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Rakhisheva A., Rakhymzhan Zh., Beisenova R.

Eurasian National University named after L.N. Gumilev, Astana, Kazakhstan

E-mail: Aizhan_enu@mail.ru

PHYTOREMEDIATION OF SOILS IN INDUSTRIAL AREAS: BIBLIOMETRIC ANALYSIS OF SCIENTIFIC PUBLICATIONS

Annotation. This study presents a bibliometric analysis of 6,832 scientific publications on the topic of phytoremediation of heavy metals in soils, published between 2000 and 2025 and retrieved from the Web of Science Core Collection database. The aim was to conduct an international bibliometric assessment and to identify the potential applications of phytoremediation in the industrial regions of Central Kazakhstan. Data processing and visualization of scientific networks were performed using VOSviewer (version 1.6.20), while graphs were generated with Microsoft Excel. The publication dynamics revealed approximately 458 articles in 2000–2009, 989 articles in 2010–2017, and 5,385 articles in 2018–2025. Network analysis using VOSviewer identified China (2,173 articles), India (1,460 articles), and the USA (828 articles) as the leading countries, based on author affiliation data. Cluster analysis of keywords highlighted “phytoremediation,” “heavy metals,” and “bioremediation” as the main thematic directions of the research field. The bibliometric findings suggest the following steps for applying phytoremediation methods in the industrial zones of Central Kazakhstan: mapping contaminated areas, determining heavy metal concentrations in soils, selecting plant species adapted to the local climate, and conducting experimental trials.

Keywords: phytoremediation, phytoextraction, phytostabilization, bibliometric analysis, heavy metals, contaminated soils, Web of Science Core Collection, VOSviewer.

Introduction

Soil pollution of industrial areas with heavy metals is currently one of the most pressing environmental problems. As a result of intensive economic development and uncontrolled mining in Kazakhstan, soil, vegetation, atmosphere and water ecosystems are heavily polluted with heavy metals [1]. Environmental pollutants are classified into organic and inorganic [2]. Inorganic pollutants in soil are persistent in the environment and do not decompose. Excessive concentrations of heavy metals are caused by human activities [3]. Heavy metals are considered one of the most dangerous groups of inorganic pollutants due to their properties such as high toxicity, easy migration, long - term persistence in the environment, bioaccumulation and teratogenic effects on the human body [4,5]. Living organisms require a certain amount of heavy metals, including Cu, Fe, Zn, Se and Mn, for normal functioning [6]. Other metals such as As, Pb, Cd and Hg can be very dangerous even in small quantities [7]. Heavy metals pose a significant threat to aquatic ecosystems and human health due to their toxicity, environmental persistence, and bioaccumulative potential [8]. The main anthropogenic sources of heavy metals in the natural environment include heavy

industry (metallurgical, chemical, or petroleum refining), fossil fuel combustion (power plants, boilers, road transport), and intensive agriculture (artificial fertilizers, plant protection products) [9, 10]. With industrialization and technological progress, human impact on the environment has increased significantly over the past two centuries [11]. Metallurgy, mining, metal plating, electroosmosis, electrolysis, distilleries, tanning, photography, paints, varnishes, textiles, plastics, rubber, leather, paper, cosmetics, food, pharmaceuticals, steel, energy, fertilizers, pesticides, aerospace and nuclear power plants are among the main sources of pollutants [12]. Central Kazakhstan is one of the most industrialized regions of the country, where the historical development of metallurgy and mining has led to significant soil contamination with heavy metals. Exceeding the permissible maximum concentrations of Pb, Zn and Cu in soils poses a significant threat to ecosystems and public health [13]. The results obtained indicate significant environmental risks. Recultivation and the introduction of sustainable technologies are necessary to restore degraded lands [14].

Chemical and physical methods are used to remove heavy metals. However, they are more expensive, create secondary pollutants, and can damage soil properties [15]. In this regard, it is important to clean up soils contaminated with heavy metals using an economical and environmentally friendly technology - phytoremediation. Phytoremediation is a sustainable and environmentally friendly technology [16]. Two main methods are used in phytoremediation of heavy metals: phytostabilization and phytoextraction. Plants that inhibit the transfer of metals to the upper parts of the plant (stems) and allow them to accumulate only in the roots are considered phytostabilizers and bioindicators [17]. Both of these methods are based on the ability of plants to survive in heavily contaminated soils, produce high biomass, and exhibit low levels of phytotoxicity [18]. The main advantage of phytoremediation is the ability to accumulate pollutants in plant biomass and then remove them by processing. The collection and subsequent processing of biomass (burning the plant and safely disposing of the resulting ash or using it as a secondary raw material) increases the suitability and sustainability of this method [19 , 20].

As indicated in the literature, bibliometrics is a method of analyzing scientific publications using quantitative and statistical methods, assessing the structure and dynamics of the literature system [21]. In addition, the WoSCC is the largest academic database widely used for bibliometric analysis. It provides information on authors, journals, institutions, countries, and funding. For visualization, programs such as CiteSpace, HistCite, and VOSviewer are used [22]. VOSviewer is a Java application that uses visualization and cluster analysis to map the dynamics of research areas [23] Despite the significant volume of scientific research on phytoremediation of contaminated soils, a systematic bibliometric analysis of scientific publications in this area has not yet been fully explored. The number of studies assessing global scientific trends and their application to industrially contaminated areas of Central Kazakhstan is limited. The purpose of this article is to conduct a bibliometric analysis of international scientific publications on phytoremediation of soils contaminated with heavy metals and to identify the possibilities of their application in Central Kazakhstan. We aim to conduct the following analyses:

• Analytical review of international scientific publications in the Web of Science Core Collection on the topic of phytoremediation of heavy metal contaminated soil;

• Identification of leading research areas and description of their development dynamics;

• Analysis of the scientific network of keywords and countries using the VOSviewer program;

• Proposal of promising directions for the Central Kazakhstan region.

Materials and methods

Data source and search strategy

A bibliometric analysis was performed using data indexed in the WoSCC system. The literature search was conducted using the following keywords: "phytoremediation", "phytoextraction", "phytostabilization", "heavy metals", "industrial soils", "soil contamination", "industrial area". The search was performed using the following one-way query equation: TS=("phytoremediation") AND TS=("heavy metal") AND TS=("industrial soil"). Research area: environmental sciences, ecology. Only scientific articles (articles) and review articles (review articles) were included in the analysis. The analysis period covered the period from 2000 to 2025. This period was chosen to reflect the period of active development of phytoremediation technologies and modern methods of soil restoration. The search resulted in approximately 6832 publications. The search for publications was conducted in January 2026. The analysis of publication activity by year was conducted based on the publication year of each document.

Bibliometric analysis methodology

Bibliometric analysis was conducted using the VOSviewer (1.6.20) [24] program based on WoSCC data. The fractional counting method was used to create maps. The minimum occurrence for keywords was set at 5. During the analysis, a network of scientific collaboration (co-authorship) between countries and clusters of frequently occurring keywords (co-occurrence) were identified. The results of the visualization allowed us to identify the main research directions. The graphs were created using Microsoft Excel.

Research results

Dynamics of publication activity

Analysis of the dynamics of publication activity from 2000 to 2025 showed a steady increase in interest in phytoremediation of contaminated soils in industrial areas. Figure 1 shows the dynamics of the number of publications in 2000-2025. The number of publications in 2000-2009 was about 458 articles, which indicates the development period of this scientific field. In 2010-2017, there were about 989 articles, during which years there was an increase in the number of publications due to the increased global attention to environmental safety and sustainable development. The most intensive growth was observed in 2018-2025, when about 5385 articles were published. This indicates the transition of phytoremediation from experimental research to applied environmental technologies.

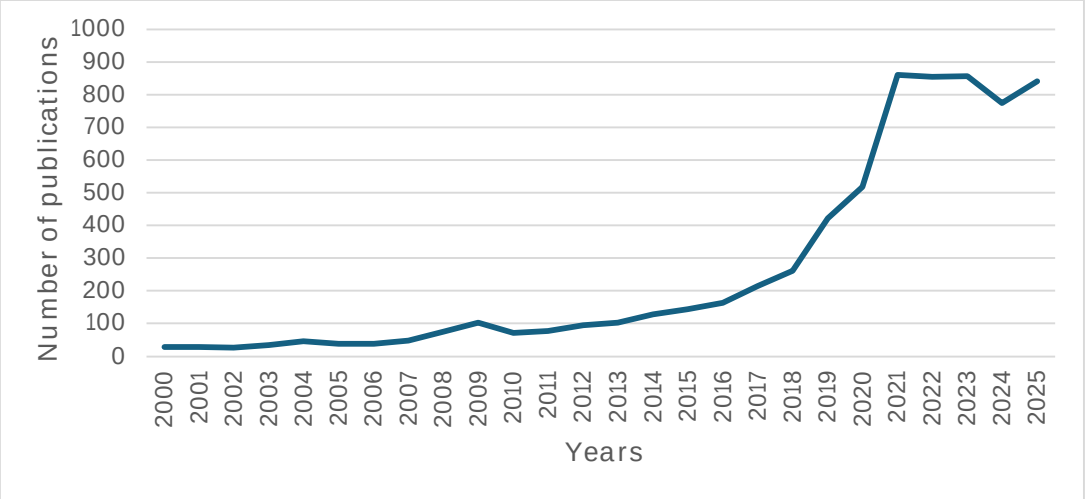


Figure 1. Dynamics of the number of publications registered in the WoSCC database from 2000 to 2025.

These data confirm the emergence of a sustainable scientific trend and the expansion of the research base in this field. The graph shows a long-term growth in scientific activity.

Analysis of the geography of research

Figure 2 shows the distribution of publication activity by country for the period 2000-2025. The graph shows the top 20 countries in terms of the number of publications. The top three in terms of the number of publications are China, India, and the United States. The remaining countries have relatively low figures. The analysis was based on author affiliation data. If one publication belongs to authors from several countries, it was counted separately for each country. This approach allows for a more complete reflection of international scientific cooperation.

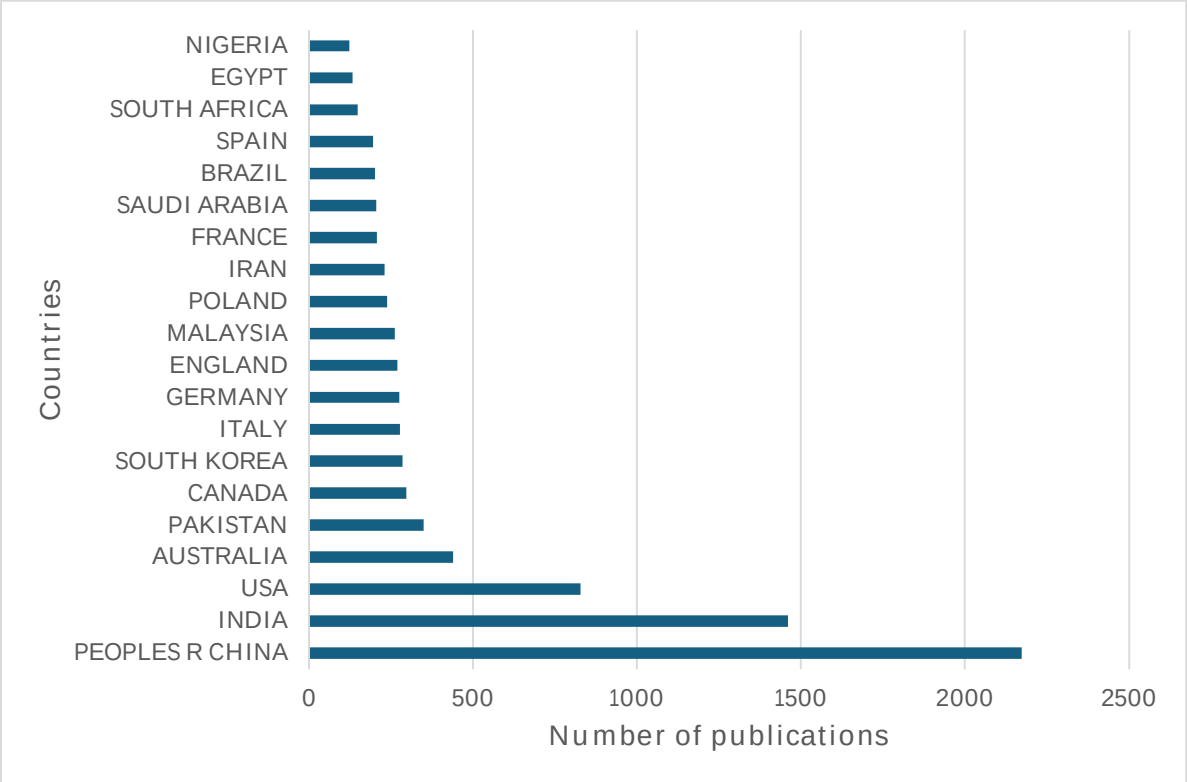


Figure 2. Top 20 countries by number of publications registered in the WoSCC database for 2000–2025.

The distribution of publications across countries reflects a structure of scientific collaboration, with a few key countries dominating, while the remaining countries act as anchor nodes in an international network.

Figure 3 depicts the network of scientific collaboration across countries in terms of publications. Each node represents an individual country, and the size of the nodes corresponds to the volume of publications. The lines between the nodes indicate joint publications between countries. The colors divide the countries into clusters, which indicate their level of clustering in scientific collaboration. The People's Republic of China, India, and the United States appear as the largest nodes, leading the way in international collaboration.

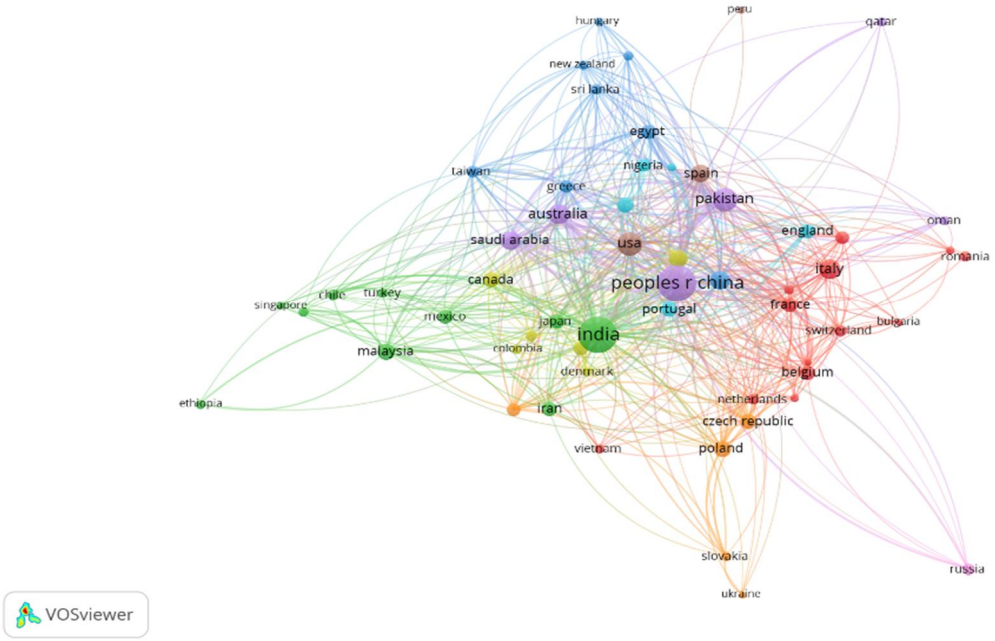


Figure 3. Network of scientific collaboration (co-authorship) between countries based on the WoSCC database (VOSviewer, 2026).

The co-authorship map clearly demonstrates the international nature of the field under study. Leading countries act as the main centers for the development of scientific collaboration.

Frequent keywords

A cluster analysis of keywords identified the main thematic areas of the research area. Figure 4 shows a network map based on the co-occurrence of keywords. The size of the nodes indicates their frequency, and the lines indicate their interconnections. The colors represent clusters, i.e., thematic groupings. In the center are key concepts such as “phytoremediation”, “heavy metals” and “bioremediation”, which indicate the main areas of the research area. The green cluster contains terms related to phytoremediation and bioremediation, the red cluster contains heavy metals and soil remediation, the blue cluster contains soil pollution and plant species, and the yellow cluster contains the most common heavy metals. This map clearly shows the interconnections of research topics and the structure of scientific areas.

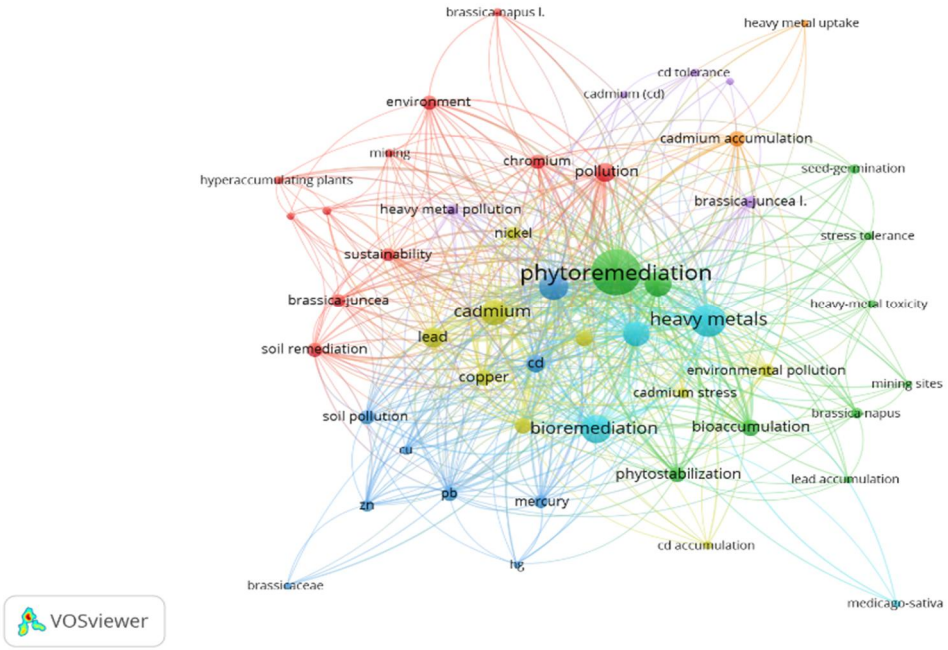


Figure 4. The most common keyword network for the topic “phytoremediation of heavy metals in soil” (VOSviewer, 2026).

The keyword structure reflects the interdisciplinary nature of this field and its development at the intersection of soil science, ecology, biotechnology, and environmental engineering.

Overlay analysis to identify current scientific trends

Overlay analysis allowed us to identify the evolution of thematic areas in the field of phytoremediation of heavy metals in soils over time. In the period 2000-2009, publications were mainly focused on studying the mechanisms of accumulation of heavy metals and physiological responses of plants. During this period, keywords such as "heavy metals", "accumulation", "plant uptake", "tolerance" are often found. In 2010–2015, the emergence of terms such as "bioremediation", "microorganisms", "rhizosphere", "nanoparticles" indicates the development of biotechnological approaches and increased interest in methods for enhancing phytoremediation. In 2016–2025, keywords such as "sustainability", "risk assessment", "green technology", "environmental management" became widespread. These years indicate a shift in the direction of research towards sustainable development and environmental safety. The identified trends indicate a gradual shift in scientific research from the fundamental level to complex, technological and applied solutions.

Prospects for the use of phytoremediation in the industrial zones of Central Kazakhstan

The industrial zones of Central Kazakhstan are characterized by the widespread distribution of soils contaminated with heavy metals as a result of the long-term intensive development of mining and metallurgy [25,26]. In the industrial zone of Central Kazakhstan, the soils around the Qarmet metallurgical complex located in the city of Temirtau are characterized by high levels of heavy metals. Geospatial studies have recorded levels exceeding the maximum permissible concentrations, which indicates a high anthropogenic load [27]. Harmful emissions from the Zhezkazgan copper smelter have a negative impact on

urban air pollution and public health. [28]. Metal losses in the slags of the Balkhash copper smelter were studied, and it was found that industrial waste has environmental consequences [29]. Among modern technologies for the restoration of contaminated areas, phytoremediation is currently considered one of the most promising and actively developing methods, especially in industrially developed regions [30]. The use of tolerant species of local flora, such as alfalfa (*Medicago sativa*), wormwood (*Artemisia absinthium L.*), mustard (*Brassica juncea*) and other plants, can reduce the accumulation of heavy metals and improve the ecological status of the soil [31]. Modern studies show that phytoremediation can be adapted to the arid and continental conditions of Kazakhstan, taking into account the specifics of the local environment. For example, experimental data indicate a high potential of drought - resistant sweet sorghum (*Sorghum bicolor L.*) for phytoremediation of Pb, Cd and Co contaminated soils [32]. The use of different plant species gives effective results in phytoremediation. Brassicaceae hybrids, amaranths and cereals are able to reduce the concentration of heavy metals in the soil and reduce their bioavailability. The growth and metal accumulation characteristics of different plants allow us to select the most effective species adapted to local conditions [33]. The results obtained provide important information for designing a plant selection strategy.

The results obtained indicate the possibility of using phytoremediation technologies in the industrial zones of Central Kazakhstan. Bibliometric analysis shows that in recent years, research has shifted to the areas of applied and sustainable development, which provides grounds for considering this approach at the regional level. In addition, when implementing the technology, it is necessary to take into account the limitations specific to the region. Arid climate and water scarcity affect plant growth, and soil salinization can contribute to the movement of heavy metals. In addition, the management of the collected biomass and the risk of heavy metals entering the food chain require an environmental assessment. In this regard, the implementation of phytoremediation should be carried out in the following stages: mapping of contaminated areas, determining the composition of the soil and the bioavailability of heavy metals, plant selection, testing with plants, biomass management and monitoring.

Conclusion

• The conducted bibliometric analysis showed a steady increase in the number of publications in the WoSCC on the topic of phytoremediation of soils contaminated with heavy metals between 2000 and 2025. Approximately 458 articles were published between 2000 and 2009, approximately 989 articles between 2010 and 2017, and approximately 5385 articles between 2018 and 2025. A total of 6832 publications were included in the analysis. This proves the growing scientific interest in biological remediation methods.

• The dynamics of the development of research areas revealed the rapid development of the areas of phytoextraction, phytostabilization, and the use of hyperaccumulating plants. These areas are aimed at increasing the efficiency of technologies in various climatic conditions.

• Based on the network analysis conducted using VOSviewer, China (2173 articles), India (1460 articles) and the USA (828 articles) were identified as the leading countries. The analysis of keywords revealed the following main areas of research: phytoremediation and bioremediation in the green cluster, heavy metals and soil remediation in the red, soil pollution and plant species in the blue, and common heavy metals in the yellow.

• Taking into account the results obtained, the following steps are recommended for the application of phytoremediation methods in the conditions of Central Kazakhstan:

mapping of contaminated areas, determination of heavy metals in the soil, selection of plants adapted to the local climate and testing with plants.

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Рахишева А.Д., Рахымжан Ж., Бейсенова Р.Р.

ӨНЕРКӘСІПТІК АУМАҚТАРДАҒЫ ТОПЫРАҚТЫҢ ФИТОРЕМЕДИАЦИЯСЫ: ҒЫЛЫМИ ЖАРИЯЛАНЫМДАРҒА БИБЛИОМЕТРИЯЛЫҚ ТАЛДАУ

Аңдатпа. Бұл зерттеуде Web of Science Core Collection дерекқорыннан алынған 2000-2025 жылдар аралығындағы топырақтағы ауыр металдардың фиторемедиациясы тақырыбына қатысты 6832 ғылыми жарияланымдарға библиометриялық талдау жасалды. Мақсаты халықаралық жарияланымдарға библиометриялық талдау жүргізу және Орталық Қазақстанда қолдану мүмкіндіктерін айқындау. Деректерді өңдеу және ғылыми байланыстарды визуализациялау үшін VOSviewer (1.6.20) бағдарламасы пайдаланылды. Графиктер Microsoft Excel бағдарламасының көмегімен жасалды. Жарияланымдардың жылдар бойынша динамикасы келесідей анықталды: 2000-2009 жылдары шамамен 458 мақала, 2010-2017 жылдары шамамен 989 мақала, 2018-2025 жылдары шамамен 5385 мақала жарияланған. VOSviewer арқылы жүргізілген желілік талдау негізінде Қытай (2173 мақала), Үндістан (1460 мақала) және АҚШ (828 мақала) жетекші елдер ретінде айқындалды. Талдау авторлардың аффилиация деректеріне негізделді. Кілт сөздерге жүргізілген кластерлік талдау нәтижесінде «phytoremediation», «heavy metals» және «bioremediation» зерттеу саласының негізгі тақырыптық бағыттарын анықталды. Жүргізілген библиометриялық талдау Орталық

Қазақстанның өнеркәсіптік аймақтарында фиторемедиация тәсілдерін қолданудың келесі қадамдарын ұсынады: ластанған аумақтарды карталау, топырақтан ауыр металдарды анықтау, жергілікті климатқа бейімделген өсімдіктерді таңдау және өсімдіктермен сынақ жүргізу.

Кілт сөздер: фиторемедиация, фитоэкстракция, фитостабилизация, библиометриялық талдау, ауыр металдар, ластанған топырақ, Web of Science Core Collection, VOSviewer.

Рахишева А.Д., Рахымжан Ж., Бейсенова Р.Р.

ФИТОРЕМЕДИАЦИЯ ПОЧВ ПРОМЫШЛЕННЫХ ТЕРРИТОРИЙ: БИБЛИОМЕТРИЧЕСКИЙ АНАЛИЗ НАУЧНЫХ ПУБЛИКАЦИЙ

Аннотация. В данном исследовании проведен библиометрический анализ 6832 научных публикаций по теме фиторемедиации почв, загрязнённых тяжёлыми металлами, за период 2000–2025 гг., извлечённых из базы данных Web of Science Core Collection. Цель работы заключалась в проведении международного библиометрического анализа и определении возможностей применения полученных результатов в условиях Центрального Казахстана. Для обработки данных и визуализации научных связей использовалась программа VOSviewer *(*версия 1.6.20). Графики были построены с помощью Microsoft Excel. Динамика публикаций по годам показала: в 2000–2009 гг. опубликовано около 458 статей, в 2010–2017 гг. около 989 статей, а в 2018–2025 гг. – около 5385 статей. Сетевой анализ, выполненный в VOSviewer, выявил ведущие страны: Китай (2173 публикации), Индия (1460 публикаций) и США (828 публикаций). Анализ проводился на основе данных об аффилиации авторов. Кластерный анализ ключевых слов показал, что основными тематическими направлениями исследований являются «phytoremediation», «heavy metals» и «bioremediation». Проведённый библиометрический анализ позволяет предложить следующие шаги для применения фиторемедиации в промышленных районах Центрального Казахстана: картирование загрязнённых территорий, определение содержания тяжёлых металлов в почве, подбор растений, адаптированных к местному климату, и проведение экспериментальных испытаний.

Ключевые слова: фиторемедиация, фитоэкстракция, фитостабилизация, библиометрический анализ, тяжёлые металлы, загрязнённые почвы, Web of Science Core Collection, VOSviewer.