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EVOLUTION OF PHYTOREMEDIATION RESEARCH: FROM HEAVY METAL REMOVAL TO MICROBIOME-ASSISTED NATURE-BASED SOLUTIONS

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Phytoremediation has become one of the most promising nature-based approaches for restoring contaminated ecosystems by combining environmental sustainability, economic feasibility, and ecosystem resilience. The aim of this study was to comprehensively analyze the evolution of phytoremediation research, identify major scientific trends, research hotspots, geographical distribution of scientific production, funding patterns, international collaboration, and future research directions using bibliometric methods.

The results reveal a substantial increase in scientific output, particularly after 2015, reflecting the growing global interest in ecological restoration and sustainable environmental management. China emerged as the leading contributor to phytoremediation research, followed by the United

States, India, and several European countries. Funding analysis demonstrated the significant role of major national and international research programmes in advancing phytoremediation studies. Keyword mapping illustrates a clear evolution of research priorities from heavy metal uptake and plant physiology toward microbiome-assisted phytoremediation, biochar applications, remote sensing, Geographic Information Systems, artificial intelligence, machine learning, Digital Twins, and Nature-based Solutions. The analysis also identified important research gaps related to AI-driven predictive modelling, digital environmental monitoring, remediation of mixed contaminants and PFAS, war-contaminated soils, and climate adaptation.

The findings demonstrate that phytoremediation has evolved from a narrow plant-based remediation technology into a multidisciplinary scientific field integrating environmental science, microbiology, digital technologies, and sustainability concepts. Bibliometric analysis not only reveals the historical evolution of scientific knowledge but also provides valuable insights into emerging research themes and future directions for sustainable environmental remediation.

Key words: *phytoremediation, bibliometric analysis, science mapping, VOSviewer, Web of Science, Scopus, heavy metals, microbiome, artificial intelligence, Nature-based Solutions.*

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Еволюція досліджень фіторемедіації: від видалення важких металів до природоорієнтованих рішень на основі мікробіому

Фіторемедіація є одним із найбільш перспективних природоорієнтованих підходів до відновлення забруднених екосистем, що поєднує екологічну безпечність, економічну доцільність та принципи сталого розвитку. Метою дослідження є комплексний аналіз еволюції наукових досліджень у сфері фіторемедіації, визначення основних тенденцій розвитку, ключових напрямів досліджень, географічної структури наукової продуктивності, фінансування, міжнародної співпраці та перспектив подальших досліджень на основі бібліометричного аналізу.

Результати дослідження свідчать про стрімке зростання кількості наукових досліджень, особливо після 2015 року, що відображає підвищення глобального інтересу до екологічного відновлення та сталого управління природними ресурсами. Лідером за кількістю публікацій є Китай, вагомий внесок також належить США, Індії та країнам Європи. Аналіз фінансування показав визначальну роль великих національних і міжнародних наукових програм у розвитку фіторемедіаційних досліджень. Картування ключових слів продемонструвало еволюцію наукової тематики від досліджень механізмів накопичення важких металів рослинами до інтеграції мікробіому, біочару, дистанційного зондування, геоінформаційних систем, штучного інтелекту, машинного навчання, цифрових двійників та природоорієнтованих рішень. Визначено основні прогалини сучасних досліджень, пов'язані з використанням цифрових технологій, ремедіацією змішаних типів забруднення, PFAS, військово забруднених територій та адаптацією до зміни клімату.

Отримані результати демонструють трансформацію фіторемедіації з вузькоспеціалізованої технології очищення ґрунтів у міждисциплінарний науковий напрям, що інтегрує екологію, мікробіологію, цифрові технології та концепції сталого розвитку. Проведений бібліометричний аналіз дозволяє визначити сучасні тенденції розвитку галузі та окреслити перспективні напрями майбутніх досліджень.

Ключові слова: *фіторемедіація, бібліометричний аналіз, картування науки, VOSviewer, Web of Science, Scopus, важкі метали, мікробіом, штучний інтелект, природоорієнтовані рішення.*

Introduction. Background. Soil pollution has become one of the most serious environmental challenges of the twenty-first century. Rapid industrialization, intensive agriculture, mining activities, urbanization, and improper waste disposal have resulted in the continuous accumulation of contaminants in soils worldwide. Among these contaminants, heavy metals such as cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), chromium (Cr), nickel (Ni), and zinc (Zn) are of particular concern because they are persistent, non-biodegradable, and can accumulate in food chains, posing significant risks to ecosystems and human health. In many regions, soil contamination has reached levels that threaten agricultural productivity, biodiversity, water quality, and food security.

Traditional soil remediation technologies, including excavation, soil washing, thermal treatment, and chemical stabilization, are often effective but remain expensive, energy-intensive, and may cause additional environmental disturbance. These limitations have stimulated growing interest in sustainable remediation approaches that can restore contaminated environments while preserving ecosystem functions.

Phytoremediation has emerged as one of the most promising environmentally friendly technologies for soil restoration. It relies on the natural ability of plants to extract, stabilize, degrade, or transform pollutants from contaminated soils and water. Compared with conventional remediation methods, phytoremediation is generally less expensive, requires lower energy inputs, improves soil quality, supports biodiversity, and contributes to carbon sequestration. As a result, it has become an important component of sustainable land management and ecological restoration strategies.

Today, the research landscape is considerably broader and more interdisciplinary. The effectiveness of phytoremediation is increasingly being enhanced through the integration of plant-associated microbiomes, biochar amendments, nanomaterials, remote sensing technologies, artificial intelligence, machine learning, and other digital tools. At the same time, phytoremediation is no longer viewed solely as a remediation technique but as a key element of nature-based solutions that support ecosystem restoration, climate resilience, sustainable agriculture, and circular bioeconomy initiatives.

These developments indicate a clear shift in the scientific paradigm – from studying plants as individual remediation agents toward developing integrated, intelligent, and ecosystem-based remediation systems. Understanding how this transformation has occurred is essential for identifying current research priorities and future directions.

In recent years, the importance of phytoremediation has become even more evident due to the increasing number of environmental disasters caused by armed conflicts. The ongoing war in Ukraine has created new challenges for soil protection and environmental restoration. Military activities, including shelling, explosions, destruction of industrial facilities, fuel spills, and the widespread use of military equipment, have resulted in the contamination of agricultural and natural ecosystems with heavy metals, petroleum hydrocarbons, explosive residues, and other hazardous substances. Given Ukraine's significant role as one of the world's major agricultural producers, restoring contaminated soils has become not only a national priority but also an important contribution to global food security and sustainable land management. These circumstances further highlight the need for effective, environmentally friendly, and economically feasible remediation technologies, among which phytoremediation represents one of the most promising solutions.

Rather than simply describing publication growth, this study investigates the evolution of scientific thinking in phytoremediation. It traces the transition from plant-centered approaches focused on heavy metal accumulation to integrated remediation strategies that combine plant science, microbial ecology, advanced materials, digital technologies, and nature-based solutions. This evolutionary perspective provides a more comprehensive understanding of how the field has developed and where future research is likely to emerge.

Research Gap. The rapid growth of phytoremediation research has generated thousands of scientific publications covering diverse contaminants, plant species, remediation strategies, and emerging technologies. Several bibliometric studies have analyzed publication performance, influential authors, countries, institutions, and collaboration networks within this field. These studies have provided valuable insights into the scientific productivity and structure of phytoremediation research.

Nevertheless, existing bibliometric analyses have several limitations. Most focus on descriptive publication indicators or specific subtopics, such as heavy metal remediation or particular plant species, while paying limited attention to the long-term evolution of research themes. In particular, little effort has been made to investigate how phytoremediation has evolved from conventional heavy metal removal approaches into a multidisciplinary research field incorporating microbiome engineering, biochar-assisted remediation, artificial intelligence, digital monitoring technologies, and nature-based solutions.

Furthermore, recent advances associated with climate change adaptation, ecological restoration, sustainable agriculture, and smart environmental management have significantly expanded the scope of phytoremediation research. However, these emerging directions have rarely been examined within a comprehensive science mapping framework that reveals how scientific priorities have changed over time.

A systematic analysis of thematic evolution can therefore provide a deeper understanding of the development of phytoremediation research, identify emerging knowledge domains, and reveal future research opportunities.

Aim of the Study. The aim of this study is to investigate the evolution of global phytoremediation research between 2000 and 2026 using bibliometric analysis and science mapping techniques.

Specifically, the study seeks to:

- analyze the growth of scientific publications and citation trends;
- identify the leading countries, institutions, authors, and journals contributing to phytoremediation research;
- explore collaboration patterns within the global research community;
- examine the evolution of research themes through keyword co-occurrence and thematic mapping;
- identify emerging topics and technological trends, including microbiome-assisted phytoremediation, biochar, artificial intelligence, digital monitoring, and nature-based solutions; and
- highlight current research gaps and future directions for sustainable phytoremediation research.

By combining conventional bibliometric indicators with science mapping approaches, this study provides a comprehensive overview of how phytoremediation has evolved over the past twenty-five years and how the field is transitioning toward integrated, technology-driven, and ecosystem-oriented remediation strategies.

Materials and Methods. Data Collection. The bibliometric dataset was compiled using Scopus and the Web of Science Core Collection (WoSCC) as the primary sources of bibliographic records. To complement the international analysis with a national perspective, the Open Ukrainian Scientific Content Initiative (OUCI) was additionally consulted to identify publications authored by Ukrainian researchers and to compare their visibility with global publication trends.

A comprehensive literature search was conducted independently in each database using equivalent search strategies adapted to the search syntax of the respective platforms. The search was performed within the Title, Abstract, and Keywords fields to maximize retrieval accuracy while minimizing irrelevant records.

The search strategy included the principal concept *phytoremediation* together with its major remediation mechanisms: *phytoremediation, OR phytoextraction, OR phytostabilization, OR rhizoremediation, OR phytovolatilization, OR phytodegradation, OR rhizofiltration.*

In Scopus, the search was implemented using the TITLE-ABS-KEY field, whereas in the Web of Science Core Collection the equivalent Topic Search (TS) option was applied. For OUCI, keyword searches were performed within indexed publication metadata using the same terminology.

The retrieval period covered publications published between January 2000 and December 2026.

Only peer-reviewed journal articles and review papers written in English were included in the final dataset. Editorials, conference abstracts, notes, corrections, book reviews, duplicate records, and publications lacking complete bibliographic metadata were excluded from further analysis.

After retrieval, bibliographic records were exported in CSV (Scopus) and Plain Text (Web of Science) formats, including complete citation information, abstracts, author keywords, affiliations, references, funding information, and citation counts.

Data Cleaning and Harmonization. The exported datasets were merged into a unified bibliographic database before analysis.

To improve the quality and consistency of the dataset, several preprocessing steps were performed:

- removal of duplicate publications retrieved from multiple databases;
- standardization of author names using author identifiers where available;
- harmonization of institutional affiliations to account for variations in institutional names;
- normalization of country names according to current international standards;
- merging of synonymous keywords (e.g., *heavy metal* and *heavy metals*; *microorganism* and *microorganisms*);
- correction of spelling inconsistencies and abbreviation variants.

Keyword normalization was performed manually to reduce semantic fragmentation within co-occurrence analyses and to improve the reliability of thematic clustering.

The cleaned dataset served as the basis for all subsequent bibliometric analyses.

Bibliometric Analysis. The bibliometric analysis combined descriptive performance indicators with science mapping techniques to evaluate the development of phytoremediation research over time.

Publication dynamics were assessed using annual publication output, annual citation counts, average citations per publication, and cumulative publication growth.

Scientific productivity was analyzed at four different levels: *countries; institutions; authors; scientific journals.*

Citation impact was evaluated using total citation counts, average citations, and identification of highly cited publications.

To investigate the intellectual and conceptual structure of the research field, the following network analyses were performed: *keyword co-occurrence analysis; author collaboration networks; institutional collaboration networks; international collaboration networks; document co-citation analysis; author co-citation analysis; bibliographic coupling.*

Special attention was given to the temporal evolution of research themes to identify shifts in scientific priorities during different stages of phytoremediation development.

Science Mapping. Science mapping analyses were conducted using complementary software tools to visualize relationships among publications, authors, research topics, and institutions.

Bibliometrix (R package) was used as the primary analytical environment for bibliometric calculations. The package was employed to calculate descriptive indicators, generate publication statistics, identify the most productive authors and journals, evaluate collaboration patterns, and perform thematic analyses.

The graphical interface Biblioshiny facilitated interactive exploration of the dataset and was used to construct thematic maps, trend topic diagrams, thematic evolution plots, and Sankey diagrams illustrating changes in research themes across successive time periods.

VOSviewer was applied to construct bibliometric networks based on similarity relationships among scientific entities. Network maps were generated for: *keyword co-occurrence; co-authorship; institutional collaboration; country collaboration; co-citation; bibliographic coupling.*

Association strength normalization was applied to optimize clustering and improve visualization of relationships among nodes. Node size represented publication or citation frequency, while link thickness reflected the strength of relationships between nodes.

Overlay visualization in VOSviewer was additionally employed to identify recently emerging research topics and to visualize the temporal development of keywords across the study period.

CiteSpace was used to investigate the temporal evolution of the scientific knowledge base. Citation burst detection was applied to identify publications and keywords that experienced rapid increases in scientific attention. Timeline visualization and cluster analysis were used to reconstruct the chronological development of major research themes and to identify emerging research fronts.

Analysis of Landmark Publications. The development of phytoremediation research has been strongly influenced by several landmark publications that established the conceptual framework of the field and guided its subsequent evolution. An analysis of these highly influential studies reveals a clear transition from fundamental investigations of plant-based contaminant removal towards multidisciplinary approaches integrating ecology, microbiology, environmental engineering, and digital technologies.

The modern concept of phytoremediation emerged during the mid-1990s, when pioneering studies introduced plants as effective biological tools for removing contaminants from polluted environments. One of the earliest milestone publications was the work of Kumar et al. [4], who introduced the concept of phytoextraction and demonstrated the potential of plants to remove heavy metals from contaminated soils. This study provided the theoretical basis for phytoremediation and established phytoextraction as one of the principal remediation strategies.

A few years later, Salt et al. [7] further expanded this concept by describing phytoremediation as an environmentally friendly alternative to conventional remediation technologies. Their comprehensive review explained the major mechanisms of contaminant removal, including phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration, and highlighted the ecological and economic advantages of plant-based remediation over physical and chemical approaches. This publication became one of the most influential references in environmental remediation research and significantly increased scientific interest in phytoremediation.

During the early 2000s, research shifted from demonstrating the feasibility of phytoremediation towards understanding its biological mechanisms. McGrath and Zhao synthesized knowledge on metal hyperaccumulation and provided a comprehensive overview of metal uptake, transport, and accumulation processes in plants. Their work emphasized the importance of hyperaccumulator species and stimulated extensive research on plant physiology, metal transporters, and detoxification mechanisms [6].

As the field matured, scientific attention expanded beyond plants themselves to include the surrounding soil environment. A major milestone was the review by Ali et al. [1], which integrated existing knowledge on phytoremediation mechanisms, practical applications, advantages, and limitations. Unlike earlier publications focusing primarily on plant physiology, this review highlighted the importance of soil properties, environmental conditions, and ecological interactions in determining remediation efficiency. During the same period, van der Ent et al. [8] proposed a revised definition of metal hyperaccumulators, providing standardized criteria for identifying hyperaccumulator species. This contribution improved the consistency of phytoremediation research and facilitated comparisons among studies worldwide.

Over the past decade, the scientific paradigm has continued to evolve toward integrated ecosystem management. Numerous studies have demonstrated that remediation efficiency depends not only on plant characteristics but also on interactions with rhizosphere microorganisms and soil amendments. In particular, biochar-assisted phytoremediation has emerged as one of the fastest-growing research topics, with studies reporting enhanced contaminant immobilization, improved soil fertility, increased microbial activity, and greater plant tolerance to environmental stress [2, 3, 5].

More recently, phytoremediation research has entered a new stage characterized by the integration of digital technologies. Artificial intelligence, machine learning, remote sensing, Geographic Information Systems, hyperspectral imaging, unmanned aerial vehicles, Internet of Things sensor networks, and Digital Twins are increasingly applied to monitor contaminated sites, predict remediation efficiency, and support environmental decision-making. Unlike earlier studies that primarily evaluated remediation performance through field measurements, contemporary research increasingly relies on data-driven approaches capable of integrating biological, climatic, and geospatial information into predictive models [5].

The evolution of landmark publications illustrates a progressive expansion of phytoremediation research. During the 1990s, the primary objective was to demonstrate the feasibility of plant-based remediation. The 2000s were dominated by studies investigating physiological mechanisms of contaminant uptake and hyperaccumulation. The following decade witnessed increasing integration of microbiology, rhizosphere ecology, and soil amendments, while the current research landscape is characterized by the convergence of environmental science, artificial intelligence, remote sensing, precision agriculture, and Nature-based Solutions. This progression demonstrates that phytoremediation has evolved from a narrow remediation technique into an interdisciplinary scientific field addressing complex environmental and sustainability challenges.

Results. Growth of scientific publications. The bibliometric analysis revealed a substantial and sustained increase in global scientific production on phytoremediation over the past twenty-six years. Both Scopus and the Web of Science Core Collection demonstrated remarkably similar publication dynamics, indicating that the observed trends represent genuine developments within the research field rather than database-specific effects.

According to the **Scopus database**, the annual number of publications increased from 144 documents in 2000 to 2,518 documents in 2024, with 2,456 publications indexed in 2025. The value reported for 2026 (1,548 publications) reflects an incomplete publication year and therefore should not be interpreted as a decline in scientific activity.

The overall increase corresponds to approximately a 17-fold growth in annual scientific output over the study period, highlighting the remarkable expansion of phytoremediation research worldwide.

The publication dynamics reveal four major stages of scientific development.

Phase I (2000–2007): Establishment of the research field

The first stage was characterized by relatively modest but stable growth, with annual publications increasing from 144 to 556 documents. During this period, phytoremediation was primarily investigated as an alternative to conventional remediation technologies. Research concentrated on identifying hyperaccumulator plant species, understanding metal uptake mechanisms, and evaluating the feasibility of phytoextraction and phytostabilization under different environmental conditions.

The growing scientific interest during this period coincided with increasing international awareness of soil contamination caused by industrialization, mining activities, and intensive agriculture. At the same time, stricter environmental regulations adopted in North America and Europe stimulated research into environmentally sustainable remediation technologies.

Phase II (2008–2014): Methodological expansion

Between 2008 and 2014, publication output almost doubled, increasing from 569 to 1,044 publications annually.

This acceleration reflected the transition of phytoremediation from a primarily botanical discipline toward a broader environmental technology. Researchers increasingly investigated the role of soil amendments, rhizosphere processes, chelating agents, and biomass utilization in improving remediation efficiency. During the same period, advances in molecular biology and plant biotechnology provided new opportunities for understanding plant stress responses and contaminant uptake mechanisms.

The publication growth also coincided with increasing international attention to sustainable environmental management and ecosystem restoration, particularly following the adoption of several international environmental policy initiatives addressing contaminated land and sustainable resource management.

Phase III (2015–2019): Rapid interdisciplinary development

A further acceleration occurred after 2015, when annual publication output increased from 1,175 to 1,672 publications.

This period corresponds closely with several major global policy developments. The adoption of the United Nations Sustainable Development Goals (SDGs) in 2015, particularly SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 15 (Life on Land), substantially increased scientific interest in sustainable remediation technologies. In the same year, the Paris Agreement further emphasized ecosystem restoration and climate-resilient land management.

Scientifically, phytoremediation evolved into a highly interdisciplinary field incorporating microbiology, environmental engineering, nanotechnology, biotechnology, and agricultural sciences. Research increasingly explored microbial-assisted remediation, biochar amendments, and integrated remediation strategies rather than relying solely on plant uptake.

Phase IV (2020–2026): Transition toward Nature-Based Solutions

The most pronounced increase in publication activity occurred after 2020, when annual scientific production exceeded 2,000 publications for the first time.

Several factors likely contributed to this rapid expansion. The launch of the United Nations Decade on Ecosystem Restoration (2021–2030) placed ecological restoration among the highest global environmental priorities. Simultaneously, the European Green Deal, the EU Biodiversity Strategy for 2030, and increasing international investment in climate adaptation and sustainable agriculture significantly expanded research on nature-based solutions.

During this period, phytoremediation research increasingly incorporated artificial intelligence, machine learning, biochar, microbial ecology, precision agriculture, remote sensing, unmanned aerial vehicles (UAVs), and digital environmental monitoring. Consequently, phytoremediation became viewed not only as a remediation technology but also as an important component of ecosystem restoration, climate resilience, carbon sequestration, and circular bioeconomy strategies.

The **Web of Science Core Collection** exhibited publication dynamics highly consistent with those observed in Scopus. Annual scientific output increased from 209 publications in 2001 to 1,992 publications in 2021, remaining above 1,800 publications annually thereafter and reaching 2,010 publications in 2025. Similar to Scopus, the lower value reported for 2026 (1,133 publications) reflects partial database coverage during an incomplete publication year.

Although the absolute number of indexed publications was consistently lower than in Scopus, both databases demonstrated nearly identical long-term growth patterns. This consistency indicates that the expansion of phytoremediation research represents a genuine global scientific trend rather than differences in database coverage.

The temporal evolution observed in the Web of Science closely mirrors the four developmental phases identified in Scopus. Early research focused primarily on heavy metal accumulation by hyperaccumulator plants. Subsequently, research expanded toward integrated remediation strategies involving soil chemistry, microbial ecology, and environmental biotechnology. More recently, the field has increasingly emphasized digital technologies, nature-based solutions, and ecosystem restoration, reflecting broader transformations in environmental research priorities.

The slightly lower publication counts recorded by the Web of Science are primarily attributable to its more selective journal indexing policy, whereas Scopus includes a broader range of international journals, particularly within environmental sciences, agricultural research, and engineering disciplines.

Despite differences in database coverage, the overall publication trajectories are remarkably similar (Figure 1). Both databases demonstrate continuous growth throughout the study period without prolonged periods of decline. This agreement strengthens the robustness of the bibliometric analysis and confirms that phytoremediation has become one of the fastest-growing research areas in environmental remediation.

The synchronized increase observed after 2015 and the particularly rapid expansion after 2020 suggest that global environmental policies, climate-related initiatives, and the growing emphasis on sustainable and nature-based remediation strategies have fundamentally reshaped the scientific landscape of phytoremediation. Rather than remaining a specialized technology for heavy metal removal, phytoremediation has evolved into an interdisciplinary research field integrating environmental science, biotechnology, microbiology, digital technologies, and ecosystem restoration.

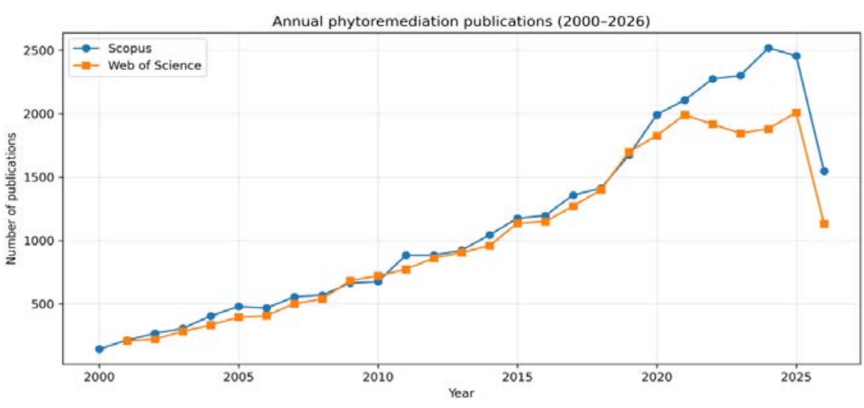

Fig. 1. Comparison between Scopus and Web of Science

Subject Area Distribution. Phytoremediation research is inherently multidisciplinary, integrating concepts from environmental sciences, agriculture, biology, chemistry, engineering, and increasingly digital technologies. The distribution of publications across subject areas in Scopus reflects this interdisciplinary character and illustrates how the field has expanded beyond its original scientific scope.

As expected, Environmental Science represents the dominant research area, accounting for 19,474 publications, which confirms that phytoremediation remains primarily an environmental remediation technology aimed at restoring contaminated ecosystems and improving environmental quality. The strong representation of this subject area reflects the growing global concern regarding soil degradation, heavy metal contamination, industrial pollution, and ecosystem restoration.

The second largest research domain is Agricultural and Biological Sciences, with 11,062 publications. This substantial contribution highlights the fundamental role of plant physiology, soil science, agronomy, and ecological interactions in the development of phytoremediation technologies. Many studies within this category focus on plant tolerance mechanisms, hyperaccumulator species, crop productivity on contaminated soils, and rhizosphere processes that influence contaminant uptake.

A considerable number of publications are also indexed under Biochemistry, Genetics and Molecular Biology (4,111 publications), indicating the increasing application of molecular approaches to investigate gene expression, stress-response pathways, and plant–microbe interactions. These studies have significantly improved the understanding of the biological mechanisms underlying contaminant uptake, transport, detoxification, and tolerance.

The contribution of Medicine (2,900 publications) and Chemistry (2,870 publications) reflects the close relationship between environmental contamination and human health, as well as the importance of chemical characterization of pollutants, soil amendments, and remediation processes. Engineering disciplines also play an important role, with 2,752 publications classified under Engineering, demonstrating the growing interest in designing integrated remediation systems, treatment technologies, and field-scale applications.

Other well-represented disciplines include Earth and Planetary Sciences (2,118 publications), Chemical Engineering (2,028), Immunology and Microbiology (1,712), and Energy (1,589). The increasing contribution of microbiology illustrates the shift toward microbiome-assisted phytoremediation, while the presence of energy-related research reflects the growing interest in combining remediation with biomass production and bioenergy generation.

Although traditionally considered a biological and environmental technology, phytoremediation has gradually expanded into computational and technological domains. Computer Science (687 publications), Materials Science (708), Mathematics (137), and Decision Sciences (63) collectively demonstrate the emergence of digital approaches, including artificial intelligence, machine learning, geographic information systems, remote sensing, precision agriculture, and decision-support systems. Although these disciplines currently represent a relatively small proportion of the total literature, their rapid growth during the last decade indicates an important transformation of phytoremediation into a data-driven and technology-supported research field.

Document Types. The analysis of document types indicates that phytoremediation research is primarily disseminated through peer-reviewed journal articles, which constitute the overwhelming majority of the scientific literature.

Among the retrieved publications, 22,564 documents were classified as research articles, representing the principal medium for communicating original scientific findings. This dominance demonstrates the high level of experimental and applied research conducted within the field and reflects the continuous generation of new knowledge related to remediation technologies, plant physiology, soil science, microbiology, and environmental engineering.

The second largest document category consists of review articles (3,042 publications). The substantial number of reviews indicates that phytoremediation has reached a level of scientific maturity where periodic synthesis of accumulated knowledge has become essential. Review papers increasingly focus not only on heavy metal remediation but also on emerging topics such as microbial-assisted phytoremediation, biochar applications, nanotechnology, climate resilience, and nature-based solutions.

A further 2,766 book chapters demonstrate the growing educational and interdisciplinary importance of phytoremediation, while 1,402 conference papers reflect active scientific communication and the rapid dissemination of emerging research findings.

Other document types including books, editorials, conference reviews, notes, short surveys, letters, and data papers represent only a small proportion of the total literature, indicating that scientific progress in this field is primarily communicated through peer-reviewed journal publications.

The predominance of original research articles and comprehensive review papers confirms that phytoremediation has evolved into a well-established research discipline characterized by continuous scientific development and strong international research activity.

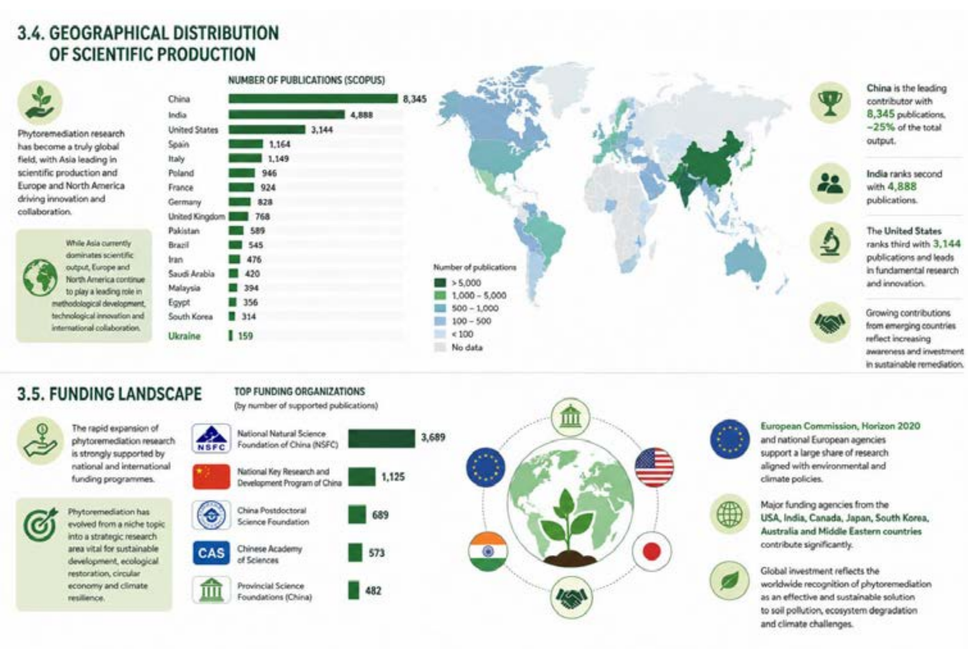

Fig. 2. Geographical Distribution of Scientific Production

Geographical Distribution. The geographical distribution of publications reveals considerable differences in national research productivity and demonstrates the increasing global interest in phytoremediation (Figure 2).

China is by far the leading contributor, with 8,345 publications, accounting for approximately one-quarter of the total scientific output indexed in Scopus. China's dominant position reflects extensive governmental investment in environmental remediation, sustainable agriculture, and ecological restoration, as well as the country's need to address widespread soil contamination associated with rapid industrialization and intensive agricultural production. Strong national funding programmes and the active participation of the Chinese Academy of Sciences and leading universities have further accelerated scientific productivity.

India ranks second with 4,888 publications, highlighting the country's long-standing interest in cost-effective and environmentally sustainable remediation technologies. The high publication output is closely related to increasing concerns regarding industrial pollution, mining activities, wastewater irrigation, and heavy metal contamination affecting agricultural soils.

The United States occupies the third position with 3,144 publications. Although the total number of publications is lower than that of China and India, the United States has made substantial contributions to the fundamental development of phytoremediation, particularly in plant physiology, molecular biology, environmental biotechnology, and risk assessment.

Several European countries also demonstrate strong research activity. Spain (1,164 publications), Italy (1,149), Poland (946), France (924), Germany (828), and the United Kingdom (768) collectively represent one of the world's most productive research regions. Their scientific output reflects long-term investments in environmental protection, sustainable land management, circular economy initiatives, and the implementation of European environmental policies, including the European Green Deal and the EU Soil Strategy.

Among emerging contributors, Pakistan, Brazil, Iran, Saudi Arabia, Malaysia, Egypt, and South Korea have experienced particularly rapid growth in publication activity during the last decade. This expansion reflects increasing awareness of environmental degradation, rapid industrial development, and growing investment in sustainable remediation technologies.

Although Ukraine contributed 159 publications, its research output remains comparatively modest relative to leading countries. Nevertheless, increasing international collaboration and growing interest in post-conflict environmental restoration suggest significant opportunities for future development of phytoremediation research within the country.

Funding Landscape. The analysis of funding sources reveals that the rapid expansion of phytoremediation research has been strongly supported by national and international research funding programmes.

The National Natural Science Foundation of China (NSFC) is by far the largest funding organization, supporting 3,689 publications. Several additional Chinese funding programmes – including the National Key Research and Development Program of China, the China Postdoctoral Science Foundation, the Chinese Academy of Sciences, and numerous provincial science foundations – also rank among the leading sponsors. This funding landscape reflects China's strategic prioritization of environmental remediation, ecological restoration, and sustainable agricultural development.

International funding also plays an important role. The European Commission, Horizon 2020 Framework Programme, European Regional Development Fund, and various national European funding agencies have supported a substantial number of publications, highlighting the importance of phytoremediation within European environmental and climate policies.

In addition, major funding agencies from the United States, India, Canada, Japan, South Korea, Australia, and several Middle Eastern countries contribute significantly to global research activity. The diversity of funding organizations illustrates the worldwide recognition of phytoremediation as an effective and sustainable approach to addressing soil pollution, ecosystem degradation, and climate-related environmental challenges.

The strong participation of governmental funding agencies further demonstrates that phytoremediation has evolved from a niche research topic into a strategic area of environmental research with growing relevance for sustainable development, ecological restoration, circular economy, and climate resilience.

Citation Characteristics. The citation indicators obtained from the Web of Science Core Collection provide additional evidence of the scientific significance and growing influence of phytoremediation research. The dataset includes 219 Highly Cited Papers, indicating that a substantial number of publications belong to the top 1% most cited papers within their respective research fields and publication years. This reflects the strong international visibility of phytoremediation research and its important contribution to addressing environmental pollution, ecosystem restoration, and sustainable land management.

Only three publications are classified as Hot Papers, representing recently published studies that have rapidly accumulated citations and rank among the top 0.1% in their fields. Although their number is limited, these papers demonstrate that phytoremediation remains an active and evolving research area, with emerging topics attracting immediate attention from the scientific community.

The dataset contains 2,416 review articles, highlighting the maturity of the research field. The large number of reviews indicates that phytoremediation has progressed beyond the stage of isolated experimental studies toward the synthesis and critical evaluation of accumulated knowledge. These publications play a key role in identifying research trends, methodological advances, and future research priorities while supporting interdisciplinary collaboration.

A further indicator of the field's dynamic development is the presence of 191 Early Access publications, showing that new findings continue to be disseminated rapidly before assignment to regular journal issues. This reflects both the sustained research activity and the demand for timely communication of scientific results.

Open Science has become an increasingly important feature of phytoremediation research. Among the retrieved records, 8,666 publications are available in Open Access, representing a considerable share of the overall dataset. The widespread adoption of open-access publishing improves the accessibility and visibility of research findings, facilitates international knowledge exchange, and may contribute to increased citation impact.

The Web of Science dataset also includes 4,697 publications with Enriched Cited References, indicating enhanced citation metadata that supports more comprehensive bibliometric analyses. The availability of enriched reference information improves the reliability of citation network analyses, co-citation studies, and the identification of intellectual relationships within the field.

Finally, only 15 Open Publisher-Invited Reviews were identified. This relatively small number reflects the limited implementation of open peer-review practices by scientific publishers rather than any characteristic of phytoremediation research itself.

Emerging Technologies in Phytoremediation Research. The overlay visualization of keyword co-occurrence reveals a clear evolution of phytoremediation research towards the integration of advanced digital technologies and data-driven approaches. While earlier studies primarily focused on plant species, heavy metal uptake, soil contamination, and pollutant removal mechanisms, more recent publications increasingly incorporate artificial intelligence, remote sensing technologies, and digital monitoring systems.

One of the most noticeable emerging trends is the growing application of artificial intelligence (AI) and machine learning (ML) algorithms. These approaches are increasingly employed to predict remediation efficiency, optimize plant selection, model contaminant transport, and analyse large environmental datasets. The integration of AI-based methods enables researchers to improve prediction accuracy while supporting automated decision-making for site management and environmental risk assessment.

Another rapidly expanding research direction involves remote sensing, hyperspectral imaging, and drone-based monitoring. These technologies allow continuous, non-destructive assessment of vegetation health, pollutant distribution, and remediation progress across large and often inaccessible areas. Compared with conventional field measurements, remote sensing techniques provide high spatial and temporal resolution, making them valuable tools for long-term environmental monitoring.

The emergence of Geographic Information Systems (GIS) further demonstrates the increasing importance of spatial analysis in phytoremediation studies. GIS technologies facilitate the mapping of contaminated sites, assessment of environmental risks, and identification of priority areas for remediation. When combined with remote sensing data, GIS enables comprehensive spatial modelling and supports evidence-based environmental management.

Recent publications also indicate growing interest in the Internet of Things (IoT) and Big Data technologies. Networks of environmental sensors enable continuous collection of real-time information on soil, water, and atmospheric conditions, while Big Data analytics allows researchers to process large and heterogeneous datasets generated through monitoring programs. Together, these technologies improve the efficiency of environmental observations and contribute to more accurate assessments of remediation performance.

An emerging interdisciplinary direction is the development of Decision Support Systems (DSS) that integrate environmental monitoring, predictive modelling, geographic information, and artificial intelligence. Such systems assist researchers and environmental managers in selecting appropriate remediation strategies under different ecological and climatic conditions.

Finally, although still represented by a relatively limited number of publications, Digital Twins have recently appeared as a promising research topic. Digital twin technology enables the creation of virtual representations of contaminated ecosystems that continuously incorporate monitoring data, allowing simulation of remediation scenarios, prediction of long-term outcomes, and optimization of management decisions before field implementation (Figure 3).

Discussion. The bibliometric analysis demonstrates that phytoremediation research has undergone a profound transformation over the past three decades. Rather than representing a simple increase in publication output, the field has evolved conceptually, moving from a predominantly plant-based remediation strategy toward an integrated environmental management framework that combines biological, ecological, digital, and engineering approaches.

In the early stages of research, phytoremediation studies focused primarily on identifying suitable plant species capable of accumulating heavy metals and removing contaminants from soil. Scientific attention was directed towards plant physiology, metal uptake mechanisms, contaminant tolerance, and remediation efficiency. During this period, plants were considered the principal remediation agents, while environmental conditions were generally treated as external factors influencing remediation performance.

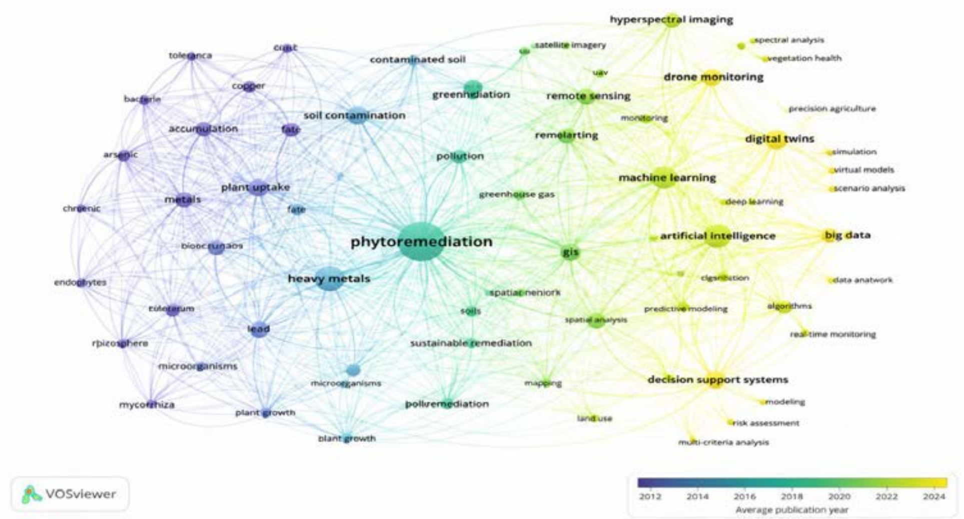

Fig. 3. Visualization of keyword

As the field matured, researchers increasingly recognized that remediation efficiency depends not only on plant characteristics but also on complex interactions among soil microorganisms, rhizosphere processes, soil chemistry, and ecosystem functioning. Consequently, new concepts such as the plant microbiome, plant–microbe interactions, biochar-assisted phytoremediation, and ecological restoration became integral components of phytoremediation research. This shift reflects a transition from studying isolated biological processes to understanding contaminated ecosystems as dynamic and interconnected systems.

More recently, the rapid development of digital technologies has further expanded the scope of phytoremediation research. Artificial intelligence, machine learning, remote sensing, hyperspectral imaging, unmanned aerial vehicles, Geographic Information Systems, Internet of Things sensor networks, Big Data analytics, and Decision Support Systems are increasingly employed to monitor contaminated sites, predict remediation outcomes, optimise remediation strategies, and support environmental decision-making. The emergence of Digital Twins represents another important step towards predictive environmental management, enabling virtual simulations of remediation scenarios using continuously updated monitoring data.

These developments indicate that phytoremediation is no longer viewed solely as a remediation technology but increasingly as a component of broader nature-based solutions addressing environmental degradation, climate resilience, ecosystem restoration, and sustainable land management. The growing integration of phytoremediation with concepts such as climate adaptation, carbon sequestration, biodiversity conservation, and circular economy reflects changing international research priorities driven by global environmental challenges.

The geographical distribution of publications supports this interpretation. China has become the dominant contributor to global phytoremediation research, reflecting sustained national investments in environmental protection, ecological restoration, and remediation of widespread industrial soil contamination. Rapid industrialisation and urbanisation have created substantial demand for efficient remediation technologies, while national research programmes have supported large-scale scientific activity in this area. The United States and several European countries continue to make important contributions, particularly through research on ecosystem restoration, ecological engineering, environmental monitoring, and advanced analytical technologies. Meanwhile, increasing research output from India and other emerging economies reflects growing concern over soil degradation, mining activities, agricultural contamination, and water quality, together with expanding investments in environmental research.

Funding patterns further illustrate the evolution of the field. A substantial proportion of highly cited publications acknowledge support from major national funding agencies, including the National Natural Science Foundation of China (NSFC), the National Key Research and Development Program of China, the U.S. National Science Foundation (NSF), the National Institutes of Health (NIH), the European Commission through successive Framework Programmes and Horizon 2020/Horizon Europe, the German Research Foundation (DFG), the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Japan Society for the Promotion of Science (JSPS). These funding programmes increasingly prioritise interdisciplinary research, digital technologies, climate resilience, and sustainable environmental management, thereby accelerating the integration of ecological and computational approaches within phytoremediation research.

The convergence of funding priorities, technological innovation, and global environmental policies has reshaped the scientific landscape of phytoremediation. Rather than focusing exclusively on pollutant removal, contemporary research seeks to develop intelligent, adaptive, and sustainable remediation systems capable of responding to complex environmental challenges. This evolution is consistent with international policy initiatives, including the United Nations Sustainable Development Goals, the European Green Deal, the Zero Pollution Action Plan, and the growing emphasis on Nature-based Solutions as effective strategies for achieving environmental sustainability.

Research Gaps and Future Directions. Despite the rapid expansion of phytoremediation research, several important scientific and technological challenges remain insufficiently addressed. The bibliometric analysis indicates that although considerable progress has been achieved in understanding plant-based remediation mechanisms, many emerging research areas are still represented by relatively few publications and remain at an early stage of development.

One of the most significant research gaps concerns the application of artificial intelligence and machine learning for predictive modelling of phytoremediation performance. Current studies primarily use AI for data analysis and classification, whereas robust predictive models capable of integrating biological, environmental, climatic, and geospatial variables remain limited. The development of explainable and transferable AI models represents an important direction for improving decision-making in contaminated site management.

Another emerging area is the application of Digital Twin technology. Although the concept has recently appeared in environmental research, its implementation in phytoremediation is still in its infancy. Digital Twins have the potential to combine real-time environmental monitoring, remote sensing, process modelling, and artificial intelligence into virtual representations of contaminated ecosystems, enabling simulation of remediation scenarios and optimization of management strategies before field implementation.

The bibliometric results also reveal that the integration of unmanned aerial vehicles (UAVs), hyperspectral imaging, Internet of Things (IoT) sensor networks, and real-time environmental monitoring remains relatively limited. These technologies could substantially improve the temporal and spatial resolution of remediation monitoring while reducing operational costs and enabling continuous assessment of remediation efficiency.

Another important gap concerns microbiome engineering. Increasing evidence suggests that rhizosphere microorganisms strongly influence contaminant transformation, nutrient cycling, and plant stress tolerance. However, the targeted manipulation of plant-associated microbial communities to enhance phytoremediation efficiency remains insufficiently explored and requires greater integration of microbiology, biotechnology, and systems ecology.

Future studies should also move beyond remediation of single contaminants toward multi-contaminant systems, where heavy metals, metalloids, organic pollutants, pharmaceuticals, pesticides, microplastics, and emerging contaminants coexist within the same environment. In particular, per- and polyfluoroalkyl substances (PFAS) have become a global environmental concern due to their persistence, mobility, and resistance to conventional remediation methods. Their interaction with phytoremediation processes remains poorly understood and deserves increased scientific attention.

The growing impacts of climate change introduce another important research challenge. Future phytoremediation systems must operate under changing environmental conditions, including drought, flooding, salinity, heat stress, and extreme weather events. Consequently, stronger integration of phytoremediation research with climate adaptation strategies, ecosystem resilience, and sustainable land management is needed to ensure long-term remediation effectiveness.

An additional priority concerns the remediation of war-contaminated environments. Armed conflicts generate complex mixtures of heavy metals, petroleum hydrocarbons, explosives, combustion products, and military-related pollutants that differ substantially from conventional industrial contamination. The ongoing environmental consequences of military activities, particularly in Ukraine and other conflict-affected regions, highlight the urgent need to develop phytoremediation approaches specifically adapted to these complex contamination scenarios.

Taken together, these research gaps indicate that the next generation of phytoremediation will extend far beyond conventional plant-based remediation. Future research is expected to integrate artificial intelligence, autonomous monitoring systems, remote sensing, Digital Twins, microbiome-associated technologies, and advanced environmental modelling into comprehensive decision-support frameworks. At the same time, phytoremediation will become increasingly embedded within broader concepts of Nature-based Solutions, climate adaptation, ecosystem restoration, and the circular economy, supporting not only contaminant removal but also carbon sequestration, biodiversity conservation, resource recovery, and sustainable landscape management.

This transition reflects the ongoing evolution of phytoremediation from an environmental remediation technique into a multidisciplinary platform that combines ecological processes, digital technologies, and sustainable development principles to address increasingly complex environmental challenges.

Conclusions. This This bibliometric study shows that phytoremediation has evolved from a technology mainly focused on heavy metal removal into a multidisciplinary research field combining plant science, microbiology, environmental engineering, digital technologies, and sustainability.

Scientific output has steadily increased over the past 25 years, while research priorities have shifted from contaminant removal and plant selection toward rhizosphere microbiomes, biochar-assisted remediation, remote sensing, artificial intelligence, machine learning, and other digital tools. These developments reflect the growing role of phytoremediation within Nature-based Solutions, ecosystem restoration, climate adaptation, and the circular economy.

The geographical analysis demonstrates the global expansion of phytoremediation research. China is the leading contributor, followed by the United States, India, and several European countries, highlighting the importance of international collaboration.

The analysis of funding sources shows that the field has been strongly supported by major national and international funding agencies, which have promoted interdisciplinary research and accelerated the integration of biological, environmental, and digital approaches.

The results indicate that phytoremediation is moving toward intelligent, data-driven, and integrated environmental management. Bibliometric analysis also proved to be an effective tool for identifying research trends, knowledge gaps, and future directions. Future research is expected to further strengthen the integration of microbiome engineering, digital technologies, climate adaptation, and circular economy principles to improve the efficiency and sustainability of phytoremediation.

REFERENCES:

1. Ali H., Khan E., Sajad M. A. Phytoremediation of heavy metals–Concepts and applications. Chemosphere. 2013. Vol. 91, No. 7. P. 869–881. DOI: https://doi.org/10.1016/j.chemosphere.2013.01.075.
2. Beesley L., Moreno-Jiménez E., Gomez-Eyles J. L. Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. Environmental Pollution. 2010. Vol. 158, No. 6. P. 2282–2287. DOI: https://doi.org/10.1016/j.envpol.2010.02.003.
3. Houben D., Evrard L., Sonnet P. Mobility, bioavailability and pH-dependent leaching of cadmium, zinc and lead in a contaminated soil amended with biochar. Chemosphere. 2013. Vol. 92, No. 11. P. 1450–1457. DOI: https://doi.org/10.1016/j.chemosphere.2013.03.055.
4. Kumar P. B. A. N., Dushenkov V., Motto H., Raskin I. Phytoextraction: The use of plants to remove heavy metals from soils. Environmental Science & Technology. 1995. Vol. 29, No. 5. P. 1232–1238. DOI: https://doi.org/10.1021/es00005a014.
5. Li C., Ji X., Luo X. Phytoremediation of heavy metal pollution: A bibliometric and scientometric analysis from 1989 to 2018. International Journal of Environmental Research and Public Health. 2019. Vol. 16, No. 23. Art. 4755. DOI: https://doi.org/10.3390/ijerph16234755.
6. McGrath S. P., Zhao F. J. Phytoextraction of metals and metalloids from contaminated soils. Current Opinion in Biotechnology. 2003. Vol. 14, No. 3. P. 277–282. DOI: https://doi.org/10.1016/S0958-1669(03)00060-0.
7. Salt D. E., Smith R. D., Raskin I. Phytoremediation. Annual Review of Plant Physiology and Plant Molecular Biology. 1998. Vol. 49. P. 643–668. DOI: https://doi.org/10.1146/annurev.arplant.49.1.643.
8. van der Ent A., Baker A. J. M., Reeves R. D., Pollard A. J., Schat H. Hyperaccumulators of metal and metalloid trace elements: Facts and fiction. Plant and Soil. 2013. Vol. 362. P. 319–334. DOI: https://doi.org/10.1007/s11104-012-1287-3.
9. Zhang K., Liu F., Zhang H., Duan Y., Luo J., Sun X., Wang M., Ye D., Wang M., Zhu Z., Li D. Trends in phytoremediation of heavy metals-contaminated soils: A Web of Science and CiteSpace bibliometric analysis. Chemosphere. 2024. Vol. 352. Art. 141293. DOI: https://doi.org/10.1016/j.chemosphere.2024.141293.
10. Zhao X., Lei M., Gu R. Knowledge mapping of the phytoremediation of cadmium-contaminated soil: A bibliometric analysis from 1994 to 2021. International Journal of Environmental Research and Public Health. 2022. Vol. 19, No. 12. Art. 6987. DOI: https://doi.org/10.3390/ijerph19126987.

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