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Global Research on Contaminated Soil Remediation: A Bibliometric Network Analysis

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Abstract: Soil is an important aspect of the ecosystem that plays a crucial role in human population sustainability. Due to natural and anthropogenic activity, soil pollution has become a major environmental issue around the world. Since 1985, researchers have been studying the prevention and treatment of polluted soils. This study used bibliometric approaches to evaluate the soil remediation dataset in the Web of Science database during 2001–2020 to show current research trends and hot themes in quantitative analysis and soil remediation around the world. The findings suggest that the area of soil remediation has entered a period of rapid advancement. China excelled over all other countries in terms of the number of independent and collaborative articles published across soil pollution research worldwide. The findings revealed that the leading journals in the field of soil remediation include *Science of the Total Environment*, *Microchemical Journal*, and *Journal of Hazardous Materials*. Following closely behind the Chinese Academy of Sciences (428) and Zhejiang University (106) was the Russian Academy of Sciences (87). Furthermore, keyword frequency and co-word analyses showed the most important research subjects. Among them, the hot themes were recognized as "heavy metals", "PAHs", "bioremediation", "phytoremediation", and "electrokinetic remediation". Understanding the current situation in soil remediation as well as providing directions for future research are the goals of this study.

Keywords: soil remediation; bibliometric analysis; research trends; heavy metals; PAHs

Citation: Gao, J.; Faheem, M.; Yu, X. Global Research on Contaminated Soil Remediation: A Bibliometric Network Analysis. *Land* **2022**, *11*, 1581. https://doi.org/10.3390/land11091581

Academic Editor: Mirko Castellini

Received: 22 July 2022
Accepted: 8 September 2022
Published: 15 September 2022

1. Introduction

As humankind's most valuable material resource and the foundation for the existence of numerous animals and plants, soil is a critical component of the geographical environment. However, the rapid rise in industrial activity has significantly increased the discharge of poisonous and harmful compounds into the environment, and the toxic and harmful chemical contamination of soil has become one of the world's greatest environmental challenges today. It is estimated that there are globally over 10 million polluted soil fields, including 100,000, 80,000, and 50,000 sites in the United States, the European Union, and Australia, respectively [1]. A national soil survey from April 2005 to December 2013 in China revealed that, in total, 16.1% of all investigated soils are contaminated with inorganic or organic pollutants. Since the soil's biochemical composition has a direct impact on the growth and development of both animals and plants, these toxic substances that persist in the soil would pose adverse impacts on human health and the ecosystem because of their carcinogenic and/or mutagenic nature [2,3], such as disturbing the geochemical and energy cycles in ecosystems [4]. Shao et al. [5] estimated that the contamination of arable soils in China leads to almost 10 million tons of crop production loss every year. In this sense, soil pollution and rehabilitation are global issues that have seized the interest of policymakers and academics [6,7].

In order to maintain the protection of land use, new technologies have been continuously developed for the purpose of soil remediation and avoiding soil deterioration. Soil remediation techniques on a variety of diverse chemistry-, biology-, agroecology-, and electrodynamic-related topics have been introduced during the last two decades [8]. It is worth noting that even though numerous studies are published dealing with the different types of contaminants, a systematic evaluation of the overall research pattern and networks for soil remediation is highly desirable and necessary, which will give more implications for future technology development. The bibliometric analysis of scientific articles from the past to the present is a useful tool to provide up-to-date information on strategically selecting the best and most practical remediation option [9]. Since their first application in 1969 for books and media statistics, bibliographies are now popularly utilized for the analysis of features across long periods and the current research hotspots in the literature, as well as for the prediction of future research trends [10,11]. Usman et al. [12] applied bibliometric analysis to reveal the research landscape and most popular topics of Fenton-based technology for soil and water remediation. Zhang et al. [13] evaluated groundwater remediation using bibliometric analysis and provided a global overview by investigating both published papers and patents. Their results found that chemical oxidation, biodegradation, and adsorption were the most attractive topics in the field that appeared in journal articles and patents. In the case of soil contamination or remediation, Guo et al. [14] conducted a bibliometric investigation of soil contamination from 1999 to 2012 and found that heavy metal contamination was the most concerned topic, and bioremediation was a desirable technology in this research field. In addition, Mao et al. [15] also used social networks and the S-curve prediction, apart from bibliometric analysis, to investigate the research articles on soil remediation published from 1996 to 2015. They depicted the collaborative network of the top 20 productive institutions and pointed out that microbial remediation, phytoremediation, and electrokinetic remediation were the technologies gaining the dominant research interests. Obviously, these bibliometric studies supplied an overview research pattern for their target scientific fields. However, more detailed network interpretation for the bibliometric results of soil remediation is still highly favored, and the remediation pattern is preferred to be categorized on the basis of different soil contaminants, which require different remediation strategies.

In this study, we conducted a bibliometric analysis of published articles on soil pollution and remediation from 2001 to 2020 in order to provide better knowledge of the global research on soil remediation. The current research and development trends in the field of soil remediation were underlined using bibliometric analysis, and the articles' publication tendencies, country performance, productive journals, author and institution performance, citation, and reference co-citation analysis were discussed. The results of this study will fill the current research gap by showing the network features of soil remediation and serving as a guide for the planning and implementation of future research.

2. Materials and Methods

2.1. Data Collection

The data in this study were collected from the Web of Science (WOS) Core Collection database [16]. The title words "soil contamination", "soil pollution", and "soil remediation" were selected to search publications, wherein "soil contamination" and "soil pollution" were used to identify problems in the existing research, and "soil remediation" was used to identify the soil remediation methods. A total of 6699 articles in the time span of 2001–2020 were found on the basis of deleting irrelevant articles, non-academic articles such as news reports, and as well as duplicated documents.

2.2. Data Extraction

In the present study, bibliometric analysis was applied for data extraction because bibliometrics is a tool integrating mathematics, statistics, and other related disciplines to analyze documents and also the laws between documents [17,18]. The article information, including the title, keywords, journal, institution, country, research direction, etc., was extracted from the target papers using the COOC software. All the information was summarized in an Excel sheet, and the blank items were deleted, leaving 6648 papers. Specifically, the co-occurrence relationships of these article data were visualized through social network analysis, which can present the structure and relationship of actors inside social networks. Herein, several features of social network analysis including the co-word analysis, citation analysis, collaboration analysis, time trend analysis, etc., were employed for bibliometric illustration. The co-word analysis was carried out by using keywords as the research object to explore the links between research hotspots, and the citation analysis uses reference co-citation as the object. The co-citation analysis was performed to predict research tendencies based on which the cited literature is related to the article contents.

In addition, the cooperative network among different countries was visualized on the basis of graph theory and topology analysis using the VOSViewer 1.6.18, CiteSpace 5.6.R2, and Gephi 0.9.6 software programs. The high-frequency keywords, keyword time roadmaps, keyword clusters, co-occurrence of document publishing countries and institutions, co-citation, and co-occurrence maps were determined in the field of soil remediation technology. In the network maps, the research object was represented as the participating nodes, while the relevance of the cooperating subjects was visually displayed in different line widths. This article starts with time, key technologies, multi-dimensional analysis of clustering characteristics, evolution trends, etc., and finally leads to research insights.

3. Discussion

3.1. Publication Trend

Figure 1 depicts the publishing trend for soil remediation from 2001 to 2020, indicating that the number of papers increasingly grew each year. As a result of global economic development, soil pollution is characterized by unrestricted industrialization and urbanization [19]. Specifically, the number of publications on soil remediation to avoid environmental deterioration increased significantly from 260 in 2001 to 700 in 2014, and the number of publications almost doubled in 2020. As classified in terms of contaminant type, organic and heavy metal pollutants led the research direction, with more attention toward the organic pollutants and overall presenting a rapid growth trend. The growing global awareness of environmental deterioration caused by diverse sources of soil contamination has resulted in increased interest in soil remediation research. This finding implies that soil pollution remained a major environmental subject in recent decades.

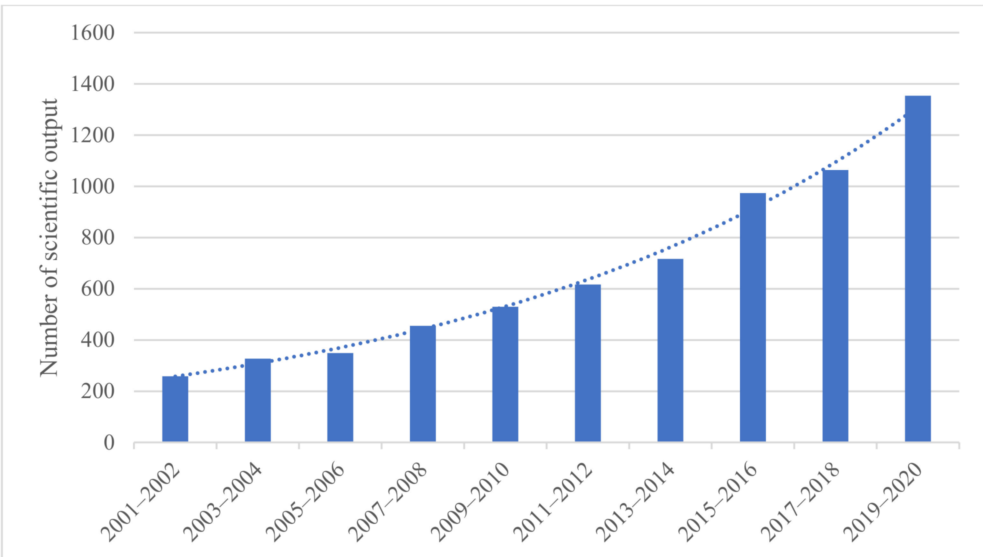


Figure 1. Trend of scientific outputs in field of soil remediation from 2001 to 2020.

3.2. Contribution of Countries and Institutions

Co-authorship networks for countries, institutions, and keyword co-occurrence networks were computed using social network analysis to visually show the spatial distribution of the literature. The distribution of major countries and institutions is shown in Table 1. The number of papers published from a certain country was monitored according to author affiliation. International cooperative publications were included in the count of each cooperative country because they were produced by all the cooperative countries. During different time intervals set in this study, the top five productive countries in terms of publishing journal articles are China (1982 publications), the United States (690 publications), Spain (365 publications), Poland (332 publications), and Russia (278 publications), as shown in Table 1. Soil remediation has been a hot topic since 2009, as reflected through the numerous studies carried out by the top five most productive countries. For example, in 1980, the United States passed the "Comprehensive Environmental Response, Compensation, and Liability Act" (Superfund law), which encouraged researchers to develop treatment options for polluted soil. Moreover, the Chinese Ministry of Environment and the Ministry of Land and Resources conducted a national soil pollution survey from 2005 to 2013. The Chinese State Council (2013) planned to thoroughly investigate China's soil environment by 2015, monitor 60 percent of the country's arable lands on a regular basis, and attempt to establish a national soil environment network. All these actions promoted soil research for pollution treatment. Especially China shows a more rapid development than other countries, reflected in its stronger financial support for technology innovation in soil remediation. Since the year of 2011, it can be noticed that China exhibited a much higher publication frequency than other countries. A growing number of published papers suggested that China would soon lead soil remediation research in both academia and field applications. On the one hand, people in developing countries show more concern about the environment and public health because of the worsening pollution challenges caused by the rapid growth of industry in the last few decades. On the other hand, because of better technologies and moving production to other countries, heavy metal pollution is not as bad in developed countries as it is in developing countries.

Academic collaboration between countries or research institutions is a key factor in facilitating knowledge dissemination and academic interchange among experts. Figure 2 depicts the academic cooperation among nations in terms of publications from 2001 to 2020. International cooperation between countries is depicted by lines linking nodes, the size of nodes and labels indicates the number of papers, and the width of the lines indicates the level of cooperation. It can be seen that the national cooperation network became denser, as the number of countries participating in cooperation significantly increased in the investigated time period. In the period from 2001 to 2005, compared with other countries, the United States, England, and Germany published more papers, and China, England, South Korea, and the United States had strong cooperative work. Then, during 2006–2010, the United States reflected a potential collaboration with China, Canada, and Spain. However, China's collaborative work has increased rapidly, compared with other countries over the 2011–2015 period. During 2016–2020, China overtook the United States in terms of the number of publications. Despite having the most publications, China has not collaborated closely with other countries, in contrast to the United States, and hence should considerably increase its academic cooperation with other countries. Furthermore, there are still many opportunities to improve international cooperation and exchange in the field of soil remediation research. For example, the United States and China, the two largest publishing countries, have rarely partnered with Russia and Spain.

Table 1. Top 15 countries/region and frequency of papers published.

Order	2001–2005		2006–2010	
	Countries/Region	Frequency	Countries/Region	Frequency
1	United States	147	China	203
2	China	56	United States	119
3	Germany	48	Spain	77
4	Canada	47	Italy	64
5	Italy	38	Poland	52
6	France	35	India	48
7	Australia	34	Germany	47
8	England	34	England	44
9	Poland	33	Canada	43
10	Russia	30	Japan	42
11	Japan	30	France	38
12	Spain	28	Russia	36
13	South Korea	25	Belgium	32
14	Finland	21	South Korea	31
15	Netherland	21	Turkey	29
Order	2011–2015		2016–2020	
	Countries/Region	Frequency	Countries/Region	Frequency
1	China	587	China	1136
2	United States	166	United States	258
3	Spain	104	Spain	156
4	Poland	97	Russia	153
5	India	72	Poland	150
6	Italy	69	India	130
7	France	63	Iran	106
8	Russia	59	Australia	104
9	South Korea	55	South Korea	103
10	Australia	49	Italy	89
11	Iran	48	France	86
12	Japan	43	Canada	72
13	Canada	38	Germany	72
14	Taiwan, China	37	Brazil	69
15	England	35	England	65

Table 2 lists the top 15 productive institutions along with their related metrics, which mainly show affiliations in China, Russia, the United States, Canada, and the Netherlands. It is noteworthy that none of the top 10 most productive institutions are from India, Brazil, or Germany. With 428 articles, the Chinese Academy of Science (CAS) has the most publications in different time intervals given that the CAS is a large organization with many branches in different cities, and papers categorized according to these branches resulted in its incomparable leading position. It is worth noting that, in the period from 2001 to 2010, most of the top 15 institutions came from Europe and the United States but only 2–3 of them came from China. However, during 2011–2020, most of the top 15 institutions were from China, indicating a forceful development of soil research in China, which was consistent with the above statistical results of the analyzed countries. Aside from the CAS, the Russian Academy of Sciences (87) and the French National Institute of Agronomic Research were the top institutions in Europe, while the University of Illinois in the United States was the top institution from 2001 to 2010.

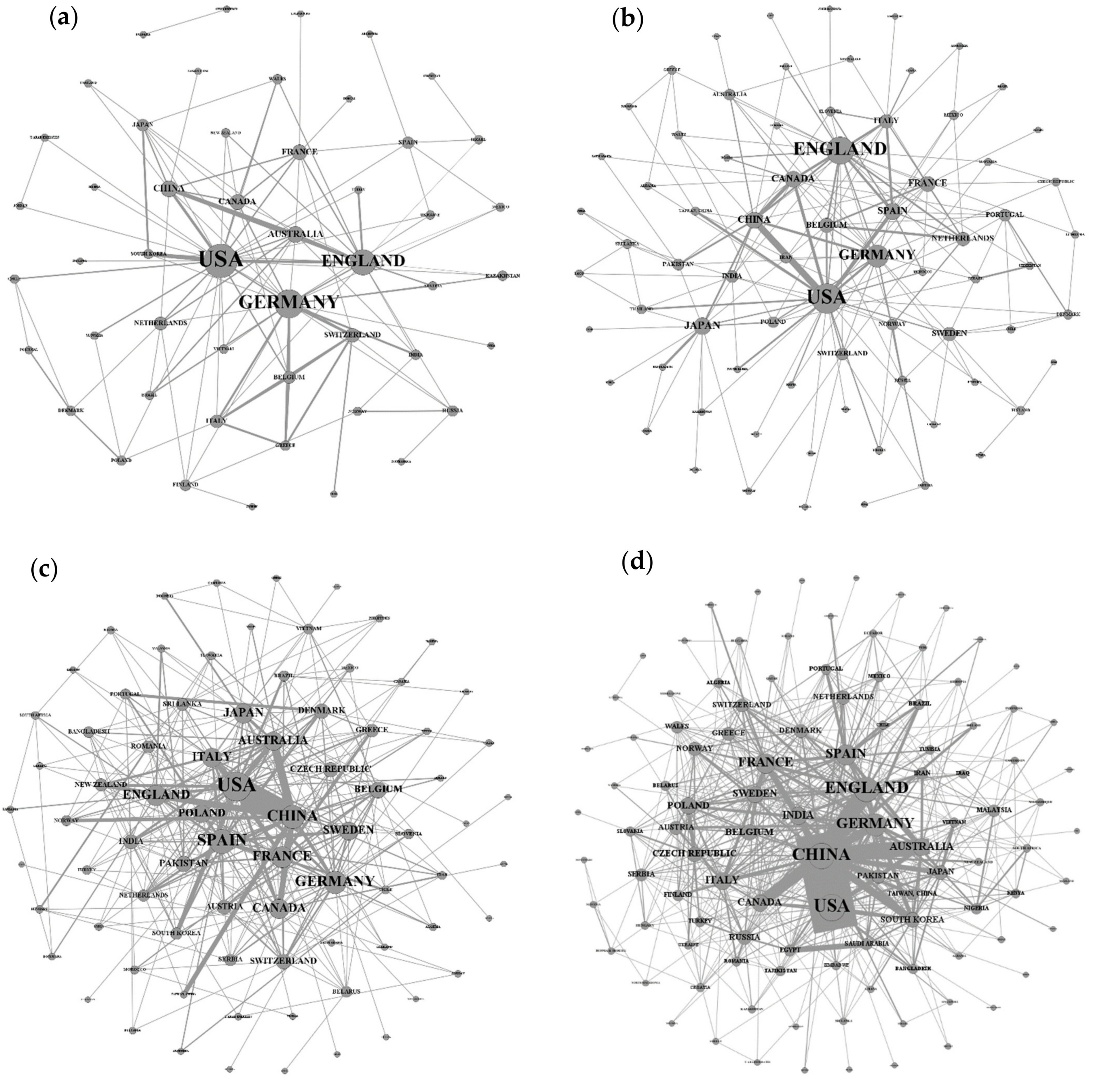


Figure 2. Map of co-occurrence of national cooperation: (**a**) 2001–2005, (**b**) 2006–2010, (**c**) 2011–2015, and (**d**) 2016–2020.

Table 2. Top 15 institutions and frequency of papers published.

Order	2001–2005 Institutions	Frequency	2006–2010 Institutions	Frequency
1	Chinese Academy of Sciences	25	Chinese Academy of Sciences	59
2	Russian Academy of Sciences	13	Zhejiang University	21
3	University of Helsinki	11	China State Shipbuilding Corporation	18
4	University of Illinois	11	Shanghai Jiao Tong University	16
5	Zhejiang University	10	Russian Academy of Sciences	13
6	University of Naples Federico II	9	University of Illinois	10
7	French National Institute of Agronomic Research	8	University of Ljubljana	9
8	Moscow MV Lomonosov State University	7	Helmholtz Centre for Environmental Research	9
9	University of Rome La Sapienza	7	National Institute for Agro-Environmental Sciences	8
10	U.S. Environmental Protection Agency	7	University of Turin	8
11	Spanish National Research Council	6	French National Institute of Agronomic Research	8
12	McGill University	6	University of Ghent	8
13	Concordia University	6	University of Florida	7
14	Kansas State University	6	University of Vigo	7
15	Vrije Universiteit Amsterdam	5	University of Granada	7
Order	**2011–2015 Institutions**	**Frequency**	**2016–2020 Institutions**	**Frequency**
1	Chinese Academy of Sciences	133	Chinese Academy of Sciences	211
2	Beijing Normal University	34	University of Chinese Academy of Sciences	76
3	University of Chinese Academy of Sciences	24	Zhejiang University	54
4	University of Warmia and Mazury	21	Russian Academy of Sciences	40
5	Zhejiang University	21	University of Warmia and Mazury	36
6	Russian Academy of Sciences	21	Beijing Normal University	35
7	Shanghai Jiao Tong University	20	Tsinghua University	34
8	French National Institute of Agronomic Research	18	Northwest A&F University	31
9	China University of Geosciences	18	Shanghai Jiao Tong University	30
10	Chinese Research Institute of Environmental Sciences	17	Chinese Research Institute of Environmental Sciences	27
11	Tsinghua University	16	Islamic Azad university	26
12	Nanjing University	16	Nankai University	25
13	University of Vigo	15	University of Castilla-La Mancha	23
14	Nanjing Agricultural University	15	China University of Mining and Technology	23
15	University of Tehran	13	China University of Geosciences	23

3.3. Characterization of Research Keywords

Keywords are theme indicators of an article, and the bibliometric analysis of high-frequency keywords reveals the research hotspots and the overall evolutionary contexts in a specific field. Therefore, the VOSviewer bibliometric software was used to visualize the research field information through bibliometric modeling and mapping [20], so as to cluster the literature keywords and analyze the existing research hotspots [21]. Table 3 contains the top 15 most commonly used keywords from 2001 to 2020, organized by year of occurrence. It can be found that lead, cadmium, mercury, and copper were the most concerned heavy metals in the past 20 years, while arsenic and polycyclic aromatic hydrocarbons (PAHs) were mostly investigated as non-metallic pollutants. The most often used keyword (1175 times) was "heavy metals", indicating that heavy metal pollution is currently the trendiest topic in soil contamination studies. Soil heavy metal pollution can be caused by industrialization and urbanization, mining and emissions, wastewater discharge, sewage irrigation, long-term fertilizer and pesticide use, etc.

Table 3. Top 15 keyword frequency over time.

Keyword	2001–2005	2006–2010	2011–2015	2016–2020	Total Number
Heavy metal	121	257	343	582	1303
Lead	24	49	50	72	195
Bioremediation	15	39	51	78	183
Phytoremediation	11	29	44	94	178
Cadmium	19	39	34	69	161
Arsenic	17	31	38	49	135
Electrokinetic remediation	13	19	39	52	123
Risk assessment	6	12	28	56	102
PAHs	7	23	27	38	95
Bioavailability	11	15	20	43	89
Soil washing	9	11	28	39	87
Copper	9	19	26	23	77
Mercury	5	14	22	34	75
Spatial distribution	4	4	13	48	69
Biochar	0	0	6	63	69

Additionally, bioremediation, phytoremediation, electrokinetic remediation, and soil washing were observed as the most popular technologies for soil treatment; the first three are typically applied for in situ remediation strategies, while soil washing is commonly used for ex situ remediation. Compared with other technologies, bioremediation is an economic and environmentally friendly process that uses animals and microbes to remove, break down, and change soil contaminants [22]. Some scholars have investigated collaborative remediation strategies such as co-bioremediation remediation, physical–biological remediation, and chemical–biological remediation due to the limitations of single remediation procedures. Moreover, the risk assessment and spatial distribution of pollutants are listed as the most frequent keywords because they are important factors influencing soil remediation [23]. It is noteworthy that the application of biochar for soil remediation purposes has gained much attention since 2011 because biochar is also a well-known soil conditioner with low-cost and multi-functional characteristics. It is also noticed in Table 3 that the frequency of all these top keywords greatly increased from 2001 to 2020, but the order of their frequency remained unchanged during this period, indicating a stable research hotspot for soil remediation.

The employment of a significant number of low-frequency keywords revealed a diverse variety of study topics and research focuses in this specific field. As illustrated in the thermodynamic chart in Figure 3, the brighter the keywords are, the more frequently they appear. Aside from the above keywords, chromium, pesticides, atrazine, and DDT are also prevalent soil contaminants [24], and overall, heavy metal contamination is more common according to the report of the China Ministry of Environmental Protection. Hence, the electrokinetic remediation and soil washing of heavy-metal-contaminated soils received more attention.

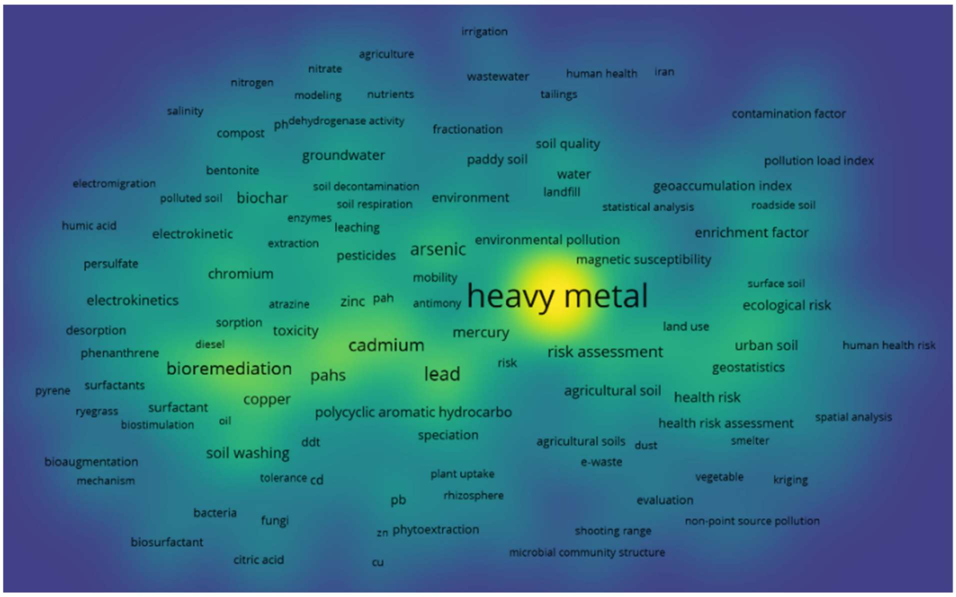
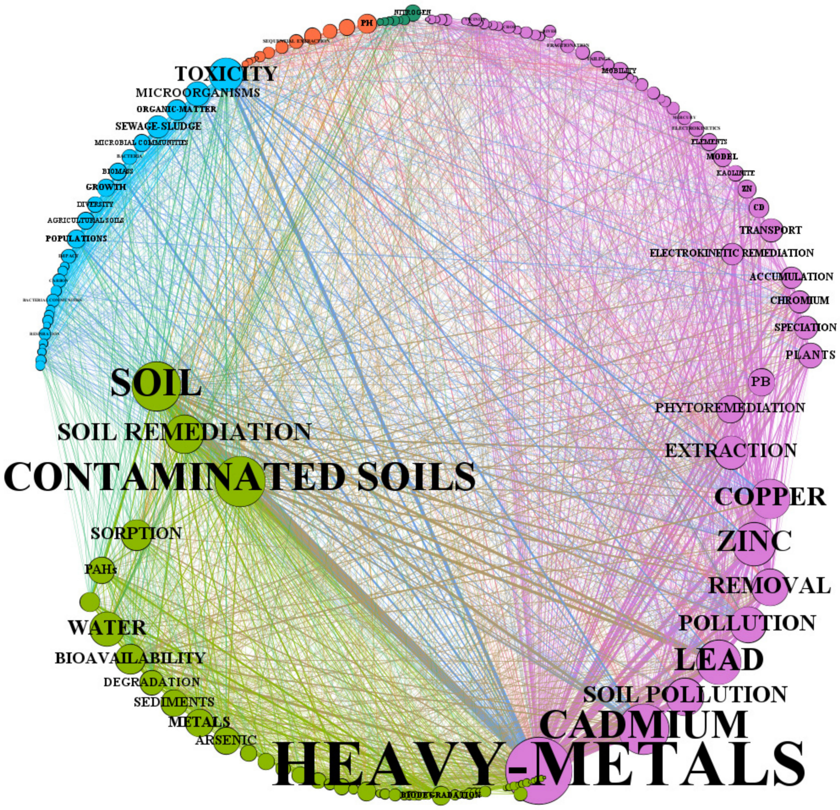


Figure 3. Thermodynamic chart of keyword occurrence.

3.4. Evolution Trend of Co-Occurrence Keywords

This study used cluster analysis to assess the major research direction in this discipline and to highlight the significant association between keywords. The high frequency of co-occurrence of keywords in the same cluster indicates that they are related to the same research field. The cluster analysis of the keywords indicates that "heavy metals", "phytoremediation", "bioremediation", "electrokinetic remediation", "lead", "cadmium", "adsorption", "immobilization", "toxicity", "risk assessment", "health concern", and "polycyclic aromatic hydrocarbons" have been the most discussed issues since 2001. It is worth noting that the keyword "heavy metals" had the most connections of all the other keywords, and it frequently appeared with the other keywords, which reflected heavy metals as a hot issue in this field. In addition to heavy metals, soil contaminated by PAHs has also attracted much concern. As a response, chemical extraction, which is effective on both heavy metal and PAH contaminants, was mainly adopted in the time span of 2001–2005. After that, since 2006, the research intensity in the field of soil pollution and contaminant remediation has remarkably increased, and the research trend is shifting away from extraction toward the implementation of comprehensive remediation technologies such as bioremediation, sorption, phytoremediation [25], and electric remediation [26], as demonstrated in Figure 4.

Compared with chemical and physical methods, such as extraction, immobilization, and electrokinetic remediation, bioremediation and phytoremediation are recognized to be cost-efficient and environmentally friendly. However, soil bioremediation and phytoremediation also face the problem of long implementation time and low efficiency. Therefore, combined remediation utilizing different technologies has emerged as a new research trend since 2011, which is reflected by the intensive research connections between different soil remediation technologies (Figure 4). For example, bioremediation has been popularly combined with electrokinetic remediation as well as phytoremediation. Additionally, it can be noticed that "water" has increasingly appeared along with "soil", suggesting combined pollution and remediation strategies for water and soil together. From 2011 to 2020, risk assessment in terms of health concerns and spatial distribution also received much attention due to the vegetable intake and ecological perspective for sustainability concerns [27]. Meanwhile, with the rapid urbanization since 2006, some research interest has transferred from agriculture soil to urban soil remediation. This study will assist researchers in determining the current state of soil remediation research and will serve as a guide for future research.



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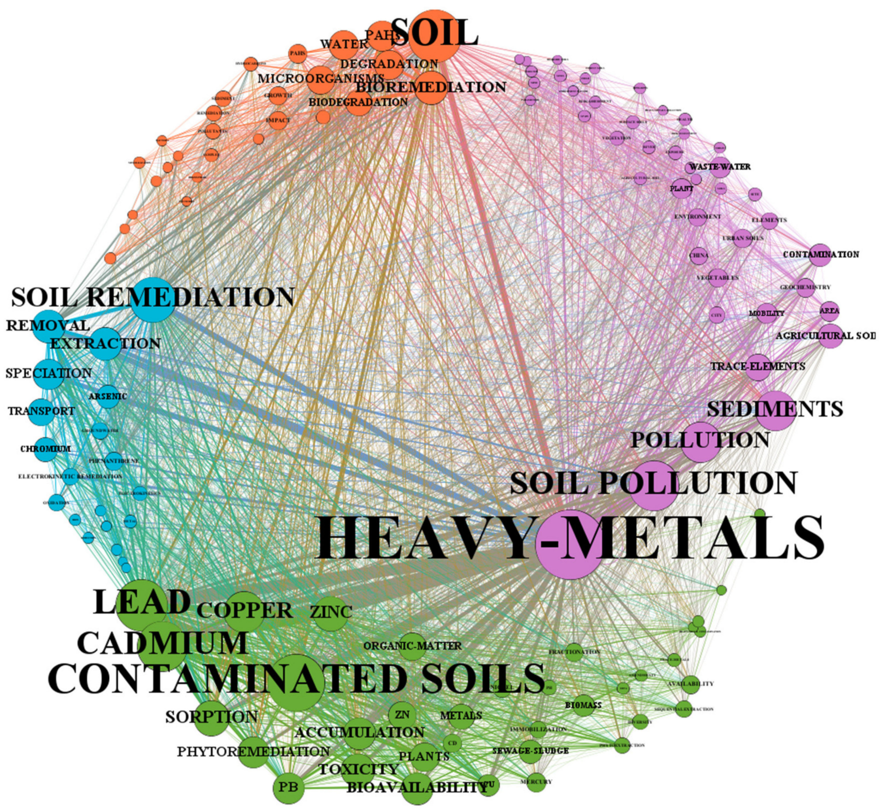
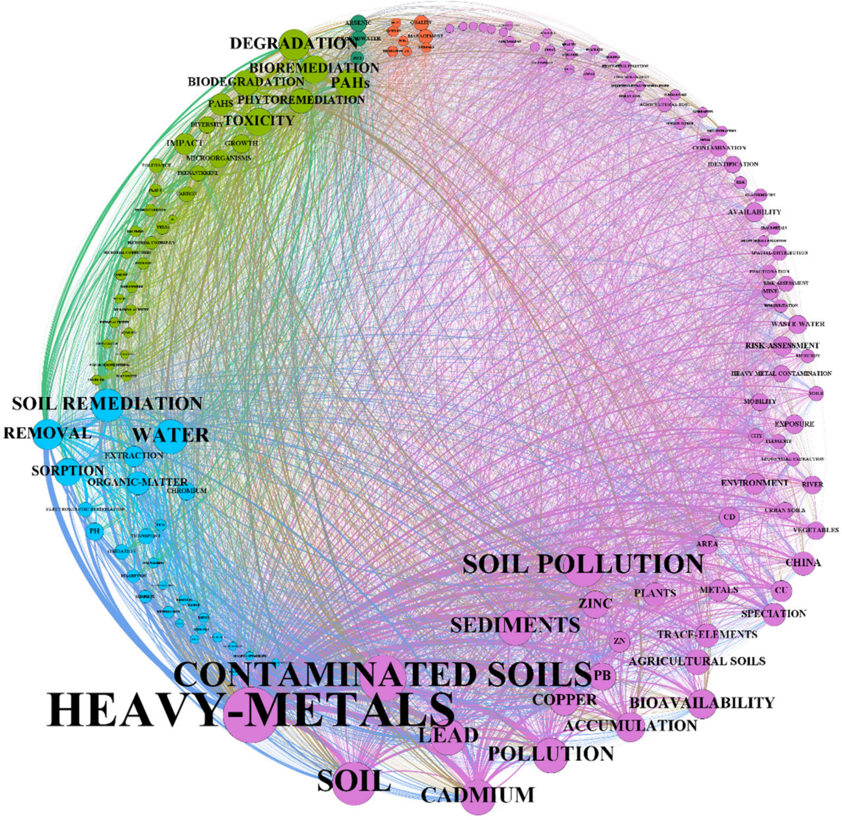


(**b**)

Figure 4. *Cont.*



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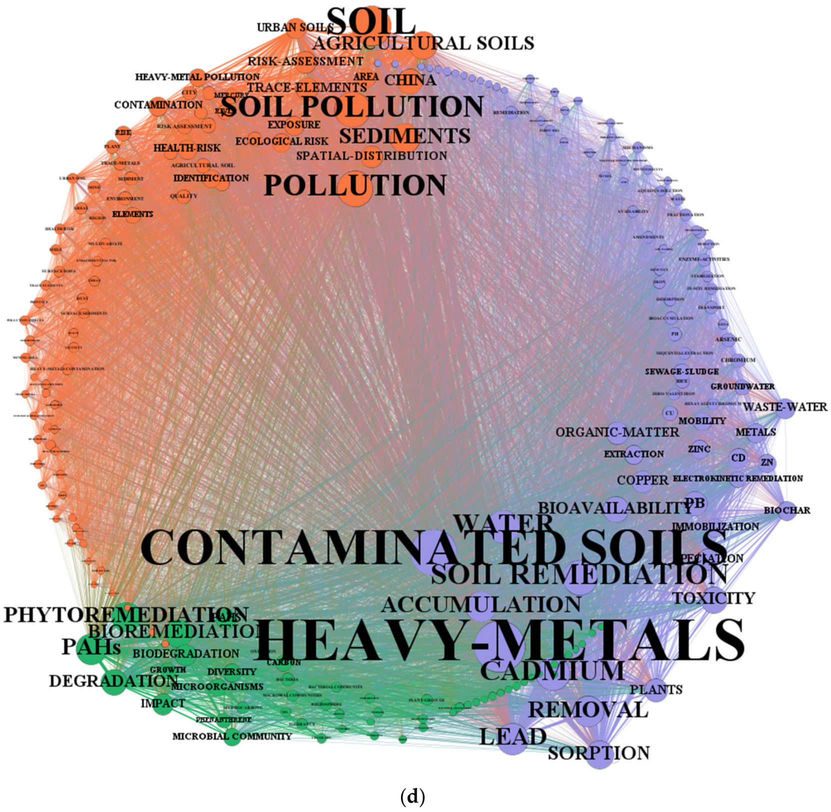

(**d**)

Figure 4. Keyword clustering for 4 time intervals: (**a**) 2001–2005, (**b**) 2006–2010, (**c**) 2011–2015, and (**d**) 2016–2020.

3.5. Most Highly Cited Literature

In bibliometric research, citation analysis has been recognized as an important sign for determining the quality of papers, and it symbolizes a study's influence and the attention it receives in academic circles. Table 4 summarizes the most frequently cited works on the subject of soil remediation from 2001 to 2020, including the title, journal, total number of citations, and publication year. Four of the top ten referenced papers' first authors are from China, including one from Hong Kong, and the rest most widely cited publications come from developed countries. The article "A Review of Soil Heavy Metal Pollution From Mines in China: Pollution and Health Risk Assessment" published in the *Science of the Total Environment* in 2014 received the highest citations of 1560 times [28]. The second was published in the *Microchemical Journal* in 2010 and was titled "A Review of Heavy Metal Contaminations in Urban Soils, Urban Road Dusts, and Agricultural Soils from China" with 1406 citations [29]. It is worth noting that 8 of the top 10 most highly mentioned publications were review articles. This could indicate that there are authoritative and complete assessments of concepts, traits, and affecting elements in this discipline, which will serve as the foundation for future research. According to our review of the highly cited literature, the bioremediation technologies that garnered the most attention were primarily microbial in situ remediation techniques, with the primary methods relying on the degradation effects of indigenous bacteria in soils [30].

Table 4. Top 10 highly cited studies in the literature.

Year	Title	Journal	Total Cites	Country
2014	A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment	Science of The Total Environment	1560	China Review article
2010	A review of heavy metal contaminations in urban soils, urban road dusts, and agricultural soils from China	Microchemical Journal	1406	China Review article
2014	Remediation of heavy metal(loid)s contaminated soils—To mobilize or to immobilize?	Journal of Hazardous Materials	1071	Australia Review article
2001	Remediation technologies for metal-contaminated soils and groundwater: an evaluation	Engineering Geology	1041	Canada Review article
2011	A review of biochars' potential role in the remediation, revegetation, and restoration of contaminated soils	Environmental Pollution	1036	UK Review article
2015	Soil contamination in China: current status and mitigation strategies	Environmental science and technology	994	China Review article
2001	Heavy metal contamination of urban soils and street dusts in Hong Kong	Applied Geochemistry	945	China Research article
2001	Surfactant-enhanced remediation of contaminated soil: a review	Engineering Geology	774	Canada Review article
2008	The mobility and degradation of pesticides in soils and the pollution of groundwater resources	Agriculture, Ecosystems, and Environment	771	Spain Review article
2003	Arsenic contamination of Bangladesh paddy field soils: implications for rice contribution to arsenic consumption	Environmental science and technology	740	UK Research article

3.6. Reference Co-Citation Analysis

A scientific study must be founded on prior knowledge gleaned from pertinent prior research. In other words, later publications frequently cite the previously published literature and research findings within a certain area or other closely connected subjects. A co-citation relationship is built when two papers appear in the same reference list at the same time [31,32]. The papers having co-citation associations typically have inherent relationships, and hence co-citation analysis can disclose relationships and structures in an academic field [33]. The clusters of keyword categories from co-citation papers are presented in and Table 5 to evaluate potential research opportunities.

Table 5. Clustering information of co-cited keywords in the literature.

Cluster ID	Size	Related Keywords for Clustering of Co-Cited Documents
0	35	soil treatment; electrokinetic soil remediation; electrokinetics; sequential extraction analysis; chelate agents; remedial action; migrate; iodide; speciation; clays; electroremediation; mercury; mitigation; zero-valent iron; organic contaminated soil; heavy metal; sand; electro-osmosis; chelating agent; desorption; cesium; kaolinite; carbonate; mathematical model; remediation technologies; Triton X; pilot-scale electrokinetic remediation; uniform electric field; sandy loam; adsorbent; health risk; pesticides; etc.
1	29	contaminant solubilization; coupling of remediation technologies; enhancement techniques; soil pH control; electrochemical remediation; reductive process; heavy metals; electrokinetics; electrolyte; soil remediation; fractionation; electrolyte conditioning; pretreatment; multi-heavy metals; clay; nitroaromatic contaminant; combined methods; Fenton treatment; chlorinated organic contaminant; integrated Fenton; organic pollutants; Fenton-like treatment; etc.
2	29	urban soils; multivariate statistical analysis; gastric juice simulation test; mobility; soil remediation; multivariate statistics; geo-statistics; GIS; urban road dust; tanneries; anthropogenic activities; integrated pollution index; heavy metal contamination; land use; PCBs; functional area; factor analysis; risk analysis; spatial pattern; integrated contamination index; administrative region; pollution index; roadside soil; pollution load index; etc.

The first cluster is soil treatment (#0). Electrokinetic remediation appeared frequently in co-citation papers for the remediation of soil contamination. The contaminants of heavy metals and PAHs move faster by applying electric current to an in situ soil field. Some materials can also be used during the electroremediation to promote its working efficiency or enhance the final contaminants' removal. Correspondingly, zero-valent iron, cheating agents, and clays are developed to remove or immobilize heavy metals in soil with the processes of adsorption, desorption, redox immobilization, etc. In addition, to fulfill precise remediation and avoid geological constraints, an investigation of contaminant species and spatial distribution coupled with mathematical modeling seems to be highly necessary, all of which co-existed in the first cluster along with soil treatment.

The second cluster is contaminant solubilization (#1). This can be accomplished in a number of ways, including soil flushing, soil washing, vitrification, and solidification. Soil flushing and washing is the process of applying water-containing surfactant agents to the soil in order to increase the solubility of toxic elements given that many contaminants would be adsorbed by soil matrixes [34]. During this process, these toxic pollutants are extracted from the soil via an ex situ process and then further removed in the following washing wastewater treatment. Soil type and moisture content are two of the most important factors in determining the type of washing chemical that should be used. Numerous studies have suggested a variety of cleaning agents, including organic acids, saponin, chelating agents, plain water, etc. Moreover, sequential extraction has been widely recognized as a crucial approach for fractionating soil contaminants so as to change the bioavailability and transformation forms of contaminants [35,36]. A progressive extraction process has been used to divide the total concentrations into various operational fractions with varying degrees of biotoxicity. Similarities and variations in behavior were described in a chemometric study [37]. In contrast to soil washing and flushing, vitrification and solidification are hot topics, during these are processes, various materials are mixed with polluted soils in order to reduce the mobility of the toxic elements [38]. During contaminant solubilization, organic pollutants such as chlorinated and nitroaromatic organics can be degraded through

Fenton and Fenton-like processes, which use H_2O_2 as the oxidant, after which those organic pollutants can finally be mineralized to carbon dioxide and water.

The third cluster refers to health risk assessment (#2). The large-scale pollutant discharge because of rapid industrialization and urbanization caused devastating consequences on urban soil qualities and human health over the past few decades. Considering the interaction between soil and groundwater, an investigation of contaminant mobility could be important for effective soil remediation while protecting public interests and the ecological environment [39]. Statistical tools and GIS were considered valuable resources to investigate soil quality and contaminants' spatial distribution, the results of field investigations have a vital role in final remediation plans. Moreover, many studies have found that pollution in agricultural land has a significant detrimental influence on food production, the food chain, and the health of the ecological environment. Therefore, the frameworks for the risk analysis of contaminants in urban and agricultural soil based on their bioavailability can shed light on the complex relationships between urban soil, pollutant exposure, and human health [40]. It is vital to develop methods for faster, more reliable, and cost-effective pollution assessment so that the necessary remediation measures can be adopted on a priority basis at the appropriate time.

4. Conclusions

This work focused on soil remediation progress, research hotspots, and possible research directions from 2001 to 2020 using bibliometric approaches based on the WOS core database. The continued and rapid growth in the number of articles implies that soil remediation is gaining attention. China contributed the most publications (1476), followed by the United States (690), Spain (365), Poland (332), and Russia (278 publications). Since 2016, the main issuing agencies are Chinese academic organizations, and the international cooperative studies between countries directly promote rapid scientific outputs. Based on keyword evolution, heavy metals including Pb, Hg, Cr, Zn, Cu, and Cd, and organics including PAHs and pesticides were the mainly targeted soil contaminants. Regarding remediation technologies, bioremediation, phytoremediation, soil washing, electrokinetic treatment, biochar, etc., were ranked among the top research frontiers in the field of soil remediation in the past 20 years. Moreover, the risk assessment of soil pollution related to health has received extensive attention since 2011. According to social network analysis, pollution and health risk assessment as well as the spatial distribution of soil contaminants provide important perspectives for subsequent soil remediation. These findings assist researchers in analyzing the existing papers in this field, so as to refine their research directions and stay current with research frontiers.

Author Contributions: Conceptualization, J.G.; methodology, J.G.; software, J.G.; formal analysis, J.G. and M.F.; data curation, J.G.; writing—original draft preparation, M.F.; writing—review and editing, J.G. and M.F.; visualization, J.G.; supervision, X.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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