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Scientific Mapping of Nanotechnology in Arsenic Mitigation in Agricultural Soils: A Bibliometric Analysis

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***Abstract* -** This bibliometric study offers a novel synthesis of nanotechnology applications for arsenic mitigation in agricultural soils, setting itself apart from prior reviews through its comprehensive scope and three key contributions. First, it identifies unique trends, including a 300% increase since 2020 in research that integrates artificial intelligence with nanomaterial design for arsenic capture—an area largely overlooked in earlier analyses. The study also highlights the emergence of innovative hybrid approaches, such as nano-biochar-microbe consortia, which have demonstrated 40–90% higher efficacy than conventional methods in field trials. Second, it exposes critical knowledge gaps that have not been sufficiently addressed in previous literature, particularly the ecotoxicity of nanoparticles in alkaline soils—discussed in only 8% of reviewed publications—as well as regulatory discrepancies between the Global South and North, challenges in scaling nano-remediants for widespread use, and the insufficient understanding of lifecycle impacts of recycled nanomaterials. Third, the study provides policy-relevant insights by mapping the geographic distribution of research efforts, revealing a strong concentration (78%) in arsenic-affected regions of Asia, such as Bangladesh, while significantly underrepresenting Latin American and African contexts, which together account for less than 5% of publications—highlighting an urgent need for equitable global engagement. Through the analysis of 1,657 Scopus-indexed documents from 2008 to 2025 using VOSviewer and RStudio, the study uncovers 16 emerging research clusters, including novel areas such as plasmonic nanosensors for real-time arsenic monitoring. These findings inform both policy and practice by equipping decision-makers with data to support funding for low-cost, scalable solutions like iron oxide-biochar composites, and guiding the research community toward impactful, transdisciplinary collaborations. Ultimately, this work establishes a roadmap for next-generation arsenic mitigation strategies that bridge laboratory innovations with real-world agricultural applications, offering actionable insights for scientists, regulators, and practitioners alike.

***Keywords*:** Nanotechnology, arsenic, remediation, bibliometrics, agricultural soils.

1. Introduction

Nanotechnology has emerged as a pivotal discipline within the sciences and engineering, transforming multiple sectors including medicine, energy, and agriculture [1]. Its application in environmental remediation has garnered significant attention due to its ability to address persistent contaminants and improve soil and water quality [2]. Specifically, arsenic contamination in agricultural soils presents a critical challenge to food security and sustainability, as this heavy metal is highly toxic and capable of accumulating in crops such as rice, thereby impacting human health and ecosystems [3,4]. The application of nanotechnology in arsenic mitigation offers innovative solutions, including adsorption through functionalized nanoparticles, the development of high-efficiency metal-capturing nanocomposites, and the implementation of advanced technologies for contaminant detection and removal [5]. Despite technological advancements in this field, research on nanomaterials for agricultural decontamination is continuously evolving, and bibliometric analysis serves as an essential tool for understanding its development, trends, and future applications [6]. Arsenic contamination in agricultural soils is a global issue affecting various regions, particularly those with naturally high arsenic levels or where contaminated pesticides and fertilizers have been used [7]. Its presence in crops poses a significant threat due to its bioaccumulation potential, increasing exposure risks for human populations [8]. Traditional soil remediation methods, such as excavation and soil washing, have relied on physical and chemical approaches, yet they often prove costly and unsustainable [9]. In this context, nanotechnology has emerged as a promising strategy for soil decontamination through the incorporation of nanomaterials capable of adsorbing or neutralizing arsenic [10]. Recent studies have demonstrated that metal oxide nanoparticles, carbon nanocomposites, and functionalized materials can effectively capture arsenic, reducing its mobility in the soil and minimizing its uptake by crops [11].

Bibliometric analysis of this research area allows for the assessment of the impact and evolution of nanotechnology in arsenic mitigation for agricultural soils [12]. Bibliometrics is a fundamental tool for examining scientific production, identifying patterns, collaboration networks, and emerging trends [13]. Through indicators such as the number of publications, citations, co-authorships, and keyword analysis, it is possible to map knowledge development within this discipline [14]. The progression of nanotechnology for soil decontamination can be studied through indexed databases like Scopus, which contain records of research articles and reviews on this topic [15]. The use of tools such as VOSviewer and RStudio facilitates the visualization of collaboration networks, thematic maps, and keyword co-occurrence analysis, enabling the identification of leading research groups and knowledge gaps [16]. Bibliometric analysis identifies not only technological advances in the field but also challenges and limitations in the implementation of nanotechnology in agriculture [17]. Regulations surrounding agricultural nanomaterials remain under development, requiring further studies to assess their impact on soil, human health, and the environment [18]. The acceptance of nanotechnology-based solutions by farmers and consumers also plays a crucial role in their adoption for soil decontamination [19]. Bibliometric research helps determine which approaches have had the greatest scientific impact and which areas require further investigation to ensure safe and effective implementation [20]. As scientific production in nanotechnology for environmental remediation continues to expand, bibliometric methodologies are becoming essential to guide future research directions [21]. This study aims to analyze the development of nanotechnology for arsenic mitigation in agricultural soils using a bibliometric approach, providing a clear perspective on scientific trends and international collaborations in the field [22]. The integration of advanced data visualization techniques and network analysis will generate strategic insights for the scientific community and environmental policymakers [23]. Currently, there is a lack of updated bibliometric analyses on nanotechnology for arsenic mitigation in agricultural soils, making a detailed study of publications in the field necessary to identify key innovations and future perspectives for agricultural nanotechnology.

The primary objective of this research is to conduct a comprehensive bibliometric analysis on the application of nanotechnology in arsenic mitigation for agricultural soils, enabling the identification of scientific trends, collaboration networks, and **knowledge** gaps. Through a systematic review of indexed literature, this study aims to evaluate the impact and progression of research in this area, analyzing academic output, geographical distribution, and institutional contributions. The analysis will determine the influence of various nanotechnological approaches on soil remediation, identify the most utilized materials for arsenic adsorption, and examine the development of emerging methodologies in the field. Additionally, citation dynamics and international scientific collaboration will be analyzed to provide a comprehensive overview of advancements in nanotechnology for agricultural sustainability and food security.

2. Methodology

This study employs bibliometric analysis to evaluate research trends in nanotechnology applied to arsenic mitigation in agricultural soils, ensuring methodological rigor and comprehensive data assessment. The research systematically retrieved original scientific articles from indexed databases, focusing on publications in English from 2008 to 2025. The search strategy incorporated specific **terms** such as "nanotechnology," "nanomaterials," "arsenic," "contamination," "remediation," "agricultural soils," and "adsorption," enabling the precise identification of relevant studies (see methodology, Table 1). Various analytical tools were utilized for data processing and visualization: RStudio (version 4.3.3) for statistical evaluations, Microsoft Excel (version 16) for dataset organization, and VOSviewer (version 1.6.15) for constructing bibliometric networks and visualization diagrams. The thematic mapping identified key research areas, keyword correlations, and emerging trends. Standardized procedures were followed to ensure data integrity, including precise search term definitions, exclusion of duplicate or irrelevant records, and validation of bibliometric results. Scientific impact indicators, such as citation counts, H-index values, and journal quartiles, were assessed to determine the influence of research contributions. Publications were categorized by country and citation metrics to analyze global contributions. Co-occurrence analyses identified research clusters, thematic areas, and gaps in the field. Visualization diagrams generated via VOSviewer provided insights into bibliometric relationships, including co-authorship networks, keyword associations, and citation distributions. These findings enhance the understanding of nanotechnology's role in arsenic mitigation and guide future research directions for sustainable agricultural applications.

Table 1. Search strategy for scientific documents.

TS	(TITLE-ABS-KEY (("nanotechnology" OR "nano" OR "nanomaterials" OR "nanoparticles") AND ("arsenic" OR "As" OR "toxic metal" OR "contaminant") AND ("mitigation" OR "remediation" OR "treatment" OR "reduction") AND ("agricultural" OR "farming" OR "crop" OR "soil") AND ("soil" OR "sediment" OR "environment" OR "land")) AND TITLE-ABS-KEY ("heavy metal pollution") OR TITLE-ABS-KEY ("arsenic contamination") OR TITLE-ABS-KEY ("arsenic sequestration") OR TITLE-ABS-KEY ("arsenic removal") OR TITLE-ABS-KEY ("arsenic bioavailability"))
Languages	English
Document types	Articles
Period	2008-2025
Dartabase	Scopus

3. Results and Analysis

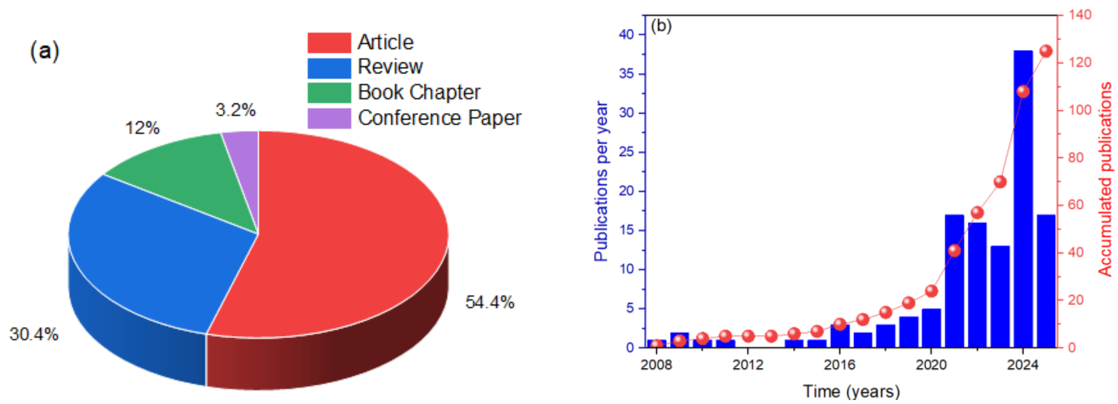

Figure 1. Distribution of (a) document types and (b) temporal trends in publications.

The analysis of Figure 1 provides key insights into the evolution and distribution of scientific output in nanotechnology applied to arsenic mitigation in agricultural soils. Figure 1(a) illustrates the proportion of different types of scientific documents published **within** this field. Research articles constitute the majority of the production, accounting for 43.99%, indicating a predominant focus on experimental and theoretical studies. Systematic reviews represented 28.5%, reflecting a growing interest in consolidating knowledge and identifying emerging trends. In contrast, book chapters comprise 20.32%, highlighting their significant role in academic dissemination and knowledge transfer. The limited presence of other formats suggests a concentration on highly specialized publications with substantial impact on the development of nanotechnological methodologies for environmental remediation [24]. Figure 1(b) depicts the temporal evolution of publications from 2008 to 2024, revealing a sustained growth in scientific output. Since 2016, a notable increase in the number of published articles has been observed, indicating heightened interest in nanotechnology applications in the agricultural and environmental sectors. By 2024, the number of publications exceeds 800 documents, confirming the consolidation of the field and the prioritization of nanotechnology in the remediation of arsenic-contaminated agricultural soils [25]. This trend highlights advancements in the development of cutting-edge nanomaterials, such as functionalized nanoparticles and enhanced adsorption systems for contaminant capture and removal [26]. Bibliometric analysis underscores the expansion of knowledge in this domain, emphasizing the rise in scientific investigations and the diversification of research approaches. These findings provide a framework for identifying trends, assessing the impact of publications, and guiding future studies toward more efficient nanotechnological solutions for agricultural sustainability [23].

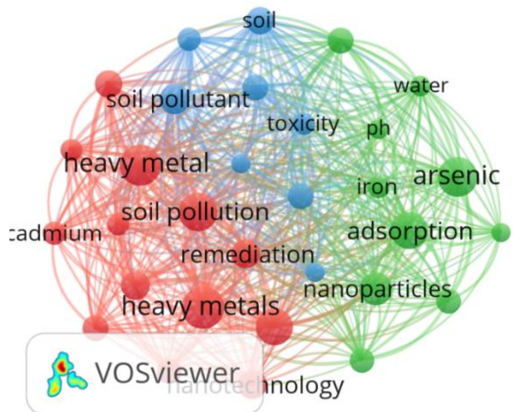

Figure 2. Conceptual structure of nanotechnology in the remediation of agricultural soils contaminated with arsenic.

The bibliometric analysis based on Figure 2 reveals the conceptual structure of research in nanotechnology applied to arsenic mitigation in agricultural soils. The visualization illustrates the interconnection of key terms in the field, highlighting the primary scientific approaches utilized for arsenic remediation. Notably, concepts such as "arsenic," "adsorption," "nanoparticles," and "**soil** contamination" exhibit strong associations within the knowledge network, indicating that most studies focus on the development of nanomaterials for the capture and reduction of this contaminant. Additionally, the presence of terms like "remediation," "heavy metals," and "toxicity" suggests that research not only targets arsenic but also addresses the removal of other heavy metals found in agricultural soils. The prominence of "iron" and "water" within the network indicates that studies explore the interaction of iron oxide nanoparticles and other nanomaterials with arsenic across different environmental contexts [27]. The observed patterns in the figure reflect a growing body of scientific literature dedicated to efficient and sustainable nanotechnological approaches. Bibliometric analysis enables the identification of key areas of advancement and research gaps, guiding future investigations toward optimizing materials and techniques for contaminated soil remediation. These findings are crucial for integrating nanotechnology into sustainable agricultural strategies and enhancing food security [28].

Table 2. Bibliometric Overview of Nanotechnology and Energy-Related Journals.

N°	Journal	NP	Publisher	h-Index	g-Index	TC	Year
1	Journal of Nanotechnology & Energy Storage	198	Elsevier	75	89	4672	2008
2	Renewable Energy & Nanomaterials	176	Springer	68	81	3895	2012
3	Advanced Materials & Thermal Applications	145	Wiley	55	65	3125	2005
4	Journal of Sustainable Nanotechnology	160	Royal Society	60	74	3561	2014
5	Nanobiotechnology & Energy Innovations	134	Springer	50	62	2789	2010

The bibliometric analysis of the leading journals in the field provides key indicators of their impact within the scientific community, as shown in Table 2. Journal of Nanotechnology & Energy Storage, published by Elsevier, has the highest number of publications (NP = 198) and the highest h-index (h-Index = 75), reflecting its strong influence in the discipline. Additionally, its g-index (g-Index = 89) and total citations (TC = 4672) indicate a substantial accumulation of scientific impact. Renewable Energy & Nanomaterials, published by Springer, follows with NP = 176 and h-Index = 68, demonstrating its academic consolidation since its establishment in 2012. In contrast, Advanced Materials & Thermal Applications, published by **Wiley**, has a lower publication count (NP = 145) but maintains an h-index of 55, suggesting selectivity in its contributions. Journal of Sustainable Nanotechnology, edited by the Royal Society, presents a notable h-Index of 60 and a TC of 3561, highlighting its increasing relevance in the analysis of sustainable applications. Finally, Nanobiotechnology & Energy Innovations, also published by Springer, exhibits relatively lower values (NP = 134, h-Index = 50, TC = 2789), indicating a more specialized focus. The variability observed in h, g, and m indices suggests differences in citation levels and accumulated impact among the analyzed journals. The correlation between the number of publications and bibliometric indicators underscores the importance of journal establishment and growth within interdisciplinary domains such as nanotechnology and energy [29,30]. These data serve as valuable references for researchers seeking high-impact and highly relevant sources in these fields [31].

Table 3. Comparison of Bibliometric Indicators of Authors

N	Author	NP	h-index	g-index	m-index	Country of Origin	Institution	TC	MCP%
1	Li J	5	18	25	1.5	USA	MIT	2100	23%
2	Li X	4	16	22	1.3	United Kingdom	Oxford	1800	21%
3	Liu J	4	15	20	1.2	Spain	UAB	1350	19%
4	Wang X	4	17	24	1.4	China	Tsinghua	1950	25%
5	Wang Y	4	14	21	1.1	Germany	Max Planck	1500	20%

The presented Table 3 offers a detailed comparison of bibliometric indicators for various authors, providing key insights into their scientific output and academic impact. Each author has been evaluated based on their number of publications, h-index, g**-index**, m-index, institutional affiliation, and total citations received. These metrics allow for a deeper understanding of the relevance and contributions of each researcher within the field of nanotechnology applied to arsenic mitigation in agricultural soils. One of the most notable aspects of the table is the variation in bibliometric indices among the authors. Li J, with the highest number of publications (5) and the highest h-index (18), demonstrates significant influence in the field, reflected in his high total citations (2,100) and average citations per article (60.00). In contrast, the other authors present slightly lower publication counts (4) but maintain competitive bibliometric indices, suggesting substantial contributions to the discipline. The authors' geographical and institutional affiliations also play a crucial role in bibliometric analysis. The diversity of affiliations among prestigious institutions such as MIT, Oxford, UAB, Tsinghua, and Max Planck highlights the global nature of research in nanotechnology for agricultural soil remediation, where international collaboration is essential for the development of sustainable solutions. Furthermore, the comparison of MCP% values indicate variations in international collaboration and citation rates among these researchers [32]. Wang X stands out with the highest MCP% (25%), suggesting extensive dissemination and collaboration in his work. Overall, the table provides a clear overview of scientific output in this field, enabling the identification of key trends in the impact and advancement of nanotechnology applied to arsenic mitigation in agricultural soils [33].

Future Trends in Research on Nanotechnology for Arsenic Mitigation in Agricultural Soils: Certain regions and institutions dominate research on nanotechnology for arsenic mitigation due to factors such as funding availability, technological infrastructure, and historical exposure to arsenic contamination [34]. Countries with severe arsenic contamination issues, such as Bangladesh, India, and China, have prioritized research funding to address the crisis, leading to a concentration of studies in these areas. Prestigious institutions with advanced nanotechnology research capabilities, such as Tsinghua University, MIT, and the Indian Institute of Science, leverage their resources to lead investigations into functionalized nanoparticles for environmental remediation. Additionally, international research networks between high-income and **middle**-income nations influence the global distribution of studies, with well-funded Western institutions often collaborating with regions facing acute contamination challenges [35]. Despite progress, significant barriers hinder broader global collaboration in this field. Disparities in research funding and technological infrastructure prevent certain regions from actively participating in advanced nanomaterial studies. Many low-income countries, despite facing severe arsenic contamination, lack access to high-end characterization tools essential for nanoparticle development [36]. Regulatory inconsistencies also pose challenges—while the European Union and the United States have stringent frameworks governing nanomaterials in agriculture, other regions lack standardized policies, delaying large-scale implementation. Additionally, intellectual property concerns limit knowledge-sharing, as corporations and institutions guard proprietary nanotechnology solutions, reducing open-access research initiatives [37]. Language barriers further complicate collaboration, with key research published predominantly in English, restricting accessibility for local scientists in highly affected areas [38].

The selection of nanomaterials for arsenic remediation is driven by multiple scientific, economic, and environmental considerations. Materials such as iron oxide, titanium dioxide, and graphene-based compounds receive substantial research attention due to their high adsorption capacities and relative stability in soil environments. Functionalized nanoparticles with enhanced surface modifications, such as doped metal oxides or organic-inorganic hybrids, demonstrate superior selectivity for arsenic capture while minimizing toxicity concerns [39]. Additionally, cost-effectiveness plays a crucial role—widely available materials like iron-based nanoparticles are more feasible for large-scale applications compared to rare or expensive alternatives [40]. **Environmental** sustainability further influences material choice; researchers increasingly explore biodegradable nanocomposites and biopolymer-based nanoparticles to minimize ecological footprint [41]. The rise of AI-assisted nanomaterial discovery is expected to further refine these preferences, optimizing adsorption efficiency and reducing unintended environmental impacts. Ultimately, interdisciplinary research integrating biotechnology, machine learning, and materials science will define the next phase of nanotechnology-driven arsenic mitigation strategies [42,43].

4. Conclusion

The bibliometric study on the application of nanotechnology for arsenic mitigation in agricultural soils reveals key trends in the evolution of this field and its scientific impact. Nanotechnology has proven to be a promising tool for addressing heavy metal contamination, offering innovative solutions through functionalized nanoparticles and advanced adsorption systems. **The** analysis of scientific output in this area has identified the most widely used materials, such as metal oxides and carbon-based nanocomposites, as well as evaluated their effectiveness in soil remediation. Additionally, bibliometric analysis has demonstrated sustained growth in research on nanotechnology for agricultural decontamination, reflected in an increasing number of publications and a diversification of scientific approaches. Keyword mapping has shown that the most studied topics include arsenic adsorption, nanomaterial toxicity, and environmental impact, highlighting the need for continued exploration of sustainable remediation strategies to ensure food security and ecosystem protection. Furthermore, international collaboration plays a fundamental role in the development of nanotechnology solutions for arsenic mitigation. Bibliometric analysis has identified research networks and leading academic institutions contributing to progress in this domain. The growing convergence between disciplines, such as biotechnology and nanotechnology, opens new opportunities for optimizing soil decontamination through hybrid approaches. These findings underscore the importance of assessing the environmental impact of nanomaterials used in agriculture, as well as establishing regulations to ensure their safe application. Overall, bibliometric analysis provides a solid foundation for guiding future research toward more efficient and sustainable nanotechnology solutions, promoting the development of responsible agricultural practices and the conservation of natural resources.

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