and Cd^{2+}, the presence of these metal ions also decreased the mobility of GO within the coated sand columns. Elution experiments demonstrated that GO facilitated the remobilization and release of previously adsorbed Pb^{2+} and Cd^{2+} from the coated sand. However, it was noted that GO could not release these metal ions from smectite-coated sand columns, likely due to smectite's stronger adsorption affinity for heavy metals compared to GO [41].

Bossa et al. (2017) [58] examines the use of nZVI for the in-situ remediation of groundwater and other environmental matrices. The study focuses on a novel approach where nZVI are stabilized on cellulose nanocrystal (CNC) supports, which enhances their contact with contaminants, reduces the electron transfer path to the target, and increases reactivity. The researchers synthesized CNC-nano-ZVI composites with a weight ratio of Fe/CNC = 1, utilizing a classic sodium borohydride synthesis method. The final nanocomposites were characterized, and their reactivity was assessed through methyl orange (MO) dye degradation tests. Flow-through transport column experiments were conducted to evaluate the mobility of the CNC-nano-ZVIs in porous media (sand/glass bead). The results indicated that the synthesized CNC-nano-ZVI formed a stable colloidal suspension and demonstrated high mobility in the porous media, with an attachment efficiency (α) value of less than 0.23. Notably, the reactivity of the CNC-nano-ZVIs towards MO increased by up to 25% compared to bare ZVI. The findings suggest that using CNC as a delivery vehicle significantly enhances the capability and applicability of nZVI for in situ groundwater remediation [58].

Hao et al. (2021) [39] explore a green synthesis method for iron nanoparticles using green tea extract, achieving high removal efficiency for hexavalent chromium (Cr(VI)). The research investigates the effects of various synthetic conditions on the remediation performance of the resulting nFe. The study revealed that the nFe particles had a core–shell structure, consisting of a core made of ZVI and a shell composed of iron oxide. A proposed mechanism for the synthesis of nFe using green tea extract was presented, highlighting how biomolecules in the extract acted as reducing and capping agents. These biomolecules, such as 1,2,3-benzenetriol, caffeine, and bis (2-ethylhexyl) phthalate, facilitated the reduction of Fe^{2+} to ZVI and helped stabilize the nFe surface, preventing oxidation and enhancing atmospheric stability. The results demonstrated that the green tea extract effectively enabled the synthesis of nFe with a removal efficiency of 91.6% for Cr(VI) in aqueous solutions. This optimized synthesis approach allows for the practical application of nFe in water treatment, potentially offering advantages over existing methods [39].

2.6. Comprehensive Comparison of Nanomaterials for Soil and Groundwater Remediation

Nanomaterials offer innovative solutions for addressing soil and groundwater contamination due to their unique properties, such as high surface area and enhanced reactivity. However, their implementation necessitates careful consideration of synthesis methods, ecological impacts, and sustained performance.

This overview synthesizes current knowledge regarding various types of nanomaterials and their applications in soil and groundwater remediation, highlighting their efficiencies, advantages, and potential drawbacks. The integration of nanomaterials into traditional remediation methods, such as phytoremediation, adsorption, and photocatalysis, can enhance the overall effectiveness of these approaches, making them more viable for addressing contemporary environmental concerns. However, while the potential benefits of nanomaterials are substantial, there are significant challenges to consider, including their environmental fate, potential toxicity to non-target organisms, and the need for standardized methodologies for evaluation. Table 7 summarizes various types of nanomaterials discussed in previous studies, highlighting their compositions, primary applications, efficiency metrics, advantages, and disadvantages.

Table 7. Comprehensive comparison of nanomaterials for soil and groundwater remediation.

Nanomaterial Type	Composition and Properties	Primary Applications	Efficiency Metrics	Advantages	Disadvantages	Ref.
nZVI	Iron nanoparticles with zero-valent iron core	Reductive dechlorination of organic contaminants, heavy metal immobilization	High reactivity; effective in reducing contaminants in groundwater.	High reactivity, cost-effectiveness, adaptability for various contaminants.	Surface passivation can limit effectiveness; potential for aggregation and toxicity to some organisms.	[39,59,60]
Carbon Nanotubes (CNTs)	Cylindrical molecules of carbon atoms; available in single-walled and multi-walled forms.	Adsorption of organic and inorganic pollutants, including heavy metals and dyes.	High adsorption capacity; effective in removing organic and inorganic pollutants.	High adsorption capacity, versatile surface modification, and strong interaction with pollutants.	High production costs; potential toxicity; difficulty in dispersion and separation after use.	[61,62]
Metal Oxides (e.g., ZnO, TiO_2, Fe_2O_3, Fe_3O_4)	Nanoparticles of metal oxides known for their photocatalytic properties.	Adsorption of heavy metals, arsenic removal, and photocatalysis for organic contaminants.	Effective photocatalytic degradation of organic contaminants; high removal efficiency for heavy metals.	High stability, potential for magnetic separation, and effectiveness in photocatalytic degradation.	Potential toxicity; pH sensitivity can affect performance; may require specific conditions for optimal effectiveness.	[63,64]

Table 7. *Cont.*

Nanomaterial Type	Composition and Properties	Primary Applications	Efficiency Metrics	Advantages	Disadvantages	Ref.
Graphene and Graphene Oxide (GO)	Two-dimensional sheets of carbon atoms with high surface area and functional groups	Adsorption of heavy metals, organic pollutants, dyes, and as a support for other nanomaterials.	Excellent contaminant adsorption; potential for dual-functionality in remediation.	Excellent adsorption capacity, environmental compatibility, and potential for enhancing the efficiency of other remediation processes.	High production costs; potential for aggregation; challenging to separate after use.	[65,66]
Bimetallic Nanoparticles (BNPs)	Combinations of two different metals to enhance reactivity and stability.	Arsenic removal, degradation of chlorinated organic compounds, and heavy metal remediation.	Enhanced reactivity for specific contaminants; effective in heavy metal removal.	Enhanced reactivity through synergistic effects; improved performance compared to single-metal nanoparticles.	Complex synthesis processes; potential toxicity and environmental risks.	[67]
Quantum Dots (QDs)	Semiconductor nanocrystals with unique optical properties.	Environmental sensing, contaminant detection, and photocatalysis in various remediation settings.	High sensitivity for detection applications; potential for efficient removal of pollutants.	High sensitivity and tunability make them suitable for detecting low concentrations of pollutants; potential for dual-functionality in remediation.	Potential toxicity due to heavy metal components; environmental impact requires careful assessment.	[68]
Bio-based Nanomaterials	Derived from biological sources (e.g., chitosan, biochar), offering sustainable alternatives.	Heavy metal adsorption, organic contaminant removal, and enhancement of phytoremediation processes.	Effective in organic contaminant removal; potential for sustainable application.	Eco-friendly, biodegradable, low toxicity, and cost-effective.	Generally lower adsorption capacity compared to synthetic nanomaterials; may require modifications for enhanced performance.	[68]
Zeolite-ZnO Nanocomposite	Zeolite combined with zinc oxide nanoparticles, prepared via co-precipitation.	Nitrate removal from groundwater.	High removal efficiency (92%) for nitrates; effective in various water quality applications.	High removal efficiency for nitrates with optimal conditions; effective adsorption properties.	May require specific conditions for optimal performance; adsorption capacity can vary.	[63]
Calcium Peroxide	Advanced nanomaterial for simultaneous removal of organic micropollutants and inorganic heavy metals.	Oxidation of organic micropollutants and precipitation of heavy metals.	High efficiency in removing both organic and inorganic contaminants.	High efficiency in removing both organic and inorganic contaminants; minimal interference from common ions.	Requires optimization of dosage and pH; may have variable effectiveness based on environmental conditions.	[69]
Ethylenediamine Complex	Complexes formed with metals to enhance their properties and stability.	Arsenic immobilization, catalysis.	Significant reduction of arsenic contamination; effective stabilization in soils.	Enhances the reactivity of metal nanoparticles; potential for effective remediation.	Synthesis complexity; potential toxicity must be assessed in environmental contexts.	[68]
Titanium Nanopores	Titanium nanoparticles with modified surface characteristics through calcination.	Enhanced electrochemical reduction in nitrates in groundwater.	High catalytic activity leading to up to 95.1% nitrate removal; effective in real groundwater applications.	High catalytic activity leading to substantial nitrate removal; potential for wide application in real groundwater conditions.	Production of nanoparticles requires careful control of synthesis parameters; performance can vary based on environmental factors.	[70,71]
Carbon Nanostructure Biosensors	Carbon-based nanomaterials used in electrochemical biosensors for environmental monitoring.	Real-time monitoring of heavy metals, pesticides, and other pollutants in various environmental samples.	High sensitivity and rapid response for real-time monitoring of pollutants.	High sensitivity, rapid response, potential for on-site analysis; can reduce the use of harsh chemicals.	Development and calibration can be complex; may require specific conditions for optimal performance.	[72]
Nanoclays	Nanoclays with high surface area and tunable surface chemistry.	Adsorption of pesticides in water for remediation.	Effective in removing pesticides; environmentally friendly and recyclable.	Environmentally friendly, recyclable, effective in removing pesticide contaminants.	Limited availability and potential variations in efficacy based on pesticide type and concentration.	[73]
ZnO-based Nanomaterials	Use of zinc oxide nanoparticles for photocatalytic degradation of environmental pollutants.	Treatment of dyes and agricultural pollutants.	Effective in degrading a wide range of contaminants; utilizes visible light for photocatalysis.	Requires optimization for specific pollutants and environmental conditions; potential environmental impacts of ZnO need assessing.	Not available	[74]
Mercury Remediation Nanomaterials	Various nanomaterials designed to remove mercury from contaminated water.	Treatment of mercury-contaminated water.	High removal efficiency (up to 99.98%); addresses significant environmental health issues.	Effective for addressing a critical pollutant; high removal efficiency	Complex interactions in groundwater may affect remediation; ongoing monitoring required.	[75]
Selenium Removal Nanomaterials	Composite materials combining biochar and iron sulfide nanoparticles for selenium remediation.	Treatment of selenium-contaminated wastewater.	Effective removal at low concentrations; utilizes low-cost materials.	Utilizes sustainable materials; effective in a range of conditions.	Performance can be influenced by competing ions; requires further optimization.	[76]

Table 7. *Cont.*

Nanomaterial Type	Composition and Properties	Primary Applications	Efficiency Metrics	Advantages	Disadvantages	Ref.
Organic Micropollutants Nanomaterials	Addressing the contamination of urban soils with various emerging pollutants.	Understanding sources, effects, and remediation strategies for micropollutants.	Comprehensive overview of environmental impacts; informs policy and management strategies.	Requires extensive monitoring and regulation to mitigate risks.	Requires thorough investigation for effective management.	[77]
Fluoride Remediation Nanomaterials	Use of phytoremediation and nanomaterials for fluoride contamination in soil and water.	Enhancing phytoremediation systems with nanomaterials.	Eco-friendly and efficient method; promotes plant growth and pollutant availability.	Sustainable approach; potential for long-term solutions.	Knowledge gaps in assessing long-term impacts; requires more research.	[48]
Pesticide Removal Nanomaterials	Nanomaterials used for the degradation and removal of pesticide residues from water.	Mitigation of pesticide contamination in agricultural runoff.	Effective in achieving mineralization of organic pollutants; can be combined with other techniques for enhanced efficacy.	Environmental concerns regarding the use of nanomaterials must be addressed.	Potential toxicological effects on non-target organisms.	[78]
MXenes	Two-dimensional transition metal carbides and nitrides with high surface area and tunable surface chemistry.	Water purification and environmental remediation.	NA	Excellent properties for contaminant removal; versatile in applications-impacts of MXenes.	Scalability and cost-effectiveness of production; potential environmental impacts.	[79]
Graphite Nanomaterials	Graphene and its derivatives used to reduce nitrate leaching in agricultural soils.	Nitrate contamination suppression in groundwater.		Reduces nitrate leaching by enhancing nitrogen retention; potential for improved fertilizer efficiency.	Effects vary with environmental conditions; requires further investigation for optimal applications.	[80]

The comprehensive comparison of nanomaterials for soil and groundwater remediation presented in Table 7 highlights the diverse applications and effectiveness of various nanomaterials in addressing environmental contamination. Each nanomaterial type, such as nZVI, CNTs, and metal oxides, showcases unique properties that contribute to their remediation capabilities. For instance, nZVI is noted for its high reactivity and cost-effectiveness, making it suitable for reducing organic contaminants and immobilizing heavy metals [39,59,60]. However, it faces challenges like surface passivation and potential toxicity to aquatic organisms.

On the other hand, CNTs exhibit a high adsorption capacity for pollutants but come with drawbacks such as high production costs and dispersion difficulties [61,62]. Notably, bio-based nanomaterials present a sustainable alternative, offering low toxicity and biodegradability, albeit generally lower adsorption capacities [68].

Overall, while these nanomaterials demonstrate significant potential for effective remediation, they also pose environmental risks and challenges that require careful consideration and further research to optimize their use in real-world applications.

2.7. Primary Research Topics of the Nanomaterials in Soil and Groundwater Remediation

These studies illustrate a multifaceted approach to addressing environmental contamination through nanomaterials. Key themes highlight the effectiveness of nZVI, the importance of addressing emerging pollutants, and the potential for combining various remediation strategies. The studies emphasize the significance of in situ versus ex situ methodologies, with many authors advocating advanced treatment technologies that utilize nanomaterials to enhance traditional methods. The exploration of diverse synthesis methods, including green synthesis, demonstrates a commitment to minimizing environmental impact while maximizing effectiveness. Additionally, understanding the transport mechanisms and retention behaviors of nanomaterials is crucial for optimizing remediation strategies. Overall, the integration of nanotechnology into environmental remediation presents promising solutions for various contaminants, but ongoing research is essential to address potential risks and ensure ecological safety.

Figure 7 illustrates the network relationships among various keywords employed by researchers in the field of nanomaterials for soil and groundwater remediation. Notably, the terms "groundwater", "groundwater pollution", "nanoparticles", "nanomaterial", "remediation", "adsorption", and "soil pollution" are situated at the center of the network, highlighting their fundamental significance in the discourse. Surrounding these central keywords, clusters of related terms emerge, representing subfields within the broader domain of nanomaterials in soil and groundwater remediation research.

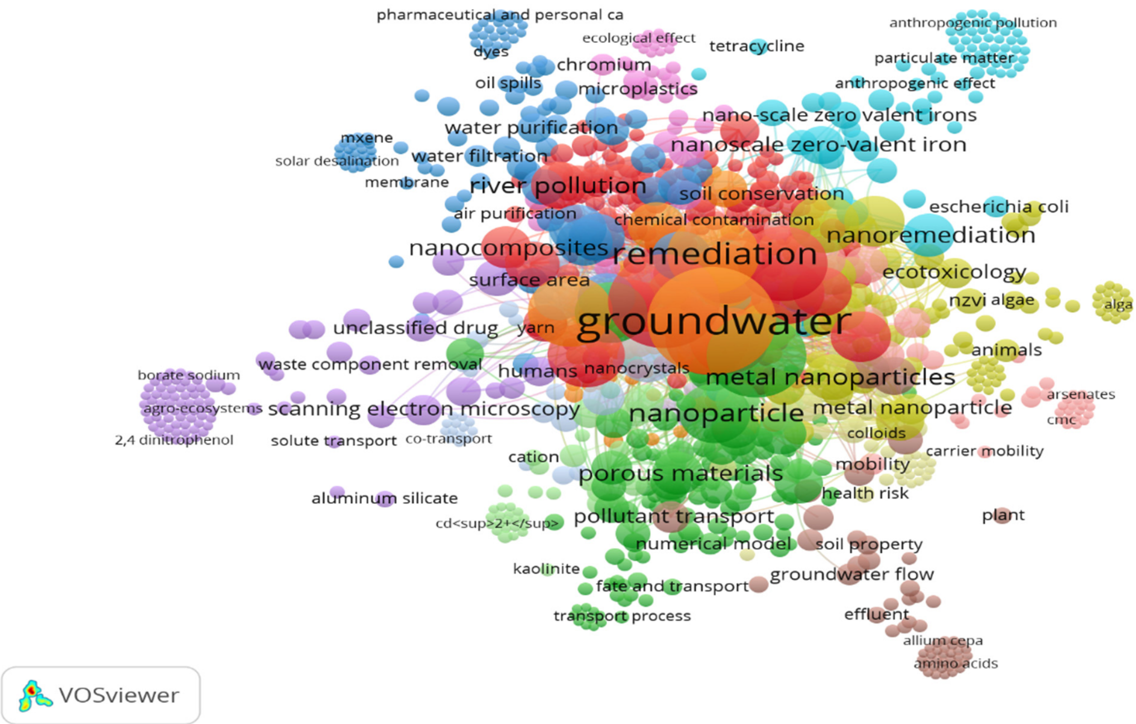

Figure 7. All keywords network visualization with author keyword co-occurrence clustering.

Figure 8 highlights the expanding research landscape on nanomaterials for soil and groundwater remediation, reflecting a growing awareness of water and soil pollution issues. Key terms such as "groundwater", "groundwater pollution", "remediation", "nanoparticles", and "nanomaterials" indicate a strong focus on groundwater quality and treatment technologies. The clustering of related keywords, including "adsorption", "nanostructured materials", and "soil pollution", suggests significant subfields within this research area. Adsorption is recognized as a key mechanism in remediation, while soil pollution directly impacts groundwater health. This complexity in the field is driven by the need for effective solutions to environmental challenges. As research publications increase, we can expect greater funding for initiatives addressing ecological sustainability and technological advancements. Collaborative efforts are likely to lead to interdisciplinary approaches, integrating nanotechnology with traditional remediation methods. Emerging themes like "engineered nanomaterials" and "toxicity" further indicate a shift toward prioritizing safety and sustainability in nanotechnology, emphasizing the balance between innovation and ecological stewardship.

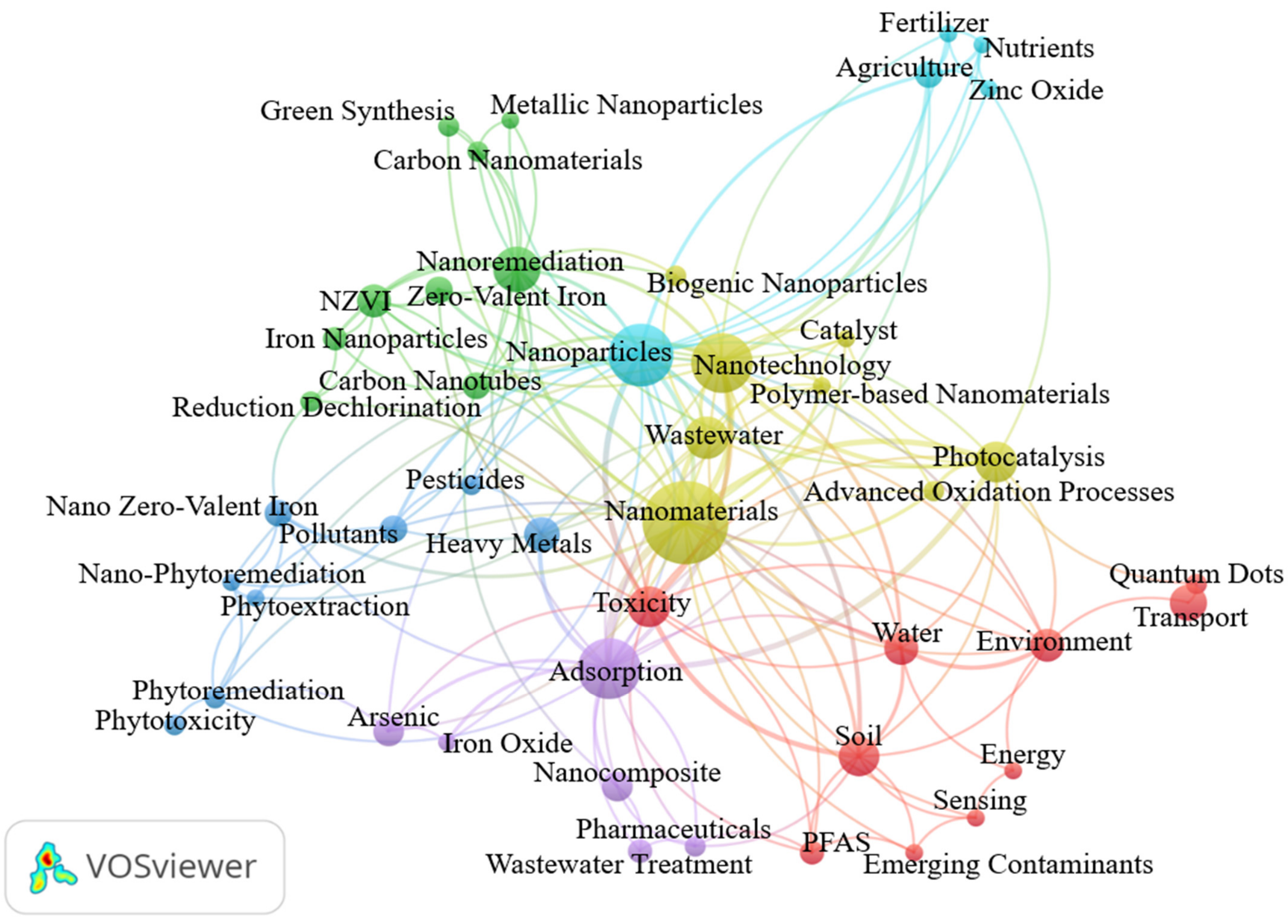

Figure 8. Co-occurrence clustering of author keywords in a network visualization.

Biberci [81] emphasized the importance of co-occurrence analysis in uncovering research topics and assessing the dynamics of research fronts within a particular field. In our investigation, we examined data from Scopus, applying a minimum occurrence threshold of 2 for keywords. This methodology enabled us to extract 46 keyword strings from a total of 825 author keywords

Table 8 presents the keywords that met or surpassed a predefined threshold for inclusion in the analysis. Specifically, the analysis focused on keywords provided by authors, rather than indexed keywords. To qualify for this analysis, keywords had to appear at least twice in the literature. The top 46 keywords are ranked in descending order based on their TLS. This ranking was determined through a comprehensive scientific analysis that considered factors such as cumulative link strength, the number of connections for each keyword, and their frequency of occurrence. By applying these criteria, we ensure that only the most relevant and impactful keywords are included in the study, allowing for a more robust and insightful analysis of the research landscape related to nanomaterials in groundwater and soil remediation.

Table 8. Top 46 keywords from the studies published on nanomaterials research related to groundwater and soil remediation.

Keywords	TLS	Cluster	Occurrences
Nanomaterials	88	4	45
Nanotechnology	73	4	24
Adsorption	59	5	25

Table 8. *Cont.*

Keywords	TLS	Cluster	Occurrences
Nanoparticles	58	6	26
Nanoremediation	41	2	14
Photocatalysis	33	4	11
Toxicity	27	1	11
Wastewater	25	4	12
Soil	24	1	10
NZVI	22	2	7
Water	21	1	7
Environment	17	1	7
Agriculture	15	6	5
Heavy Metals	15	3	8
Pollutants	14	3	5
Carbon Nanotubes	13	2	5
Arsenic	12	5	6
Nanocomposite	12	5	6
Zero-Valent Iron	11	2	5
Catalyst	10	4	2
Carbon Nanomaterials	9	2	3
Emerging Contaminants	9	1	4
Iron Nanoparticles	9	2	4
Nano Zero-Valent Iron	9	3	5
Phytoremediation	9	3	3
Polymer-based Nanomaterials	9	4	2
Fertilizer	8	6	2
Pharmaceuticals	8	5	3
Advanced Oxidation Processes	7	4	3
Biogenic Nanoparticles	7	4	3
Green Synthesis	7	2	3
Iron Oxide	7	5	2
Nutrients	7	6	2
PFAS	7	1	2
Reductive Dechlorination	7	2	3
Zinc Oxide	7	6	2
Energy	6	1	2
Metallic Nanoparticles	6	2	2
Nano-Phytoremediation	6	3	2
Phytoextraction	6	3	2
Sensing	6	1	2
Pesticides	5	3	3
Transport	5	1	9
Wastewater Treatment	5	5	4
Phytotoxicity	4	3	3
Quantum Dots	4	1	3

The analysis of the keywords presented in Table 8 reveals important insights into the current research landscape regarding nanomaterials in groundwater and soil remediation. The category of nanomaterials is foundational to the study of remediation techniques. Key terms such as “Nanomaterials”, “Nanotechnology”, and “Nanoparticles” underscore the versatility and potential applications of these materials in environmental cleanup. The prominence of these keywords, particularly “Nanomaterials” and “Nanoparticles”, indicates a growing interest in harnessing nanotechnology to enhance the efficiency of remediation efforts. Furthermore, the inclusion of specific nanomaterials, such as carbon nanotubes and zero-valent iron, highlights the ongoing exploration of tailored nanostructures designed for effective pollutant removal. The analysis reveals that treatment methods such as “Adsorption” and “Photocatalysis” are among the most frequently mentioned strategies for pollution mitigation. The keyword “Adsorption” is particularly significant as it represents a vital mechanism for the removal of contaminants from diverse matrices, including water and soil. This highlights the necessity of understanding the various mechanisms through which contaminants can be effectively managed. Additionally, terms like “Nanoremediation” and “Advanced Oxidation Processes” reflect a diverse range of methodologies employed to address contamination issues, emphasizing the need for innovative approaches in environmental remediation.

The focus on various types of pollutants is evident like “Heavy Metals”, “Arsenic”, and “Emerging Contaminants.” These keywords signify a growing awareness of specific contaminants that pose significant risks to human health and ecosystems. The substantial mention of “Heavy Metals” highlights the critical challenges posed by these pollutants, particularly in terms of their toxicity and persistence in the environment. The emergence of keywords related to “Emerging Contaminants” further underscores the need for targeted remediation strategies to address newer pollutants that may not have been adequately studied in the past. The importance of environmental resources is emphasized by the presence of keywords such as “Water”, “Wastewater”, and “Soil”. These terms highlight the significance of these resources, which are increasingly vulnerable to contamination. The keywords reflect a concentrated effort within the research community to address water-related pollution issues and to develop effective treatment strategies. The inclusion of “Environment” also points to a broader understanding of the interconnectedness of these resources and the need for holistic approaches to remediation.

The keywords associated with agricultural practices, such as “Agriculture”, “Fertilizer”, and “Nutrients”, indicate a growing interest in the role of nanomaterials in enhancing agricultural productivity while addressing soil contamination. The research in this area signifies an important shift towards integrating nanotechnology within agricultural systems, aiming to improve soil fertility and crop resilience. This dual focus on agricultural productivity and environmental health reflects a comprehensive approach to sustainability. The inclusion of keywords related to catalytic processes, such as “Catalyst”, “Iron Oxide”, and “Reductive Dechlorination”, suggests that researchers are increasingly exploring catalytic methods to enhance pollutant degradation. This focus on catalysis indicates a trend towards developing more efficient and effective remediation techniques that leverage the unique properties of nanomaterials.

In this context, Figure 8 provides a network diagram that depicts the co-occurrence of keywords identified in research articles focusing on nanomaterials for soil and groundwater remediation.

In the diagram shown in Figure 8, the nodes symbolize different elements, and their shapes and positions indicate the probability of co-occurrence among these elements. Analyzing the keyword co-occurrence network reveals six distinct clusters, each represented by unique colors, corresponding to various topics within the realm of nanomaterials research related to soil and groundwater remediation. The colored nodes represent these clusters, with each focusing on a specific area within this field. The size of the nodes reflects their frequency of occurrence, while the thickness of the connections between them demonstrates the strength of their relationships.

The first cluster, characterized by the red color, comprises ten keywords: toxicity, soil, water, environment, emerging contaminants, PFAS, energy, sensing, transport, and quantum dots. This cluster reflects a critical concern regarding the adverse effects of pollutants on human health and ecosystems. The emphasis on toxicity indicates a growing recognition of the risks posed by contaminants, particularly heavy metals and emerging pollutants like PFAS. The keywords soil and water highlight the importance of these natural resources, which are increasingly threatened by pollution. In this context, the terms emerging contaminants and quantum dots suggest an evolving focus on newer classes of pollutants that require innovative monitoring and remediation strategies. The presence of keywords like transport and sensing underscores the necessity for advanced methodologies to track and measure the movement and concentration of contaminants in the environment. This cluster indicates that future research should prioritize understanding toxicity pathways and developing real-time monitoring technologies that can enhance environmental health assessments.

The second cluster, represented in green, includes keywords such as nanoremediation, NZVI (nano Zero-Valent Iron), carbon nanotubes, zero-valent iron, carbon nanomaterials, iron nanoparticles, green synthesis, reductive dechlorination, and metallic nanoparticles. This cluster emphasizes the innovative applications of nanotechnology in remediation efforts. The term nanoremediation encapsulates the cutting-edge strategies being developed to tackle pollution. Specific nanomaterials, such as zero-valent iron and carbon nanotubes, are highlighted for their promising capabilities in effectively removing contaminants from water. The mention of green synthesis signifies a trend toward sustainable practices in the production of nanomaterials, reflecting a holistic approach to environmental remediation. Future research could focus on optimizing these materials for enhanced stability and reactivity in various environmental conditions, improving their practical efficacy.

The third cluster, illustrated in blue, features eight keywords: heavy metals, pollutants, nano zero-valent iron, phytoremediation, nano-phytoremediation, phytoextraction, pesticides, and phytotoxicity. This cluster reveals a significant concern regarding heavy metals as environmental pollutants. The integration of terms like phytoremediation and nano-phytoremediation suggests a blend of traditional remediation strategies with modern nanotechnology to enhance effectiveness. Research in this area must explore how nanomaterials can improve crop resilience while addressing soil contamination. It is essential to examine the potential risks associated with nanomaterials in agricultural contexts, ensuring that their application does not compromise soil health or ecosystem dynamics.

The fourth cluster, shown in yellow, includes eight keywords: nanomaterials, nanotechnology, photocatalysis, wastewater, catalyst, polymer-based nanomaterials, advanced oxidation processes, and biogenic nanoparticles. This cluster directly aligns with the principles of catalysis, showcasing the diverse applications of nanotechnology in environmental remediation. The terms photocatalysis and advanced oxidation processes are particularly noteworthy, as they indicate advanced methodologies that leverage the unique properties of nanomaterials for effective pollutant degradation. Photocatalytic processes utilize light-activated catalysts to drive chemical reactions that break down contaminants, offering a promising avenue for treating persistent pollutants. The integration of nanomaterials in these processes can significantly enhance reaction rates and broaden the spectrum of pollutants that can be effectively degraded. Moreover, the role of catalysts in these processes is critical. Catalysts can facilitate reactions without being consumed, allowing for more efficient and sustainable remediation approaches. Future research in this cluster should focus on optimizing the catalytic properties of nanomaterials, exploring their mechanisms in pollutant degradation, and assessing their long-term impacts on environmental systems.

The fifth cluster is characterized by purple and includes six keywords: adsorption, arsenic, nanocomposite, pharmaceuticals, iron oxide, and wastewater treatment. Adsorption emerges as a fundamental mechanism for removing contaminants from water and soil, highlighting its importance in achieving effective remediation. The presence of arsenic emphasizes the need for targeted strategies to address specific pollutants known to pose significant risks to health. This cluster suggests a future focus on optimizing adsorption materials and exploring their application in various treatment scenarios, especially in removing pharmaceuticals and other persistent pollutants from wastewater.

The final cluster, depicted in light blue, comprises five keywords: nanoparticles, agriculture, fertilizer, nutrients, and zinc oxide. The inclusion of agriculture and fertilizer indicates a growing interest in the role of nanomaterials in enhancing agricultural practices. Keywords like nutrients and zinc oxide suggest a focus on how nanomaterials can improve soil fertility and plant growth. Future research in this cluster should aim to explore sustainable agricultural practices that utilize nanotechnology to address both food security and environmental health.

Groundwater sources are often contaminated with heavy metals due to industrial activities, agricultural runoff, and waste disposal. The concept of "Nanoremediation" highlights the use of nanomaterials, particularly nZVI and carbon nanotubes, which have shown promise in effectively removing heavy metals from water through processes like adsorption and chemical reduction.

The transport dynamics of pollutants, particularly heavy metals like arsenic, are crucial for assessing their ecological and health risks. Research in this cluster should focus on the mechanisms of contaminant transport through soil and groundwater systems, exploring factors such as soil composition, moisture content, and microbial activity. Furthermore, the toxicity of nanomaterials themselves must be evaluated, as their interactions with existing pollutants could exacerbate environmental problems. Understanding these dynamics is vital for developing comprehensive risk assessments and effective remediation strategies that mitigate both contamination and toxicity.

Nanomaterials can enhance traditional remediation techniques by increasing reaction rates and improving the degradation of complex pollutants. Research should focus on the efficacy of various nanomaterials in degrading specific contaminants, including pharmaceuticals, pesticides, and industrial chemicals. Innovative approaches, such as photocatalysis and advanced oxidation processes, should be explored for their potential to break down persistent pollutants in wastewater.

The integration of nanomaterials in agricultural systems presents opportunities for improving crop health and productivity while simultaneously addressing soil and water contamination. Future research should investigate the dual impacts of nanomaterials—how they can enhance soil fertility and plant resilience, and their potential risks in terms of soil health and ecosystem dynamics. The interaction between nanoparticles and environmental pollutants, particularly in agricultural settings, necessitates a thorough examination to avoid negative repercussions on food safety and environmental quality. This holistic approach can lead to sustainable agricultural practices that contribute to both food security and environmental health.

Adsorption is a key mechanism in many water treatment processes, effectively capturing pollutants and improving water quality. The integration of photocatalytic technologies represents a promising avenue for enhancing the degradation of persistent contaminants. Research in this cluster should focus on optimizing adsorption materials and photocatalytic systems to increase their efficiency and effectiveness in real-world applications. Investigating the synergistic effects of combining these technologies could lead to innovative remediation solutions capable of addressing complex contamination scenarios.

The exploration of these clusters illustrates the multifaceted nature of nanomaterials and their potential applications in addressing environmental contamination. As the challenges of soil and groundwater pollution become increasingly complex, an integrated approach that considers the behavior of nanomaterials, their interactions with pollutants, and the implications for human health and ecosystems is essential.

2.8. Temporal Analysis and Future Directions

The temporal analysis of keywords, illustrated in Figure 9, reveals how research themes have evolved over the years. In the earlier years, particularly around 2018 and before, keywords such as nanoremediation, NZVI, iron, toxicity, soil, transport, arsenic, phytotoxicity, nanoparticles, and carbon nanotubes were prominent. This indicates that research during this period focused heavily on understanding the fundamental properties of nanomaterials and their applications in addressing soil and groundwater contamination.

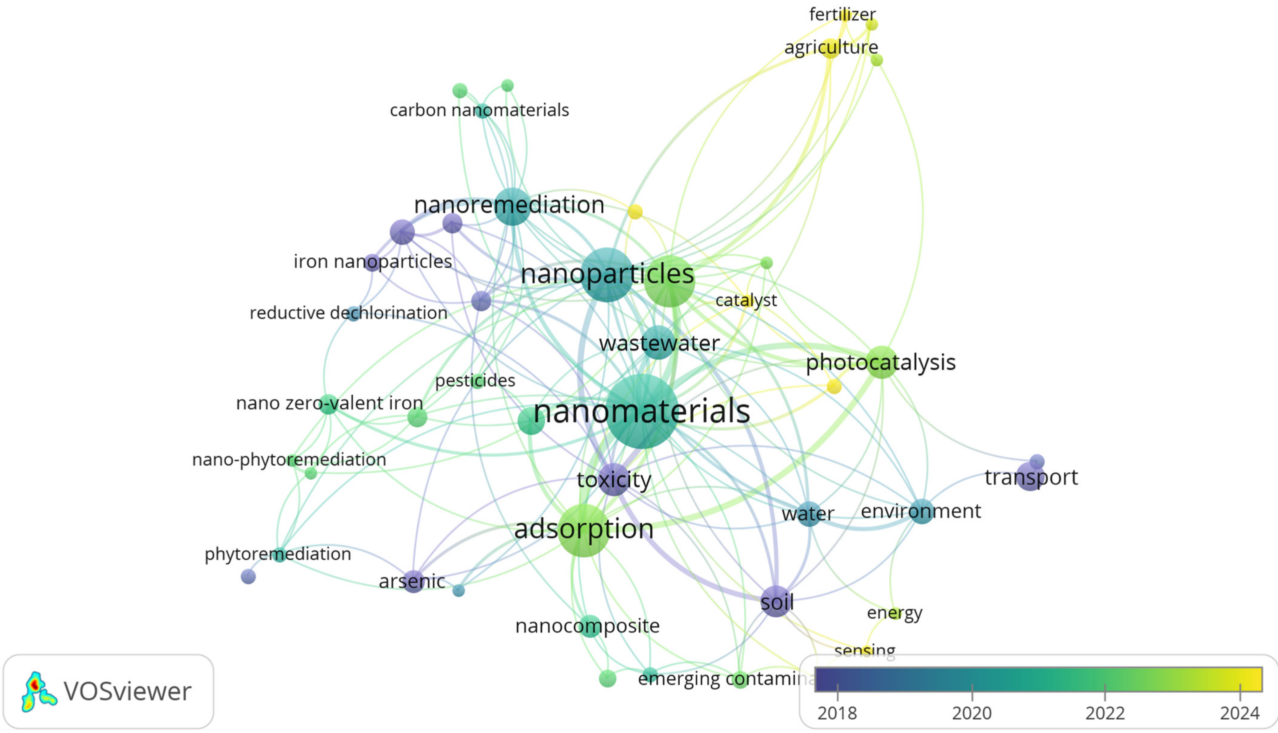

Figure 9. Overlay visualization of keyword Co-occurrence in nanomaterials research.

As we moved into the period around 2020, the research themes began to shift noticeably. Keywords like carbon, nanoremediation, nanoparticles, and wastewater gained prominence. This transition suggests a broader exploration of carbon-based nanomaterials and their applications in wastewater treatment, indicating a move towards more innovative and effective remediation strategies.

By 2022, the keyword landscape continued to evolve with the emergence of terms such as photocatalysis, adsorption, polymer-based nanomaterials, and energy. The rise in photocatalysis signifies a shift towards utilizing light-activated processes for pollutant degradation, showcasing advancements in nanotechnology that enhance the effectiveness of remediation techniques. The inclusion of adsorption indicates a continued interest in understanding how various materials can capture and remove contaminants from water and soil.

In the most recent years, particularly between 2022 and 2024, the focus expanded to include keywords like catalyst, advanced oxidation processes, sensing, agriculture, fertilizer, and biogenic nanoparticles. This evolution reflects ongoing innovations in nanotechnology, with a renewed interest in catalytic methods for enhancing pollutant degradation and developing technologies that can monitor and detect contaminants in real-time.

Despite the promising capabilities of nanomaterials in environmental remediation, several challenges persist. Cost-effectiveness remains a significant barrier, as the initial investment in nanomaterials can be high compared to traditional methods [82]. Additionally, the potential toxicity of these materials to non-target organisms necessitates thorough risk assessments before application [83]. Future research should focus on developing stabilized formulations, integrating nanotechnology with existing remediation methods, and standardizing methodologies for assessing the ecological impacts of nanomaterials [82].

Overall, the comprehensive analysis of these clusters and keywords illustrates the multifaceted nature of nanomaterials in addressing environmental challenges. The interconnectedness of these themes underscores the necessity for interdisciplinary collaboration to foster innovative solutions that effectively mitigate pollution while enhancing environmental quality and public health. By prioritizing research that bridges these clusters, researchers can contribute to a more sustainable and health-conscious application of nanotechnology in environmental remediation.

3. Methods

3.1. Data Sources and Bibliometric Approach

This study employed the PRISMA checklist to guide the literature review methodology, ensuring a rigorous adherence to PRISMA standards while intentionally excluding meta-analysis techniques [84]. Bibliometric analysis is a valuable tool in systematic literature reviews, enabling the establishment of a comprehensive and replicable database [85]. Its broad acceptance is rooted in its ability to provide an integrated overview of research sectors, outputs, organizations, and emerging trends [86]. This approach is particularly effective for reviewing extensive scholarly data, elucidating the relationships between journal citations, and offering insights into existing or nascent fields of study [86,87]. Furthermore, bibliometric analysis supports ongoing research and development while highlighting its implications, making it a popular methodology across diverse scientific disciplines [31,32].

The primary aim was to conduct a comprehensive bibliometric analysis to investigate trends and advancements concerning nanomaterials used for groundwater and soil remediation. Data were extracted from the Scopus database, covering the period from 2010 to 2024. The choice of the Scopus database was based on its extensive coverage across various fields and its large collection of pertinent published articles [88]. The literature search utilized the following query string and keywords: "(TITLE-ABS-KEY ((“NANOMATERIALS”) AND (“GROUNDWATER REMEDIATION” OR “SOIL REMEDIATION”)) AND PUBYEAR > 2009 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (DOCTYPE”,ar”) OR LIMIT-TO (DOCTYPE”,re”) OR LIMIT-TO (DOCTYPE”,cp”) OR LIMIT-TO (DOCTYPE”,bc”)) AND (LIMIT-TO (SRCTYPE”,j”) OR LIMIT-TO (SRCTYPE”,p”)))”.

Following the extraction and organization of data from the Scopus database, Comma-Separated Values (CSV) files were created for subsequent analysis. To ensure the reliability and accuracy of the data during the source selection process, several filtering procedures were implemented. These included the removal of duplicate entries and the application of specific inclusion and exclusion criteria based on language, document type, and source. After segmenting and evaluating the records, a comprehensive examination of source names, authors, and their affiliations for each year was conducted. The quality of the documents was further assessed by reviewing their titles, abstracts, and keywords. Incomplete or erroneous records were systematically eliminated through a rigorous filtration process to enhance dataset integrity. This search was confined to a time frame from 2010 to 2024, which resulted in the identification of 230 documents. A significant finding during this phase was that no duplicate records were present, simplifying the subsequent analysis.

Following the initial identification of documents, a meticulous examination of the subject areas was performed. During this review, one document was excluded as it fell under the subject area of Econometrics and Finance, which was deemed outside the scope of this study. This careful selection process ensured that only relevant subject areas were considered. In addition to subject area filtering, the study specified particular document types for inclusion in the analysis. The chosen document types included research articles, review articles, book chapters, and conference papers. As a result of this criterion, two documents were excluded because they were classified as book documents. Language was another critical factor in the selection process. The study was limited to publications in English to maintain consistency and accessibility. Consequently, nine documents were excluded due to language discrepancies. This included seven documents written in Chinese, one in Italian, and one in Ukrainian, which were not suitable for the analysis. After applying all these filtering criteria, the final dataset was refined to include 217 publications that were directly relevant to the study's focus on nanomaterials for groundwater and soil remediation. The study methodology is illustrated in Figure 10.

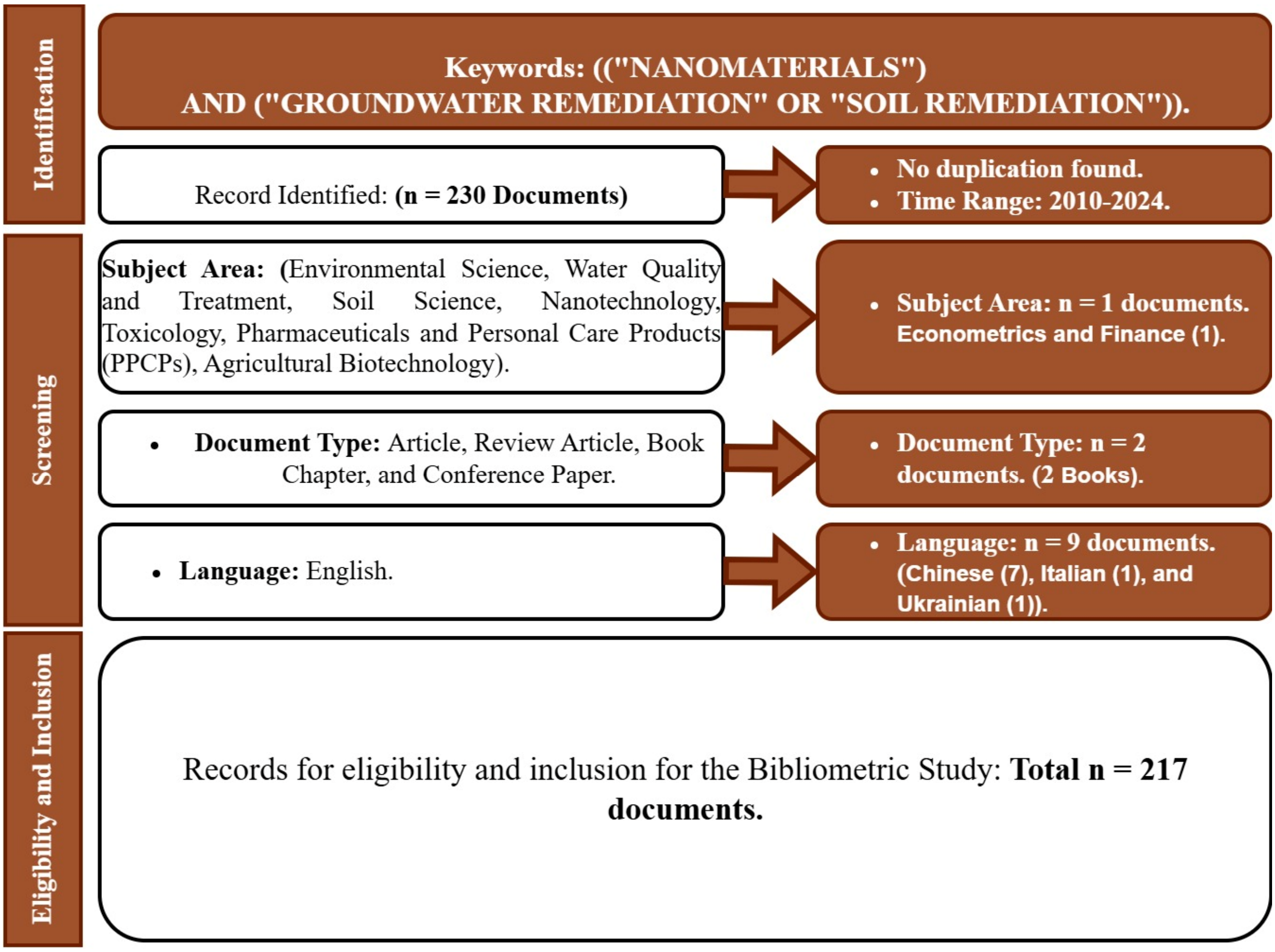

Figure 10. Flow diagram of search method.

3.2. Visualization Procedure

In bibliometric studies, the construction and visualization of bibliometric maps significantly enhance readability and the identification of relationships among diverse sources. This methodology simplifies the analysis of findings and aids researchers in comprehending the structure of bibliometric results. To analyze these findings and familiarize ourselves with bibliometric patterns, we employed VOSviewer version 1.6.20 for data processing. VOSviewer is an open-source, user-friendly software specifically designed for the visualization and networking of bibliometric data [88]. The choice of VOSviewer for data processing and analysis was based on its capacity to manage extensive networks and its advanced text-mining capabilities [86,89]. This software enables the identification of relationships and trends within the literature by generating bibliometric maps that visualize connections between selected articles [90,91]. A notable strength of VOSviewer is its dynamic label management, which adapts to algorithmic requirements, effectively displaying co-occurrences [89].

Our analysis focused on three primary aspects: the journals in which the articles were published, the author keywords utilized in the papers, and the countries of origin. These elements provide a comprehensive overview of the research landscape, making them essential for bibliometric investigations [34,35]. Key parameters for the analysis included publication counts, average normalized citations, and total link strength (TLS). For clarity, TLS is defined as a metric that quantifies the strength of connections between publications, reflecting their collaborative and citation relationships within the academic community [92].

Table 9 presents a summary of key bibliometric findings from the literature on nanomaterials for groundwater and soil remediation over the period from 2010 to 2024. The analysis reveals significant insights into the scholarly contributions and the landscape of research within this field. The search yielded a total of 217 documents, encompassing various types of publications such as journal articles, review articles, book chapters, and conference papers. These contributions were disseminated across 191 unique publication venues, indicating a broad range of academic sources engaged in this research area. The involvement of 1184 authors highlight a collaborative effort among researchers, with affiliations to 771 institutions worldwide. This extensive network of authors reflects the global interest in the application of nanomaterials for environmental remediation. Notably, contributions came from authors representing 58 countries, showcasing the international collaboration and diverse geographic engagement within this scientific community.

Table 9. Summary of key bibliometric findings.

Description	Findings
Publications	217
Authors	1184
Countries	58
Publication Venues	191
Authors' Affiliations	771
Author Keywords	825
All Keywords	2836
Index Keywords	2387
Total Citations	7284

The impact of these 217 publications is further emphasized by a total of 7284 citations, underscoring their significance and relevance to academic discourse. This high citation count points to the importance of the findings and their influence on subsequent research in the field. An examination of the keywords provided by the authors reveals valuable insights into the focus of the research. A total of 825 unique author-supplied keywords were identified, which indicates a rich diversity in research themes and topics. Additionally, the analysis included all keywords, totaling 2836, as well as indexed keywords, which amounted to 2387, providing a comprehensive overview of the terminologies and concepts prevalent in literature.

4. Conclusions

This bibliometric analysis provides a comprehensive overview of the current landscape of research on nanomaterials for soil and groundwater remediation, spanning the last decade. The results indicate that India, China, and the United States are the leading contributors to this field, illustrating a robust commitment to addressing environmental contamination challenges. Prominent institutions, such as the "Guangdong Provincial Academy of Environmental Science" and the "National Institute of Technology" in India, have been key players in advancing research in this area.

Among the prominent subjects identified in the analysis, "Environmental Science" and "Toxicology" emerge as critical themes. Environmental Science accounts for 23.5% of total publications, highlighting its essential role in addressing contamination issues. Toxicology, comprising 21.6% of the research, underscores the need to understand the health impacts of nanomaterials, which is vital for informing safety regulations and public health policies.

The analysis identifies critical research themes, particularly the emphasis on environmental toxicity and innovative remediation technologies. The recognition of contaminants such as heavy metals and emerging pollutants like PFAS highlights an urgent need for advanced monitoring and innovative remediation strategies that leverage the unique properties of nanomaterials. Despite the promising potential of nanomaterials, this study also underscores the associated risks, such as toxicity and the challenges of material stability. As the field progresses, it is essential for researchers to focus on optimizing nanomaterials to enhance their effectiveness while ensuring safety.

In terms of individual contributions, Su, C. is identified as the most productive author, with five publications, indicating a strong collaborative network. Conversely, Stefaniuk, M. stands out as the most cited researcher, with 805 citations, reflecting considerable influence in the field.

Future research should prioritize the development of standardized assessment methodologies to evaluate the ecological impacts of these materials. Additionally, interdisciplinary collaboration will be crucial in integrating insights from environmental science, engineering, and toxicology, fostering holistic approaches to remediation. By addressing these gaps and focusing on the optimization and safe application of nanomaterials, the research community can advance sustainable solutions that not only improve environmental health but also support agricultural productivity. This comprehensive approach will be key to navigating the complexities of soil and groundwater contamination in the years to come.

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