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Review

# Scientometric study of treatment technologies of soil pollution: Present and future challenges

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ABSTRACT

There are few bibliometric studies showing current technologies and their combinations for the remediation of contaminated soils. For this reason, a scientometric study was carried out in order to know the trends in soil contamination treatment technologies. The study considered original articles and reviews published in the Scopus and Web of Science databases between January 2010 and June 2021, evaluating: (a) characteristics of the publications, (b) main research sources, (c) citations and production by journals, (d) keywords used, (e) countries, institutions and authors active in research production, (f) most cited articles and (g) trends in soil treatment and remediation techniques. The results showed: (a) continuous growth of publications on soil remediation in the "Environmental Science" subject area and a limited contribution of the "Soil Science" and "Agriculture and Biological Science" subject areas, (b) leadership of countries such as China, USA, India, Italy and Spain in research production, (c) phytoremediation, bioremediation and biodegradation were the most studied treatment technologies in the last decade and (d) recent research (from 2020) studied pesticides and herbicides, including Chlorimuron-ethyl and also microplastics and other emerging pollutants. It is also noted that the current trend of combinations of techniques for the treatment of soil contamination is attractive for future research.

## 1. Introduction

Scientometric analysis provides information on the evolution of scientific research articles and specifically characterizes the domain of knowledge related to the topic (Valdiviezo Gonzales et al., 2021). Some scientometric studies on soil remediation and remediation-related topics have been developed; however, no scientometric study was found that shows soil contamination treatment technologies as a whole or the present and future trends in the development of research on this topic. This situation contributes to the lack of information necessary for decision making by researchers, managers and public officials on the selection of optimal soil treatment technologies. Xie et al. (2020) indicated the need to study the theory and technology of degraded soil restoration, and Xu et al. (2019) recommended investigating not only aspects of soil, water, and atmospheric pollution but also investigating mitigation technologies, highlighting the state of the art of soil treatment technologies and present and future challenges.

On this issue, specialists of the United Nations Convention to Combat Desertification (UNCCD, 2019) explained that 75 % of the land was transformed and 23 % was desertified (degradation without further soil production), and that >1.3 billion people live on degraded agricultural land. It is clear that land use change for urbanization, mining or mineral extraction drives habitat degradation and is a major cause of biodiversity loss in the world (Bandyopadhyay, 2021). The introduction of

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pollutants into the environment through various pathways such as flue gases, power generation from waste, leaded gasoline, heavy oil and fossil fuels, slag and among others, end up impacting the soil, water and atmosphere (Shi et al., 2021). Generally, heavy metals such as copper, chromium and arsenic found in soil represent a great concern for researchers (Shi et al., 2021); however, these pollutants are joined by organic compounds such as pentachlorophenol (PCP) and dioxins and furans (PCDD/F) that represent a major problem in industrialized countries (Guemiza et al., 2017).

It is important to understand that soil degradation is detrimental to the goals of achieving climate neutrality by 2050, preliminary calculations indicate that the full potential of European soils and the soil organic carbon pool in agricultural soils must be utilized to achieve this goal, being important to implement sustainable soil management practices (Montanarella and Panagos, 2021). Furthermore, Borrelli et al. (2020) explained that agriculture is beneficial to humans and although it only covers about 38 % of the earth's surface, agricultural systems when not sustainably managed turn out to be the main drivers of soil degradation. To improve this critical situation, countries must implement sustainable land management (SLM), with appropriate solutions to counteract the problems of desertification, land degradation, drought, climate change and threats to biodiversity (Alfaro, 2019). In this sense, many researchers developed chemical, thermal, biological and physical methods for the remediation of contaminated soils (Guemiza et al., 2017).

The review of scientometric or bibliometric literature on soil degradation and remediation has provided the following results: (a) remediation of heavy metal contaminated soils (Shi et al., 2021), (b) research situation on land degradation (Xie et al., 2020) and (c) water, soil and atmospheric pollution and their mitigation technologies (Xu et al., 2019).

Shi et al. (2021) realized a scientometric study of the soil heavy metal pollution remediation in the period 1999–2020 with the use of CiteSpace and VOSviewer software applications and document co-citation and cluster analysis techniques for data analysis. The authors presented the following: (a) distribution of publication during 1999–2020, (b) top 10 countries in soil pollution remediation in the period 1999–2020, (c) cloud diagram of the 60 most productive countries, (d) map of research institutions about this topic, (e) top 15 research institutions, (f) top 15 journal sources of heavy metal pollution soil remediation technologies, (g) co-occurrence network of keywords, (h) top 40 keywords of the publications, (i) keywords in the period 1999–2012, (j) keywords between 2013 and 2020, (k) major cluster of co-cited references, and (l) top 20 references with strongest citation bursts. In addition, they concluded that China (2173, 28.64 %) and United States of America (946, 12.47 %) were the top countries in published articles, and that Environmental Science and Pollution Research (384, 5.06 %) and Science of the Total Environment (345, 4.55 %) published the majority of articles. They also showed that the Chinese Academy of Sciences (485) produced the most publications, indicating that phytoremediation and biochar applications to remediate heavy metals in soil were critical research points and that future research should focus on the development of new technologies, combined or joint systems and remediation mechanisms.

Xie et al. (2020) developed a bibliometric study on land degradation with bibliometrix and biblioshiny (software packages of R Studio) with data mining of research papers of this topic in the period 1990–2019 in the Web of Science Core Collection database. The authors presented the following: (a) research papers published from 1990 to 2018, (b) the number of papers cited by year, (c) historical direct citation network of top cited papers since 1990 until 2019, (d) top 10 local citation scores, (e) top 10 global citation scores, (f) authors' production over time, (g) top 10 influential authors, (h) map of scientific production distribution according to the range of quantities of documents by countries, (i) country collaboration map, (j) nationalities of corresponding authors in the 20 most prolific countries, (k) world tree map of high frequency keywords, (l) multiple correspondence analysis of high frequency keywords, (m) tree dendogram of hierarchical cluster analysis of keywords, (n) thematic evolution diagram, and (o) top 30 journals about land degradation papers. In addition, they concluded the following: (a) about publication trend, this topic increased the number of publications rapidly; however, it was in four stages: (i) low production exploration, (ii) developmental sprout, (iii) expansion of promotion, and (iv) high-yield active; (b) about paper citations, the strongest development occurred in the years 2002, 2005, 2007, and since 2008 until 2013, although the attention to this topic increased over time; (c) about research power, developed countries from Europe and USA were more influential jointly with China as a major agricultural country, although cooperation among countries is not frequent; (d) about most frequent keywords, these were the following: land degradation, degradation, desertification, remote sensing, soil erosion, and soil degradation, and after cluster analysis, the following keywords as future research directions were identified: microscopic processes and mechanisms of degradation of different land types, theory and technology of restoration, reconstruction of degraded land, and sustainable use of land ecosystems; and (e) three evolutional directions are the following: (i) dynamic monitoring of land degradation, (ii) research on environmental governance of land degradation and how to achieve sustainable land use, and (c) the study of the response of land degradation to land-use change. According to these results, the paper has dealt exclusively with aspects of sustainability, development, management and sustainable land and landscape use, which invites the reader to investigate how to remediate degraded soils.

Xu et al. (2019) realized a bibliometric study of 403 papers about atmosphere, water, and soil pollution, and their mitigation technologies, which were published in the Journal of Environmental Engineering and Landscape Management (indexed in Scopus and Web of Science) since 2017 until 2019 with CiteSpace software application. The authors presented the following: (a) the scope of the published papers, (b) the types of publications, (c) publication distribution by year, (d) detailed distribution of the quantity of citations by year, (d) top 30 most cited papers, (e) country collaboration network diagram, (f) top 10 most influential countries, (g) institution collaboration network diagram, (h) author collaboration network diagram, (i) top 12 most influential authors, (j) top 11 cited authors with the strongest citation bursts, (k) top 25 cited journals with the strongest citation bursts, (l) top 7 references with the strongest citation bursts, (m) keyword network diagram, (n) cluster network of keyword research, and (o) timeline view of keywords. In addition, they concluded: (a) the quantity of publications reached the peak in 2010; (b) the article "Sustainable construction taking into account the building impact on the environment" (Medineckienè et al., 2010) had 67 citations, being the cited influential paper; (c) Lithuania was the most influential country; (d) Vilnius Gediminas Technical University was the most influential institution; (e) Baltrėnas was the most influential author; (f) Journal of Environmental Radioactivity and Chemical Engineering Journal had six years as the longest citation burst; (g) the paper "Investigation into the air treatment efficiency of biofilters of different structures" had 4 years as the longest citation burst; (h) the keywords "heavy metal", "soil", "plant", "nitrogen", "water", and "impact" occur in JEELM frequently; (i) in the cluster network of keyword research of JEELM, the biggest cluster was "waste management scenario"; (j) people begin to care more about how to restore ecology instead of investigating and studying pollution sources before. They also recommended the study of more useful and comprehensive methods, information, factors, and directions about the scope of the soil, water, and atmosphere pollution, and the technologies for their mitigation.

The literature search has identified research in the category of systematic reviews regarding current technologies and important contributions have been reported; for example, the application of amendments to improve the bioavailability and mobility of organic and inorganic soil contaminants has been highlighted (Kumar et al., 2022). The use of biochar has been developed with special emphasis due to its multifunctional capacity in phytoremediation, bioremediation, soil washing and others. The use of biochar as chelators and desorbents allows the immobilization of inorganic pollutants and potentially toxic elements (PTE), while natural and synthetic surfactants mobilize persistent organic pollutants. To this, Kumar et al. (2022) pointed out shortcomings in field studies to evaluate these mobilizing amendments during soil remediation and also noted that the analysis of the combination of microbial remediation techniques and phytoremediation with mobilizing agents for the removal of soil contaminants should be prioritized in future research. On the other hand, Bolan et al. (2022a) and Bolan et al. (2022b) reviewed research on the biogeochemistry and transformation of Sb in relation to its remediation, indicating knowledge gaps in the ecotoxicological assessment of Sb to protect ecosystems and human health, and highlighting bioremediation and phytoremediation processes as ecological and sustainable techniques for the remediation of this contaminant. Similarly, Kumar et al. (2021) reviewed problems related to remediation of soils contaminated with polyaromatic petroleum hydrocarbons using immobilization, mobilization and biological degradation techniques and emerging hybrid or integrated technologies.

Bhandari et al. (2007) classified the common soil and groundwater remediation technologies as follows: (a) physical, which includes: free product recovery, soil vapor extraction, ump-and-treat, groundwater circulation wells, air sparging, induced fracturing, multiphase extraction, and soil heating; (b) chemical, which includes: precipitation, permeable reactive barriers, chemical oxidation and reduction, adsorption and ion Exchange, stabilization/ solidification, chemical leaching, electrochemical processes, and solvent extraction, soil washing, and soil flushing; and (c) biological, which includes: biosparging, biostimulation, bioaugmentation, bioventing, aerobic biotransformation, anaerobic biotransformation, biological fixation, enzyme-catalyzed treatment, mycorrhizal fundal processes, saprotrophic fungal processes, biological reactors, phytoremediation, and monitored natural attenuation.

According to the exposed ideas, there is a lack of information about the scientific or bibliometric production of recent years in the two high-impact databases Scopus and WoS, related to the thematic areas that provide knowledge about the challenges and trends of technologies and treatments of contaminated soil. It is crucial to show the international scientific productivity, the diversity in the distribution of information sources, authors, as well as the challenges for the search of combinations of technologies to achieve less aggressive treatments with biodiversity or soil life and less costly for human beings, in the context of sustainable development.

For the mentioned reasons, a rigorous search chain has been established in this research, whose purpose is to show relevant aspects about: (a) overlapping between WoS and Scopus publications, and types of publications; (b) annual production of the publications; (c) the main thematic areas and research sources about contaminated soils; (d) the number of citations and the journals with the highest production; (e) trend analysis of the author's keywords; (f) the most productive countries in soil treatment research, the productivity of articles by institution, the most productive authors, and the 10 most cited publications; (g) trends in soil treatment research that relate to technologies and mechanisms; (h) types of pollutants; and (i) soil remediation techniques and mechanisms, in addition to biological, physical, chemical, and emerging techniques that provide a comprehensive overview of the challenges of trends for future research.

## 2. Materials and methods

### 2.1. Problem and purpose of the study

The problem of the study corresponds to the absence of bibliometric studies that show the current trends of technologies and their combinations for the remediation of contaminated soils. This situation has limited the public and researchers to have a broader and more current view on classical and emerging contaminants, technologies and their combinations, and the gaps or challenges that suggest new research, in accordance with eco-friendly and lower cost approaches for the remediation of contaminated soils. Therefore, the purpose of this research is to provide the public with relevant information on the current technological situation, advances and trends, as well as the possibility of identifying future collaborations of interest.

### 2.2. Type of study

The present study had a quantitative approach and applied type, based on direct observation and analysis of the scientific literature on the treatment of contaminated soils. Original articles and literature reviews published in two of the main academic databases such as Web of Science (WoS) and Scopus were consulted, limiting the search to the period from January 2010 until June 2021.

### 2.3. Strategies and query strings used for database searching

In both databases the search was performed in the topic field that includes article title, abstract and keywords, and the main keywords referring to the treatment of contaminated soils were used as a search strategy. In the WoS database, subject areas as "Environmental Science", "Agricultural and Biological Sciences", "Chemistry", "Biochemistry, Genetics and Molecular Biology", "Medicine", "Immunology and Microbiology", "Earth and Planetary Sciences", "Pharmacology, Toxicology and Pharmaceutics", "Chemical Engineering", "Energy", "Engineering", "Materials Science" and "Multidisciplinary" were considered, and the query string used was (("contaminated soil" OR "soil contamination*" OR "soil pollution*" OR "polluted soil") AND (treatment OR remediat* OR recover* OR repair* OR *remediation OR control) AND NOT sludge AND NOT "human health risk" AND NOT atmospheric AND NOT water AND treatment AND (LIMIT-TO (LANGUAGE, "English"))).

The subject areas in the Scopus database were the following: "Energy Fuels", "Biochemistry Molecular Biology", "Geology", "Meteorology Atmospheric Sciences", "Public Environmental Occupational Health", "Plant Sciences", "Science Technology Other Topics", "Microbiology", "Water Resources", "Toxicology", "Chemistry", "Biotechnology Applied Microbiology", "Agriculture", "Engineering", "Environmental Sciences Ecology", "Geochemistry Geophysics", "Materials Science", "Electrochemistry", "Biodiversity Conservation" and "Food Science Technology", and the used query string was ((TS = ("contaminated soil") OR TS = ("soil contamination*") OR TS = ("soil pollution*") OR TS = ("polluted soil")) AND TS = (remediat* OR recover* OR repair* OR *remediation OR control) NOT TS = (sludge) NOT TS = (atmospheric) NOT TS = (water) NOT TS = ("human health risk") NOT TS = (treatment) AND (LA==("ENGLISH"))).

For ensuring the accuracy of the search query, the authors manually randomized a sample of 100 articles from both selected and excluded articles. This procedure was performed for both databases, and the information was extracted from WoS in .txt format and from Scopus in csv format.

### 2.4. Data analysis

The information was organized in Microsoft Excel including the number of total documents, documents by year, and document by subject area, and next, the information was processed with VOSviewer. The top 10 journals and top 10 papers (most cited publications) were obtained directly from the WoS and Scopus databases. The main contaminants and soil treatment technologies, density visualization maps, and group analysis were carried out using the VOSviewer as described by previous studies (Hu et al., 2019a; Hu et al., 2019b; Oliveira Filho, 2020; Shi et al., 2021). Data analysis also included the following: (a) characteristics of publications, (b) main research sources about contaminated soils, (c) citations and journals with greatest production, (d) author keywords trend analysis, (e) active countries in soil treatment research, (f) productivity of soil treatment articles by institution, (g) production of the authors, (h) most cited articles, (i) trends in soil treatment research: technologies and mechanisms, and (j) soil remediation techniques and mechanisms.

## 3. Results and discussion

### 3.1. Overlap between WoS and Scopus publications

On the overlap between WoS and Scopus publications, in the WoS and Scopus databases together, 8571 different scientific documents (original articles and review articles) were evaluated. In WoS, 3818 scientific documents were identified, while in Scopus there were 4753. Likewise, 15.0 % of these documents were shared in both databases (overlapping), as can be seen in Fig. 1.

Mongeon and Paul-Hus (2016) reported a particular orientation of Scopus in biomedical research and natural sciences; while engineering seems to be represented to a greater extent in WoS; however, in this study the largest number of documents was reported in Scopus. Scopus is presented as the database with the largest coverage of scientific journals compared to WoS; however, WoS is more selective (Singh et al., 2021).

### 3.2. Types of publications

The types of scientific publications related to contaminated soils and their treatment are presented in Table 1. The greatest contribution of scientific documents related to the subject comes from original articles (91 %) and review articles (5.1 %), while only 3.9 % of these scientific documents is distributed among the following types of documents: proceeding paper, early access, book chapter, and data paper in WoS. In Scopus, it is observed that the distribution of the documents was as follows: (a) articles (81.1 %), (b) conference papers (11.2 %), (c) book chapters (2.6 %), (d) reviews (2.1 %), (e) books (0.6 %), and (f) others (2.4 %) which corresponds to notes, conference reviews, letters, etc.

In the pre-established range of years, a greater number of publications in the Scopus database is observed, with the notorious contribution of conference papers in this database. It could be explained because the publication of these documents is faster and easier compared to journal articles (Purnell, 2021).

### 3.3. Annual production of publications

Regarding the annual production of publications, the scientific productivity of articles and reviews published from January 2010 to June 2021 is in Fig. 2. The research published on the subject under study shows a growing trend in both academic bases. Comparing the number of publications in 2010 and 2020, there is evidence of an increase in publications of up to 3 times in WoS and 1.7 times in Scopus. The number of publications in Scopus is greater than in WoS. This superiority in publications was reduced from 2019 to June 2021. Soil contamination is one of the main concerns worldwide in recent years (Zeb et al., 2020). It generates great interest from the scientific community in research and publication related to the treatment of contaminated soils and there is also financial support from governments in research related to the subject (Guo et al., 2014).

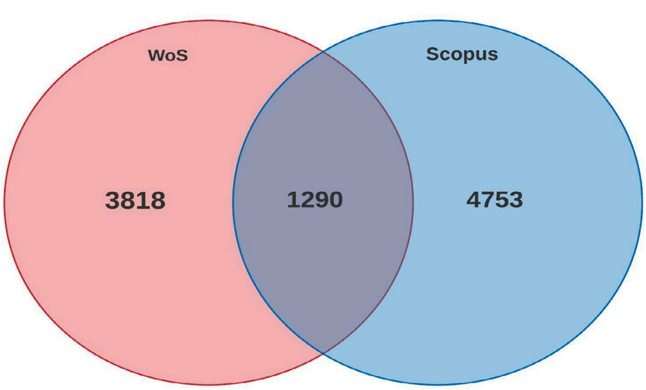


**Fig. 1.** Overlapping of publications.

### 3.4. Main subject areas

Fig. 3 shows the scientific papers published (2010–2021) in both academic databases, organized by subject areas. As shown in Fig. 3a (For WoS), the area of environmental science has covered most publications (47.4 %), followed by Engineering Environmental (9.5 %), Engineering Chemical (7.5 %), Biotechnology Applied Microbiology (7.70 %), Soil Science (5.2 %), and others (22.7 % composed by Toxicology, Water Resources, Microbiology, Engineering Chemical, Plant Sciences, and Plant Sciences Chemistry Multidisciplinary). The results are similar to the reported results of the bibliometric study of contaminated soils (1999–2012) of Guo et al. (2014), who reported: (a) the four most common categories were environmental sciences (52.9 % of the total), (b) environmental engineering (14.3 %), (c) soil science (10.8 %), and (d) applied microbiology (10.3 %). Hu et al. (2019a) identified Environmental Science Ecology and Engineering as the most important subjects related to the field of soil remediation in 1988–2018.

The main thematic areas (in Fig. 3b [Scopus database]) are the following: (a) Environmental Science (43.0 %), (b) Agriculture and Biological Science (17.6 %), (c) Chemistry (8.8 %), (d) Biochemistry, Genetics and Molecular Biology (8.4 %), (e) Immunology and Microbiology (6.6 %), and (f) others (15.5 %), composed by Earth and Planetary Sciences, Medicine, Pharmacology, Toxicology and Pharmaceutics, and Chemical Engineering. The major quantity of publications in both databases is in the subject area of Environmental Science. It is necessary to highlight the limited contribution of the subject area of agriculture and soils, being 5.2 % of Soil Science in WoS and 17.6 % of Agriculture and Biological Science in Scopus. The high quantity of subject areas of the Fig. 3a and b shows the interest and the multidisciplinary approach of the subject of contaminated soils and their treatment.

### 3.5. Main research sources about contaminated soils

Journals with ten or more papers published in this field of research during the study period were selected for identifying main research sources. A total of 747 sources were identified in WoS, of which 93 met this requirement (Fig. 4a), while in Scopus a total of 1219 sources were counted, and only 104 met the aforementioned requirements (Fig. 4b).

The 5108 WoS articles were published in 747 journals, of which 10 journals covered 34.73 % of these publications (see Table 2). These journals include Environmental Science and Pollution Research with 304 publications (5.95 % of publications), Chemosphere with 262 publications (5.13 %), and Journal of Hazardous Materials with 234 publications (4.58 %). In addition, the 6043 Scopus articles were published in 1219 journals, of which 10 journals published 32.27 %. In Scopus, only 1219 journals published all articles (6043), of which 10 journals published 32.27 %. The most important journals that published at least 10 articles on the subject under study were: Science of the Total Environmental with 291 publications (4.82 % of the publications), Chemosphere with 277 publications (4.58 %), and Environmental Science and Pollution Research with 235 publications (3.89 %) [see Table 3]. It should be noted that Mao et al. (2018) and Guo et al. (2014) found that the main sources on this topic in the WoS database were Chemosphere and Journal of Hazardous Materials in the periods 1996–2015 and 1999–2012; however, this study has shown that Environmental Science and Pollution Research and Chemosphere are the main journals that publish studies related to contaminated soils.

**Table 1**
Types of documents published: a) WoS and b) Scopus.

| a) WoS | | | b) Scopus | | |
|---|---|---|---|---|---|
| Document type | Documents | Percentage (%) | Document type | Documents | Percentage (%) |
| Article | 4833 | 91.0 | Article | 5894 | 81.1 |
| Review | 275 | 5.2 | Conference paper | 815 | 11.2 |
| Proceedings Paper | 104 | 2.0 | Book chapter | 187 | 2.6 |
| Early Access | 87 | 1.6 | Review | 149 | 2.1 |
| Book Chapter | 8 | 0.2 | Book | 43 | 0.6 |
| Data Paper | 6 | 0.1 | Others | 177 | 2.4 |
| | 5313 | 100.00 % | | 7265 | 100.00 % |

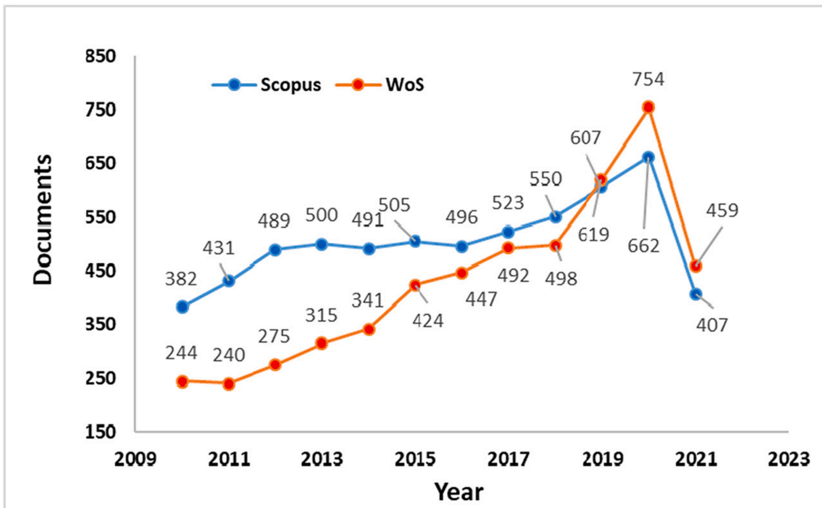


**Fig. 2.** Annual number of publications in Scopus and WoS.

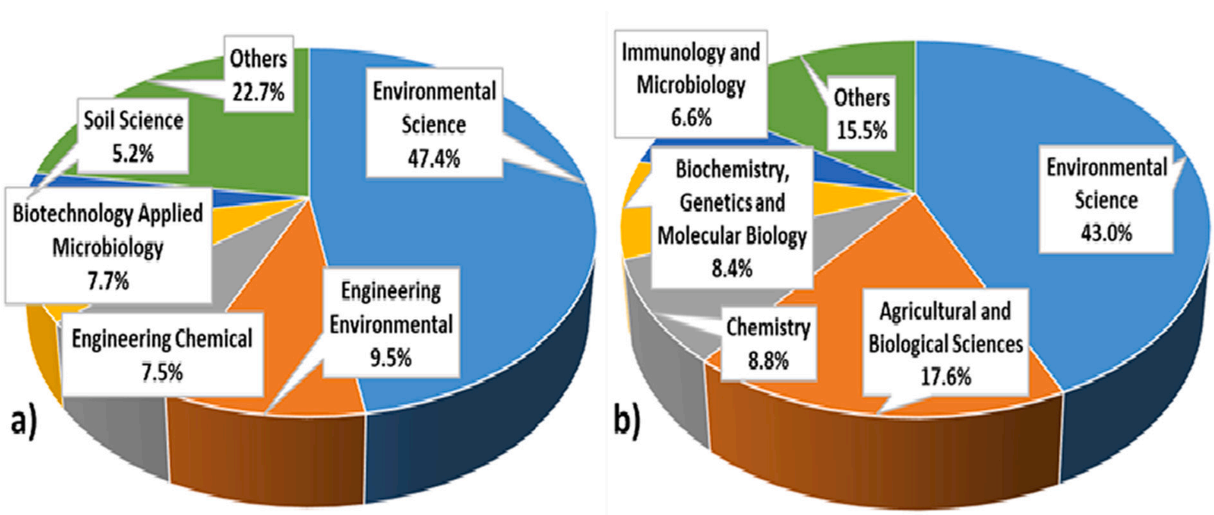


**Fig. 3.** Documents by subject area: a) WoS and b) Scopus.

### 3.6. Citations and journals with greatest production

Regarding the number of citations per source, the Journal of Hazardous Materials shows the highest citation activity, (7638) in WoS, following this Science of the Total Environment (6800), and Chemosphere (5762). Of the top 10 journals, six journals had an H-index >200. Likewise, eight journals are in the WoS Q1 quartile and two journals are in the WoS Q2 quartile (see Table 3). It should be noted that of the ten most productive journals, five are published in the United Kingdom, two in The Netherlands, two in Germany, and one in the United States of America. The thematic areas related to the topic of this study were the following: Environmental Science, Chemistry, and Agricultural and Biological Sciences.

In Scopus, the Journal of Hazardous Materials had the greatest quantity of citations (7489), followed by Chemosphere (6553), and Environmental pollution (6431). Of the top 10 journals, five journals had an H-index >200. Likewise, seven journals are in the Scopus Q1 quartile and three journals are in the Q2 quartile (see Table 3). It should

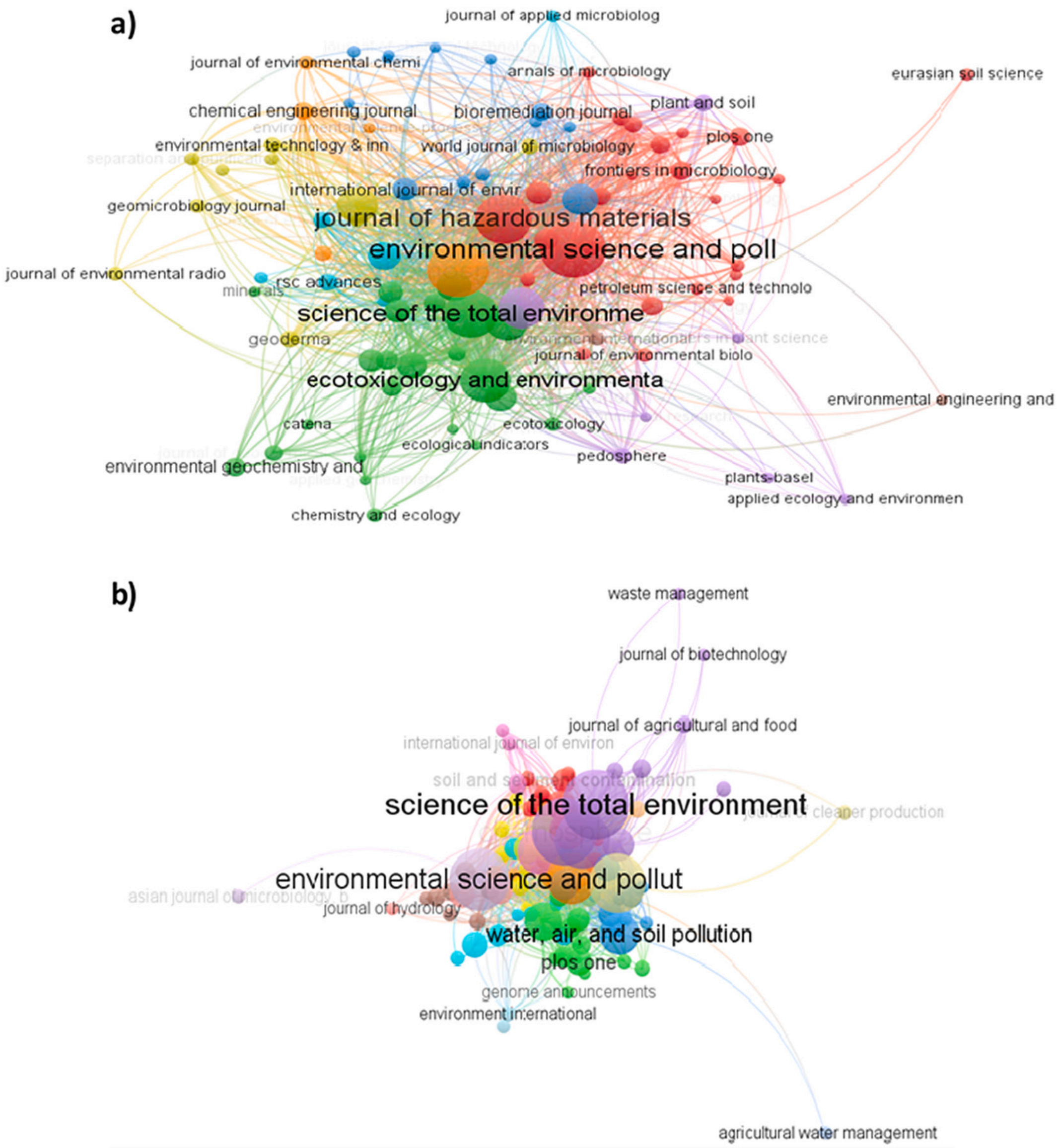


**Fig. 4.** Research sources: a) WoS and b) Scopus.

**Table 2**
Journals with the greatest scientific production in WoS.

| N° | Source | TP | Citations | Percentage of publications (%) | H | Q | Country | Subject area |
|---|---|---|---|---|---|---|---|---|
| 1 | Environmental Science and Pollution Research | 304 | 4218 | 5.95 | 113 | Q2 | Germany | Environmental Science, Medicine |
| 2 | Chemosphere | 262 | 5762 | 5.13 | 248 | Q1 | United Kingdom | Chemistry, Environmental Science |
| 3 | Journal of Hazardous Materials | 234 | 7638 | 4.58 | 284 | Q1 | Netherlands | Environmental Science |
| 4 | Science of the total environment | 208 | 6800 | 4.07 | 244 | Q1 | Netherlands | Environmental Science |
| 5 | Ecotoxicology and environmental safety | 179 | 3593 | 3.5 | 129 | Q1 | Germany | Environmental Science, Medicine |
| 6 | International journal of phytoremediation | 158 | 2097 | 3.09 | 84 | Q2 | United Kingdom | Agricultural and Biological, Environmental Science |
| 7 | Environmental Pollution | 135 | 2627 | 2.64 | 227 | Q1 | United Kingdom | Environmental Science |
| 8 | International Biodeterioration & Biodegradation | 92 | 2664 | 1.8 | 103 | Q1 | United Kingdom | Environmental Science |
| 9 | Environmental Science & Technology | 45 | 1945 | 0.88 | 397 | Q1 | United States | Chemistry, Environmental Science |
| 10 | Bioresource Technology | 32 | 2154 | 0.63 | 294 | Q1 | United Kingdom | Chemical Engineering, Environmental Science |

TP: Total number of documents, Q: Quartile, H-Index: Hirsh index.

**Table 3**
Journals with the greatest scientific production in Scopus.

| N° | Source | TP | Cites | Percentage of publications | H | Q | Country | Subject area |
|---|---|---|---|---|---|---|---|---|
| 1 | Science of the total environment | 291 | 6324 | 4.82 | 244 | Q1 | Netherlands | Environmental Science |
| 2 | Chemosphere | 277 | 6553 | 4.58 | 248 | Q1 | United Kingdom | Chemistry, Environmental Science |
| 3 | Environmental science and pollution research | 235 | 3441 | 3.89 | 113 | Q2 | Germany | Environmental Science, Medicine |
| 4 | Journal of hazardous materials | 215 | 7489 | 3.56 | 284 | Q1 | Netherlands | Environmental Science |
| 5 | Environmental pollution | 200 | 6431 | 3.31 | 227 | Q1 | United Kingdom | Environmental Science |
| 6 | Ecotoxicology and environmental safety | 164 | 3433 | 2.71 | 129 | Q1 | Germany | Environmental Science, Medicine |
| 7 | International journal of phytoremediation | 122 | 1930 | 2.02 | 84 | Q2 | United Kingdom | Agricultural and Biological Sciences |
| 8 | Water, air, and soil pollution | 106 | 1628 | 1.75 | 111 | Q2 | Netherlands | Environmental Science |
| 9 | Environmental science and technology | 91 | 3690 | 1.51 | 397 | Q1 | United States | Chemistry, Environmental Science |
| 10 | Journal of environmental management | 70 | 2016 | 1.16 | 179 | Q1 | United States | Environmental Science |

TP: Total number of documents., Q: Quartile, H-Index: Hirsh index.

be noted that of the 10 most productive journals, three are published in the United Kingdom, three in The Netherlands, two in Germany, and two in the United States of America. The thematic areas related to the subject of contaminated soils and their treatment were the following: Environmental Science, Chemistry, and Agricultural and Biological Sciences.

Mao et al. (2018) found that the most cited journals in the field of contaminated soil treatment were the following: Environmental Science

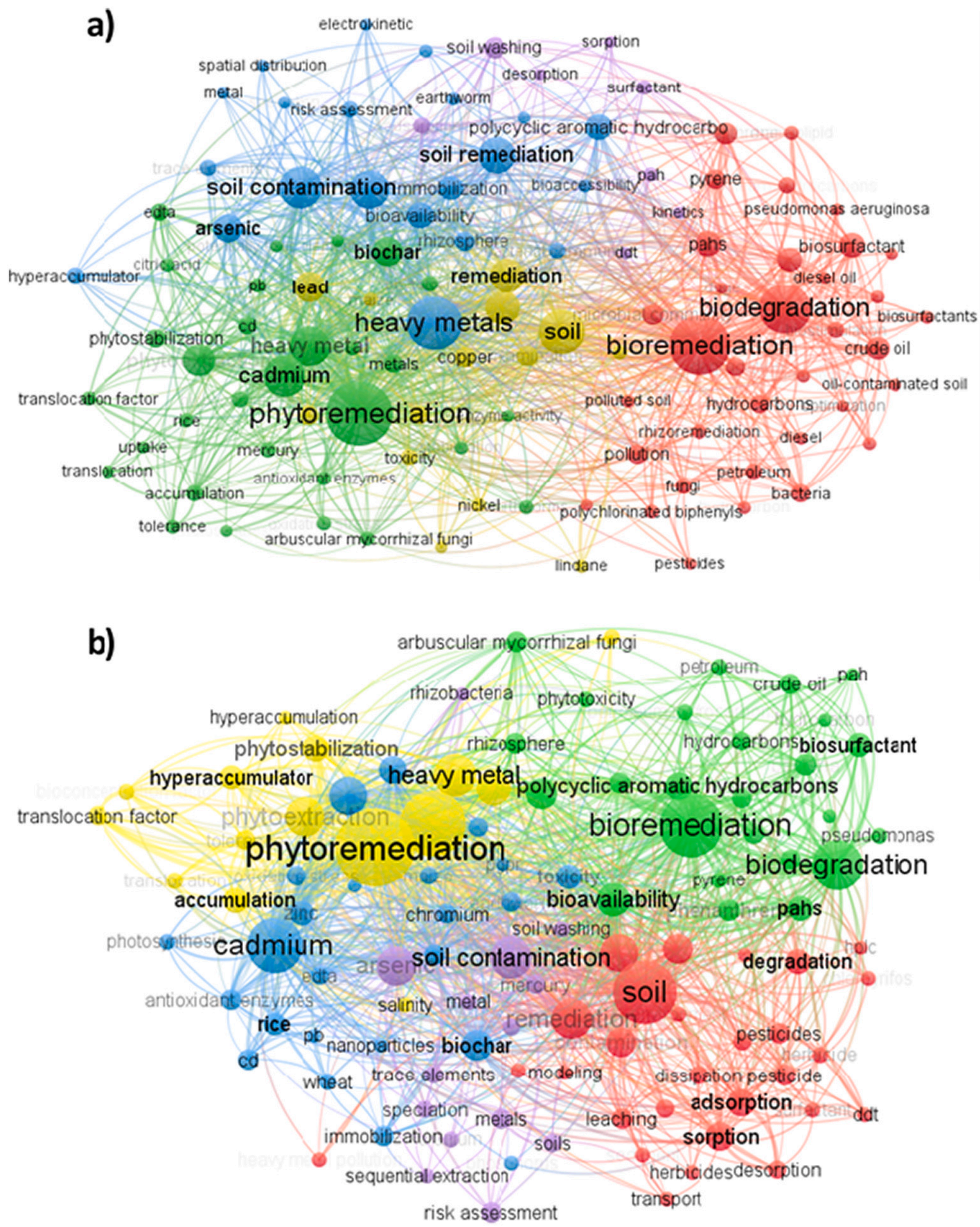


**Fig. 5.** Co-occurrence map of keywords: a) WoS and b) Scopus.

& Technology and International Journal of Phytoremediation and Environmental Pollution. Meanwhile, Guo et al. (2014) reported that the most cited journals in this field were Environmental Science & Technology, Chemosphere, and Environmental Pollution. The results of this study show that the Journal of Hazardous Materials has been the most cited in the last decade.

According to Tables 2 and 3, eight of the ten journals with the greatest scientific production and impact are indexed in both databases. All of these journals are classified in the area of environmental sciences. In addition, the diversified and wide number of sources indicated a great interest of editors and researchers in the area of treatment of contaminated soils.

### 3.7. Author keywords trend analysis

Keywords are terms or short phrases that allow to classify and address the entries in the indexing and retrieval systems of the information in the databases of a manuscript or particular thematic area. Keywords become an essential two-way tool; that is, for people who write and people who seek information on manuscripts or related thematic areas (Valdiviezo Gonzales et al., 2021; Zhu et al., 2019).

A total of 10,268 author keywords were found in the WoS database (out of 5108 articles analyzed). The criterion was to select those keywords with a minimum of 20 occurrences finding that 108 author keywords met this requirement (see Fig. 5a). In the Scopus database the frequency of keywords in the 6043 articles was examined and a total of 13,335 author keywords were found. Likewise 106 author keywords with no $<$20 appearances were identified (see Fig. 5b).

Fig. 5a shows that in the WoS database, the most used keywords are phytoremediation, with 518 (5.66 %) appearances, followed by bioremediation with 507 (4.94 %) appearances, heavy metals with 404 (3.93 %), biodegradation with 358 (3.49 %), and soil with 279 (2.72 %) appearances. Fig. 5a also shows the co-occurrence of keywords in the WoS database, grouping them into 6 categories or clusters.

The three main ones include: (a) cluster 1 (red color) that links terms related to bioremediation, such as: bacteria, bioaugmentation, biodegradation, biostimulation, rhizosphere, among others; (b) cluster 2 (green color) that is more related to the field of a specific treatment technique for soils contaminated with heavy metals such as phytoremediation and includes terms such as arsenic, biosorption, bioaccumulation, cadmium, chromium, copper, lead, zinc, among others; (c) cluster 3 (blue color) that associates terms related to soil contamination, such as: heavy metals, soil contamination, soil remediation, among others. All groups of words concur with each other, so they present a close conceptual link.

Fig. 5b shows that the most frequent keywords are "phytoremediation" in the Scopus database, with 587 appearances (4.40 %). It is followed by "heavy metals" with 399 appearances (2.99 %), "bioremediation" with 385 appearances (2.89 %), "soil" with 364 (2.73 %), and "cadmium" with 278 appearances (2.08 %). The results of co-occurrence of keywords in the Scopus database are grouped into 6 categories or clusters, and the most relevant are: (a) the first cluster (red color) revolves around soil contamination and relates terms such as: soil, contamination, degradation, adsorption, herbicide, pesticide, among others; (b) the second cluster (yellow color) is more related to phytoremediation, which is a soil remediation technique contaminated mainly with metals and includes terms such as accumulation, phytoremediation, phytoextraction, phytostabilization, hyperaccumulator, among others; and (c) the third cluster (green color) lists terms related to bioremediation, such as: bacteria, bioaugmentation, biodegradation, biostimulation, biosurfactant, rhizosphere, among others. All groups of words concur with each other, so they present a close conceptual link.

Mao et al. (2018) and Guo et al. (2014) reported that the most frequent keywords in this topic in the period 1996–2015 in the WoS database were "bioremediation" and "phytoremediation" with 1513 and 1078 concurrences, respectively. Furthermore, Guo et al. (2014) found that the keywords in this theme in the WoS database were "heavy metals" and "soil" in the period 1999–2012. In the present study, it was found that "phytoremediation" was the most used keyword in the last decade.

### 3.8. Most productive countries in soil treatment research

Soil contamination is a global concern and the intensity of research may vary among countries. It is important to conduct an analysis of published articles from around the world to determine advances in technologies for treatment and removal of various soil contaminants. Various investigations have been found that apply different technologies for the treatment of contaminated soils. In the WoS database, countries with at least 5 documents in this field of research were identified. Of a total of 115 countries, 75 countries have at least 5 documents. Similarly, 79 of 146 countries have at least 5 documents in the Scopus database.

Fig. 6 shows the network between countries of international co-authorship. In Fig. 6a (WoS), six large groups or clusters are distinguished corresponding to the countries that produce the majority of articles, of which three are the most relevant. In the first cluster, the following stand out: China, France, Scotland, and Canada, among others. The second cluster relates countries such as: India, Tunisia, and the United Arab Emirates. The third group involves Spain in a relationship with South American countries such as: Argentina, Chile, and Peru. USA has a relationship with the majority of the countries in the world. It can be seen that China is the most active country in the production of studies related to soil treatment during the last decade according to the WoS database. Researchers from China contributed 1876 articles, accounting for 36.73 %. Researchers from India contributed 427 articles, representing 8.36 %. Researchers from the USA contributed 423 articles, representing 8.28 %. There is quite a difference between China and the other countries. Among the countries of the European region, the ones that stand out the most were the following: Spain, Poland, France, and Italy, with 239, 208, 189, and 184 articles, respectively.

In Fig. 6b, China is the most productive country during the last decade, according to the Scopus database. Researchers from China contributed 1775 articles, accounting for 29.37 %. It is understandable given the significant efforts of the Chinese government to combat soil pollution (Yu and Wu, 2018). Researchers from the United States contributed 690 articles, which represents 11.42 %. Researchers from India have contributed 547 articles, which is 9.05 %. There is a big difference between China and other countries.

The countries of the European region that have contributed the most in this field of research are Spain, France, Italy, and Germany with 293, 249, 255, and 217 articles, respectively. Fig. 6b shows the co-authorship relationships of countries that due to their tendency to appear together allow them to be grouped into categories. Six large groups or clusters have been detected, of which four are the most relevant, with China standing out in the first cluster, which relates to the majority of countries. The second cluster relates the USA with other countries such as Saudi Arabia and the Philippines. The third cluster involves Asian countries such as India and Singapore that are related to European countries such as Germany, Sweden, Ukraine, among others. In a fourth cluster, European countries such as Italy, Poland, Russia, Switzerland, United Kingdom, among others are related.

### 3.9. Productivity of articles by institution

The productivity of research by institutions on the treatment of contaminated soil is shown in Fig. 7. In WoS, a total of 4240 organizations were found that support research on the topic of soil treatment. It was observed that 188 organizations are linked to a minimum of 10 articles and scientific reviews. The Scopus database found 13,840 organizations linked to these publications and 13 organizations with at least 10 documents were identified.

The contribution of The Chinese Academy of Sciences of Beijing in

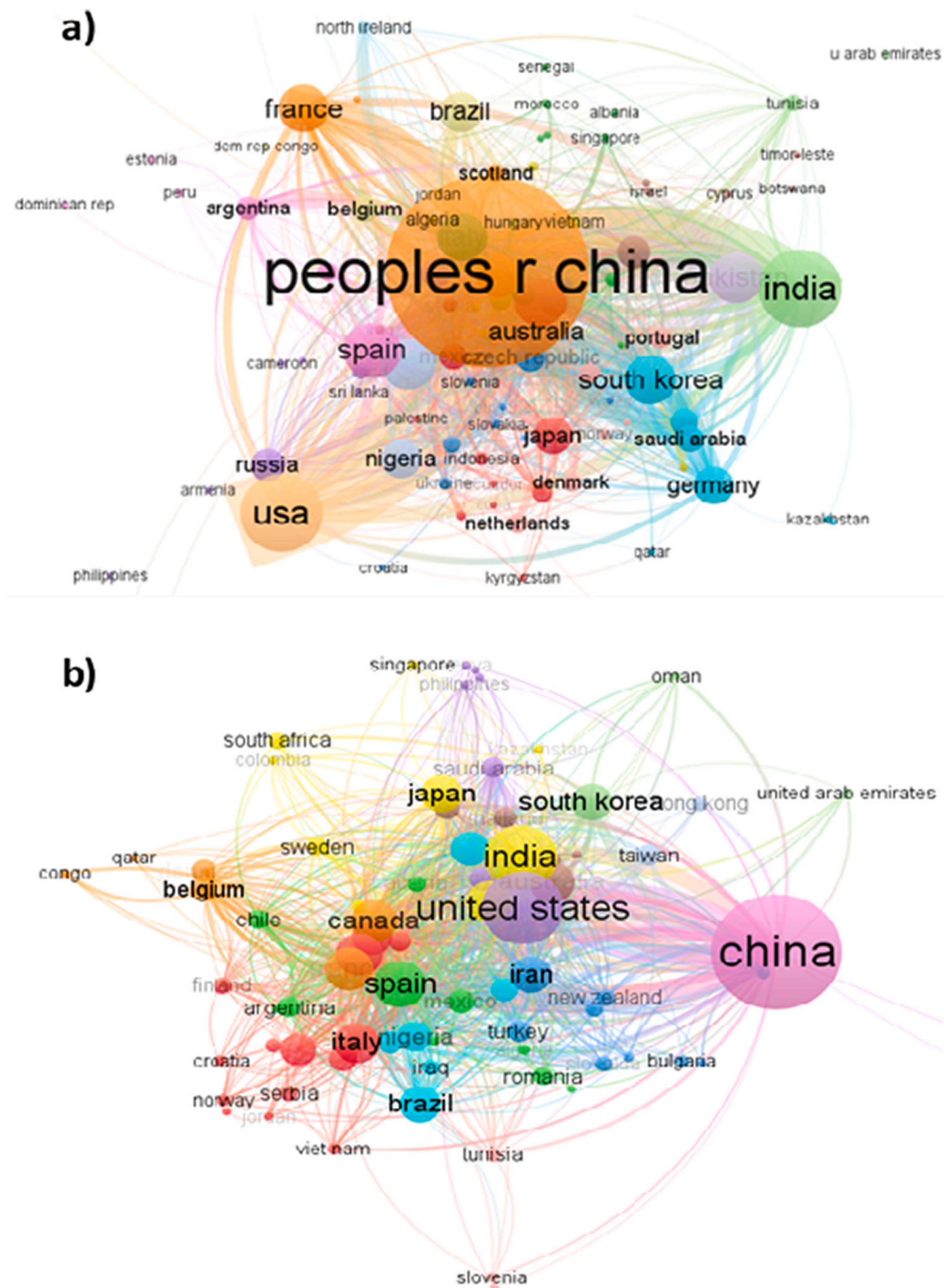


**Fig. 6.** Map of country cooperation in treatment of soils contaminated from: a) WoS and b) Scopus.

China is notably higher in this field of research with 370 papers in WoS. The University of Chinese Academy of Sciences of Beijing in China contributed 113 papers to Scopus and Zhejiang University contributed 97 papers to WoS. A dispersion of the origins of the organizations in the base of WoS is notorious; most of them were Asian and European, linked to the issue of soil contamination and treatment (see Fig. 7a).

Fig. 7b shows the main institutions that contribute to the publication of scientific papers related to the subject and indexed in Scopus. These are the institutions with which the main authors are associated as the first author and the corresponding author. The contribution of The University of Chinese Academy of Sciences in Beijing is notably higher in this field of research with 61 documents. Second, the Key Laboratory of Soil Environment and Pollution Remediation, Institute of Soil Science, Chinese Academy of Sciences, and Nanjing with 36 papers and the College of Horticulture, Sichuan Agricultural University, Chengdu, and Sichuan have contributed 13 papers. Research in these organizations is interdisciplinary.

In both WoS and Scopus, Chinese research centers and universities lead the scientific production in the last 10 years. Likewise, there is a greater diversity of institutions in the WoS academic database.

### 3.10. Authors most productive

The importance of determining the scientific production by authors allows us to know which are those elite researchers who lead the research and publications on soil pollution and treatment. Fig. 8a show the list of authors who to date have contributed the largest number of publications on soil pollution and treatment.

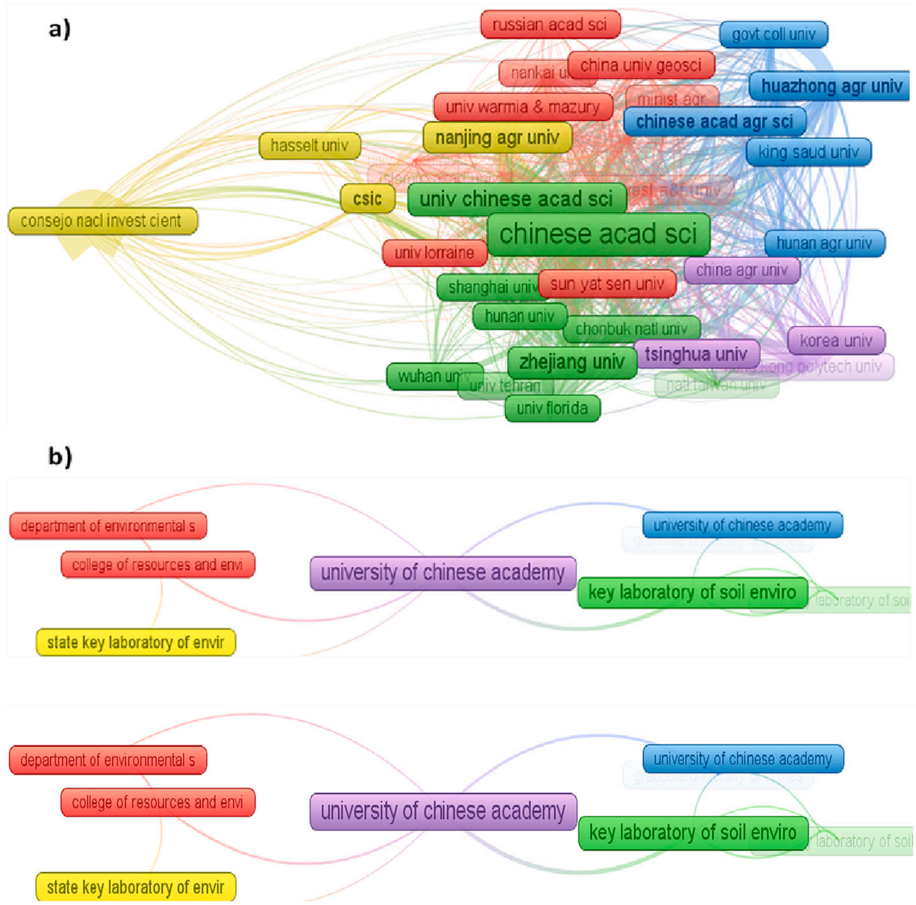


**Fig. 7.** The main institutions that contribute to the publication of scientific papers related to treatment of soils contaminated, from: a) WoS and b) Scopus.

Fig. 8a shows the participation of authors according to the number of documents published in WoS, considering 10 or more publications per author. In WoS, 78 authors with a minimum of 10 publications were identified. Five main authors were identified by the number of publications (considering a total of 19,321), whose number of publications were: (a) first author: 28 documents (Yong Sik Ok), (b) second author: 28 documents (Daniel Tsang), (c) third author: 27 documents (Ravi Naidu), (d) fourth author: 26 articles (Yongming Luo), and (e) fifth author: 25 documents (Mallavarapu Megharaj). The top ten WoS producing authors in this field comprise <5 % (4.77 %). The large number of reported authors does not indicate a concentration of publications per author in WoS.

Of the total of 18,512 authors in Scopus, 239 have at least 10 publications. As can be seen, in Scopus there is a much higher number of authors than in WoS, who meet the minimum search requirement of 10 publications. In Scopus, the 5 main authors were identified: (a) the first (Wang, Y.) published 107 documents (1.77 %), (b) the second (Li, Y.) had 102 publications (1.68 %), (c) the third (Wang, X.) with 96 publications (1.59 %), (d) the fourth (Wang, J.) with 87 documents (1.44 %), and (e) the fifth (Zhang, X.) with 85 publications (1.40 %) [Fig. 8b].

The top 10 most productive authors in Scopus in this field cover a total of 13.78 %, which is much higher than that published by the top 10 authors with the highest production in WoS (4.77 %). Greater diversity of authors is observed in Scopus; however, the greatest production of scientific documents is concentrated in a small number of researchers. A more homogeneous distribution between scientific production per author is observed in the WoS.

The Matthew effect in scientific production (Merton, 1968) implies that a small number of authors specialized in a subject have a high number of publications, while a large number of transitory authors have few publications in this field. This behavior was observed in environmental science publications (Grandjean et al., 2011), but not in this study. In general, there is no evidence of a concentration of publications in a small group of authors in both academic databases.

### 3.11. *The top 10 most cited publications*

The list of the top 10 articles with >346 citations each in the WoS database is shown in Table 4. The most cited article was "A Review of Soil Heavy Metal Pollution from Mines in China: Pollution and Health Risk Assessment", which has 1289 citations and was published in the journal "Science of the Total Environment". Comparing the first two articles, almost twice as many citations are observed between both publications and 3.7 times between the first and the tenth most cited publications. Among the scientific journals, "Science of the total environment" stands out in the publication of the first and third most cited articles and the journal "Environment international" in the publication of the fourth and fifth most cited articles.

The list of the 10 most cited articles in Scopus is shown in Table 5. Articles with >295 citations were identified in this database. The most cited article was "Effects of biochar and green waste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil", which had 765 citations and was published in the journal "Environmental Pollution".

Luke Beesley stands out as the first author in the two most cited articles in the Scopus database. The journal "Environmental Pollution" published the first, second, and ninth most cited articles in Scopus. Likewise, "Journal of Hazardous Materials" and "Ecotoxicology and Environmental Safety" were identified as journals with the most cited articles, and which are present in both databases. There is also a

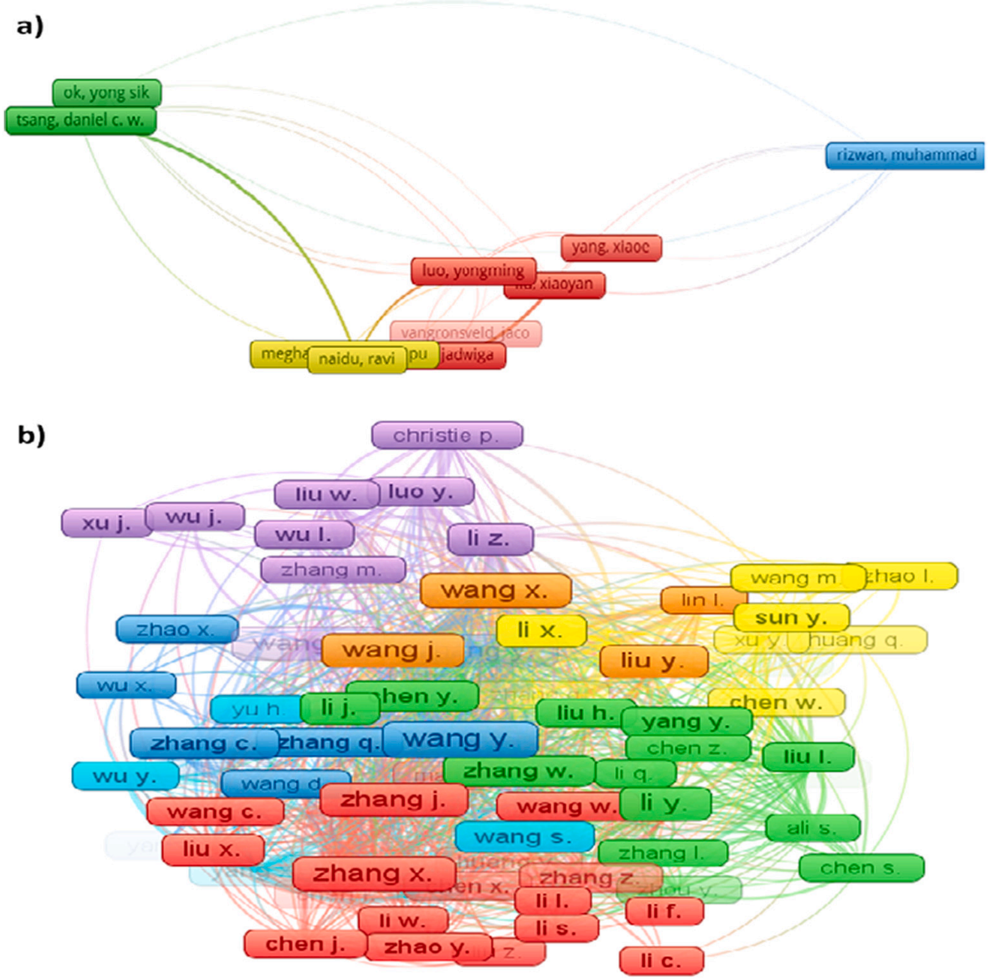


**Fig. 8.** Main authors that contribute to the publication of scientific papers related to treatment of soils contaminated, from: a) WoS and b) Scopus.

concentration of journals in both databases related to the most cited articles. This reduced number of journals allows researchers to identify the best option for publishing research more easily (Brookes, 1985).

### *3.12. Trends in soil treatment research: technologies and mechanisms. Inorganic contaminants (metals and metalloids)*

Regarding inorganic contaminants (metals and metalloids), Fig. 9 presents the occurrences of the main metals and metalloids that appear in the publications counted in the WoS (a) and Scopus (b) databases between 2010 and 2020.

Soil contamination by heavy metals has traditionally been investigated, highlighting cadmium, lead, copper, zinc, chromium, and certain metalloids such as arsenic. In addition, it is known that Zn and Cu are essential trace elements for living organisms, which when exceeding the threshold concentration, generate reactive species affecting the plasma membrane (Kim et al., 2019). Non-essential agents such as Cd, Pb, and Hg induce oxidative stress by repressing enzymatic activity and As induces oxidative stress through redox reactions (Valko et al., 2016).

Regarding Hg, its bioavailability in the soil and the implication of phytoremediation and methylation are evaluated. Studies related to mobilization, speciation, and its relationship with soil organic matter have also been identified. These findings agree with what was described by Fernandes et al. (2021) in their scientometric study of the WoS database, developed for Hg in soils between 1991 and 2020.

The search for these contaminants including the term HM (Heavy Metal) in the studied databases reported the following order for WoS: Heavy metal > Cd > Pb > As > Cu > Zn > Cr > Ni > Hg > Co > U, and for Scopus: Heavy metal > Cd > As > Pb > Cu > Zn > Cr > Hg > Ni. According to the results, at least 30 occurrences appear in the use of the term "heavy metal" in the titles of the publications each year without discriminating the metals studied. In addition, as of 2015, the WoS database shows occurrences of nickel, mercury, cobalt, and uranium in the investigations; on the other hand, chromium, mercury, and nickel appear in a lower proportion than the other metals in Scopus over the last 10 years.

This review evidenced the annual increase in publications on metal contamination (WoS: from 60 occurrences in 2010 to 260 in 2020 and Scopus from 65 in 2010 to 188 in 2020). Asia, Europe, and North America were highlighted as powerhouses in the publications, especially in spatial distribution, their presence in the soil, and the risk of exposure to human health. These results were similar to those reported by Wang et al. (2021) who evaluated 1051 articles from the WoS database between the years 2000 and 2020.

Research on contaminated soils, sites, and proximities of active sources of Hg contamination, especially in China and the US, stands out. Bandyopadhyay (2021) conducted a scientometric study on metals in mining soils between 2010 and 2020 and warned that majority of the publications are classified as Environmental Sciences as recorded in this investigation; however, the use of the native vegetation cover of the mining sites in this particular case, due to its high biomass and rapid growth, and the ability to acclimatization is one of the relevant aspects including a genomic approach for the application of genetic markers in soil remediation.

**Table 4**
The 10 most cited documents in WoS.

| N° | Authors | Article Title | Citation | Journal |
|---|---|---|---|---|
| 1 | Li et al. (2014) | A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment | 1289 | Science of the total environment |
| 2 | Tsitonaki et al. (2010) | In Situ Chemical Oxidation of Contaminated Soil and Groundwater Using Persulfate: A Review | 666 | Critical reviews in environmental science and technology |
| 3 | Chen et al. (2015) | Contamination features and health risk of soil heavy metals in China | 594 | Science of the total environment |
| 4 | Tóth et al. (2016) | Heavy metals in agricultural soils of the European Union with implications for food safety | 530 | Environment international |
| 5 | Megharaj et al. (2011) | Bioremediation approaches for organic pollutants: A critical perspective | 439 | Environment international |
| 6 | Pacwa-Plociniczak et al. (2011) | Environmental Applications of Biosurfactants: Recent Advances | 433 | International journal of molecular sciences |
| 7 | Mahar et al. (2016) | Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: A review | 424 | Ecotoxicology and environmental safety |
| 8 | Zhang et al. (2013) | Using biochar for remediation of soils contaminated with heavy metals and organic pollutants | 401 | Environmental science and pollution research |
| 9 | Mao et al. (2015) | Use of surfactants for the remediation of contaminated soils: A review | 359 | Journal of hazardous materials |
| 10 | Varjani (2017) | Microbial degradation of petroleum hydrocarbons | 346 | Bioresource technology |

**Table 5**
The 10 most cited documents in WoS in Scopus.

| N° | Authors | Article title | Citation | Journal |
|---|---|---|---|---|
| 1 | Beesley et al. (2010) | Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil | 765 | Environmental Pollution |
| 2 | Beesley et al. (2011) | The immobilization and retention of soluble arsenic, cadmium and zinc by biochar | 517 | Environmental Pollution |
| 3 | Santoyo et al. (2016) | Plant growth-promoting bacterial endophytes | 506 | Microbiological Research |
| 4 | Sun et al. (2010) | Spatial, sources and risk assessment of heavy metal contamination of urban soils in typical regions of Shenyang, China | 489 | Journal of Hazardous Materials |
| 5 | Mahar et al. (2016) | Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: A review | 488 | Ecotoxicology and Environmental Safety |
| 6 | Ghormade et al. (2011) | Perspectives for nano-biotechnology enabled protection and nutrition of plants Biotechnology Advances | 462 | Biotechnology Advances |
| 7 | Van Elsas et al. (2012) | Microbial diversity determines the invasion of soil by a bacterial pathogen | 424 | Proceedings of the National Academy of Sciences of the United States of America |
| 8 | Cao et al. (2011) | Simultaneous immobilization of lead and atrazine in contaminated soils using dairy-manure biochar | 400 | Environmental science & technology |
| 9 | Bai et al. (2011) | Assessment of heavy metal pollution in wetland soils from the young and old reclaimed regions in the Pearl River Estuary, South China | 324 | Environmental Pollution |
| 10 | Xie et al. (2011) | Spatial distribution of soil heavy metal pollution estimated by different interpolation methods: Accuracy and uncertainty analysis | 295 | Chemosphere |

### 3.13. *Organic pollutants*

On the other hand, regarding organic contaminants, Fig. 10 shows the findings in the search for the most used terms in the publications regarding organic contaminants in soils.

In WoS, the decreasing order of occurrences was: PAHs (Polycyclic Aromatic Hydrocarbons) > PH (petroleum hydrocarbons) > Crude oil > Phenanthrene > Pyrene > Diesel > DDT > Lindane > PCBs > Anthracene > Benzo[*a*]pyrene > OCPs > Chlorimuron-ethyl and in Scopus: PAHs >Pesticides> Phenanthrene > PH > PCBs> Atrazine > Crude oil > Diesel > Herbicide > Pyrene> Lindane> DDT > Endosulfan> FOAM> Chlorpyrifos.

Studies have primarily focused on the 16 PAHs of the US Environmental Protection Agency (EPA) (Wang et al., 2017), Acenaphthylene, Fluoranthene, Indeno[1,2,3-*cd*]pyrene, Pyrene, Naphthalene, Fluorene, Acenaphthene, Benz[*a*]anthracene, Dibenzo[*a*,*h*]anthracene, Benzo[*a*] pyrene, Benzo[g,h,i,]perylene, Chrysene, Benzo[*k*]fluoranthene, Benzo [*b*]fluoranthene, Anthracene, Phenanthrene (United States Environmental Protection Agency - EPA, n.d.), their polar derivatives such as polar polyaromatics (PAC) are more dangerous than the same parent PAHs due to their genotoxicity, carcinogenicity, and mutagenicity (Chen et al., 2021).

Both databases presented higher occurrences with the generic term "Polycyclic aromatic hydrocarbons"; furthermore, the WoS base included 4 PAHs: Pyrene, Benzo[*a*]pyrene, Anthracene, and Phenanthrene; while Scopus included Phenanthrene and Pyrene with higher occurrences. It is important to note that the term PAHs appears constant in the number of WoS occurrences in the last 10 years. The order of occurrences in WoS was the following: PAHs > pyrene > phenanthrene > anthracene, while in Scopus the term PAHs has decreased since 2015 and the occurrences followed the order: PAHs > phenanthrene > pyrene. Concern over the recovery of >372 thousand tons of PAHs-contaminated soil globally continues to motivate these investigations (Chen et al., 2021) because the accumulation of these contaminants in biota and plants through the food chain, resulting in direct or indirect human exposure (Kumar et al., 2021). Consequently, it is critical to

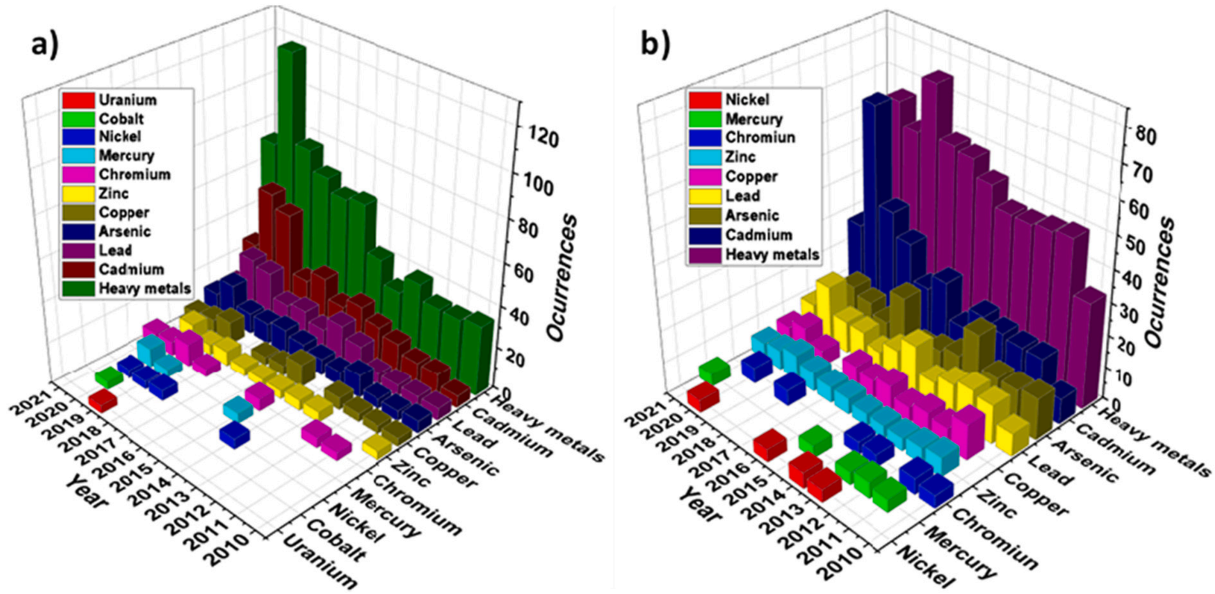


**Fig. 9.** Main metals studied in the last 10 years: a) WoS and b) Scopus.

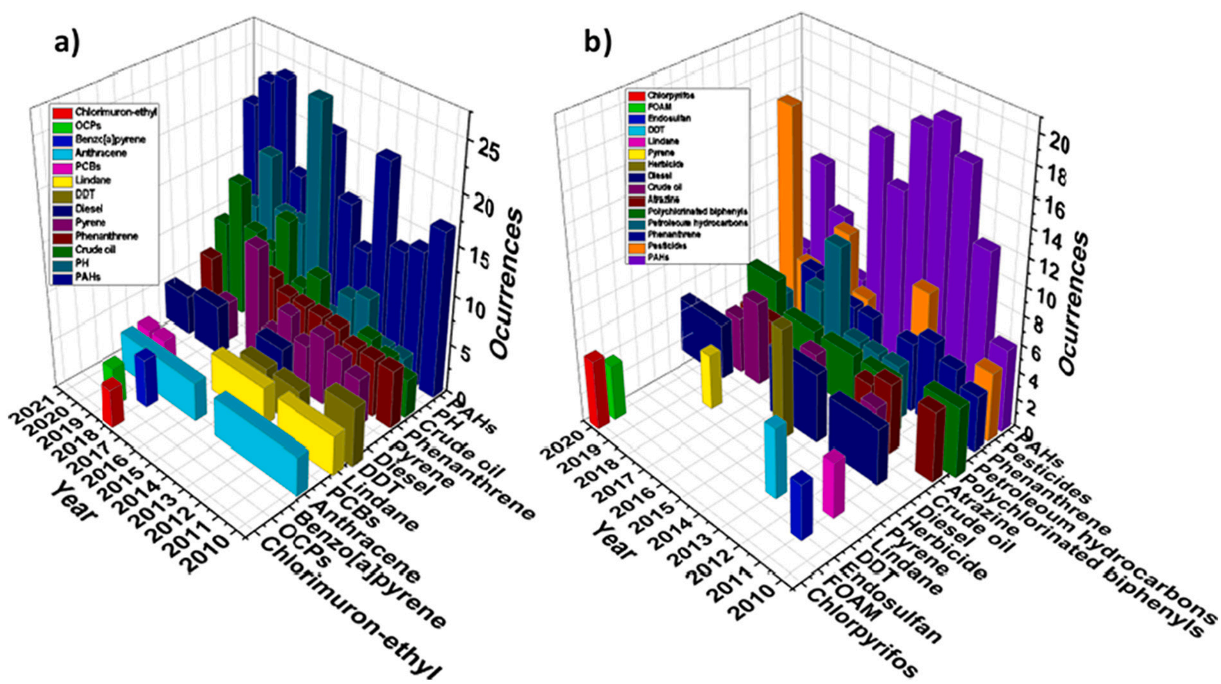


**Fig. 10.** Main organic pollutants most studied in the last 10 years: a) WoS and b) Scopus.

recognize the sources and extent of PAH contamination in soils to avoid or reduce the ecological impact and health risks (Kumar et al., 2021). Several techniques have been adopted for their remediation including immobilization (capping, stabilization and solidification, dredging, and excavation), mobilization (thermal desorption, washing, surfactant-assisted remediation, and electrokinetic remediation), degradation (chemical degradation, phytoremediation, microbial degradation, enzyme-mediated degradation, and compost-mediated degradation) and hybrid/integrated technology that combines two or more remediation techniques (Kumar et al., 2021).

Terms related to "total petroleum hydrocarbons (TPH): crude oil and diesel" have been observed. TPH represent hundreds of hydrocarbon components from crude oil, which include volatile hydrocarbons from the gasoline range (>C6–C10), the diesel range (>C11–C28), and the oil range (C29–C35); also, highlighting kerosene, hexane, benzene, toluene, xylene (BTEX) and polycyclic aromatic hydrocarbons (Kuppusamy et al., 2020) and are considered "persistent organic pollutants" (POPs). In the WoS database, the highest occurrences corresponded to the terms TPH > crude oil > diesel. This last term appears after the year 2015, while in Scopus the order of occurrences was the following: diesel > crude oil > petroleum hydrocarbons.

POPs are fat-soluble and persistent pollutants in the soil, they are transported environmentally in the atmosphere, they are deposited thousands of kilometers away, they are toxic to all living beings due to the accumulation in their adipose tissue, and they present a slow elimination process (Ren et al., 2017). This group includes organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs). Human exposure to OCPs and PCBs and their negative effects have been widely discussed in the Stockholm Convention (SC), for which their elimination or severe restriction for their production was agreed; for this reason, there are monitoring and elimination programs under different treatments at a global level (Helou et al., 2019), forming part of the different publications.

In the WoS database, the trade names of some organochlorine pesticides appear including the term OCPs (Organochlorine pesticides), in the order of occurrence: DDT > Lindane > OCPs. This last term appears in the year 2019, while the others showed a boom between the years 2010 and 2017. In Scopus, the number of occurrences of the OCPs (including said term) between 2010 and 2014 included the following order of terms: Endosulfan > DDT > Lindane. Regarding PCBs, the term PCB appears since 2019 in the WoS database, while in Scopus it appears since 2010 with a higher number of occurrences (23). As is known, PCBs are oils used for electrical transformers and capacitors, including ballasts for fluorescent lamps, and have been released into the environment through sewers, chimneys, runoff, and in some cases were used as pesticides. Its great persistence has been noted in landfills and junkyards and there have also been leaks or explosions of old electrical equipment and transformers, turning them into current sources of pollution (Stojic et al., 2017).

In 2020, the term Chlorimuron-ethyl ($C_{15}H_{15}ClN_4O_6S$) used as an herbicide appeared in the WoS database. This is an acetolactate synthase inhibitor used for weed control in peanuts, beans, among others (Adiki et al., 2021); while the term "pesticide" presented a greater number of occurrences in the period studied, followed by "atrazine" (herbicide), "herbicide", and "chlorpyrifo" in the Scopus database. The term "chlorpyrifo" appeared in the year 2020, aimed at the study of herbicides in general.

Recently, the term FOAM appears in the Scopus database, due to research on the properties of polyurethane foams, formed by porous media, achieved by co-injection of gas and surfactant solutions, which causes the diversion of flows to regions of low permeability, which results in a behavior of great interest for the remediation of heterogeneous contaminated soils (Bertin et al., 2017).

Other organic soil contaminants include endocrine disrupting chemicals (EDCs), such as phthalates and antibiotics (Kumar et al., 2021), as well as organic contaminants including polyaromatic hydrocarbons and poly- and per-fluoroalkyl substances. EDCs are widely used in manufacturing and enter into the soil through direct and indirect pathways. In addition, there are now concerns about their potential effects on soil ecosystems, and some studies have monitored EDCs in the soil environment. However, there have been few studies on EDCs in soils (Kwak et al., 2017). EDCs have not been included in articles related to soils as keywords, in the WoS or in Scopus. Some EDCs such as phthalates do not appear as keywords in any soil articles; however, Lü et al. (2018) mentioned that in recent decades, studies have been carried out on the presence of phthalates in soils, so it is necessary to continue the investigations about this topic. In addition, antibiotic appears as a keyword in 30 of the 3818 articles related to soils in WoS and it appears in 64 of the 4753 articles in Scopus.

### 3.14. Soil remediation techniques and mechanisms

Soil contamination represents a global challenge, because man depends fundamentally on the abiotic and biotic resources that are housed in this environment (Ye et al., 2019). In respect, the literature reports around 20 million hectares impacted by heavy metals and metalloids (He et al., 2015; Liu et al., 2018). Given the diversity of inorganic, organic, emerging, and especially persistent contaminants, the conventional technologies have been improved and assisted through combinations with differences in their practicality, investment costs (including logistics in situ and ex situ) in removal efficiency and its friendly condition with the environment (Liu et al., 2018; Thomé et al., 2019). The techniques and their forms of application also depend on the contaminating agents to be removed or stabilized in the soil.

Fig. 11 show the positions or occurrences of the most used words in the scientific literature, related to the most studied technologies and mechanisms in the last 10 years. Phytoremediation is the most researched technology, followed by bioremediation, in both databases.

### 3.15. Biological techniques

About the biological techniques, it was found that the success of the numerous occurrences on phytoremediation is due to the use of plants with properties to recover degraded soils and it is inexpensive, profitable, and allows the conservation of the soil structure; in addition, it generates less negative environmental impacts (Parseh et al., 2018; Rostami and Azhdarpoor, 2019), however, once harvested, the hyperaccumulators must be subjected to thermal treatments (Cui et al., 2021) as part of the environmental control. Among the main physiological processes and mechanisms reported in the publications, phytoextraction, rhizofiltration, phytostabilization, phytodegradation, rhizodegradation, and phytovolatilization have been identified (Ozyigit et al.,

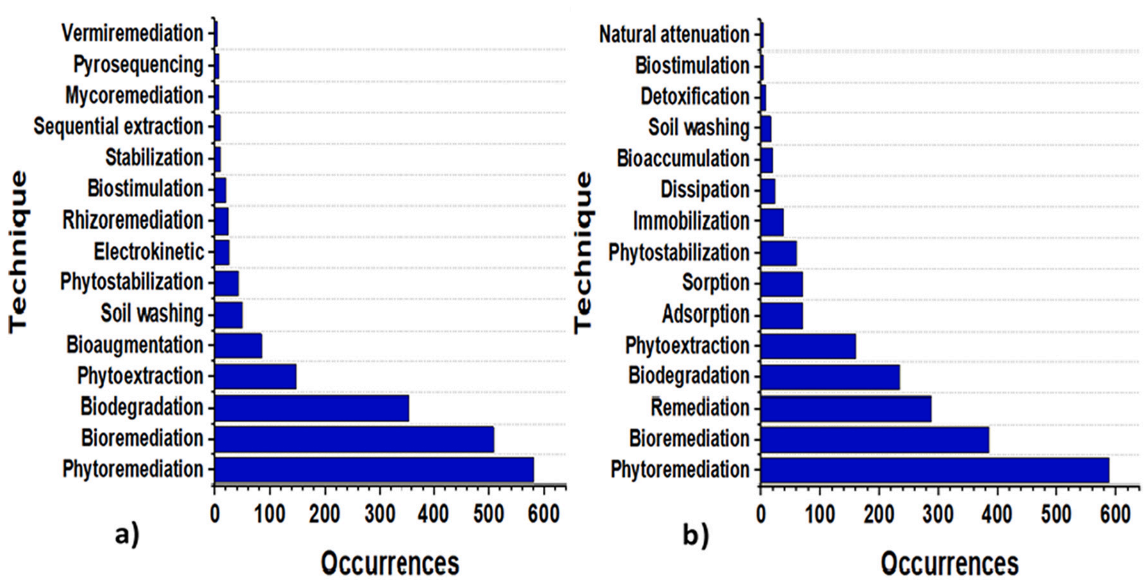


**Fig. 11.** Trends in technologies and mechanisms developed in the last 10 years, for the treatment of contaminated soils in: a) WoS and b) Scopus.

2021). Contaminant extraction from the soil to the root is a very popular process to extract heavy metals (Cabello-Torres et al., 2021; Cerrón et al., 2020) and extract organic components such as PAHs from the soil (Dolatabadi et al., 2021).

The review of occurrences in WoS gave the following occurrence results: Phytomediation (581) > Phytoextraction (147) > Phytostabilization (42) > Rhizoremediation (24), with a total of 723 occurrences, while in Scopus the order was: Phytoremediation (588) > Phytoextraction (160) > Phytostabilization (60), accounting for 808 occurrences. An extensive scientometric review of hyperaccumulators by Zhang et al. (2021) for the years 1992–2020 in the Web of Science database showed an increase in publications also observed in this study, with China, the United States, and India being the three most productive countries and the most cited journals being "Journal of Phytoremediation", "Environmental Science and Pollution Research", and "Chemosphere".

The order of occurrences for WoS was mainly as follows: phytoremediation > bioremediation > biodegradation > phytoextraction > bioaugmentation > soil washing > phytostabilization > electrokinetics > rhizoremediation > biostimulation, while in the case of Scopus the order of occurrences generated was as follows: phytoremediation > bioremediation > remediation > biodegradation > phytoextraction > adsorption > sorption > phytostabilization > immobilization > dissipation, among the most prominent.

The bioremediation uses the ability of microorganisms such as bacteria, fungi, or algae to degrade soils contaminated by metals, and publications include terms such as: bacteria, bioaugmentation, biodegradation, biostimulation, bioaccumulation, detoxification, biosurfactant, rhizosphere, among others (Boopathy, 2004). Bioremediation can use organisms indigenous to the contaminated site or from other (exogenous) sites and can be carried out in situ or ex situ under aerobic (in the presence of oxygen) or anaerobic (without oxygen) conditions (Lee et al., 2007). Although not all organic compounds are susceptible to biodegradation, bioremediation processes have been used successfully to treat soils, sludge, and sediments contaminated with petroleum hydrocarbons, solvents, explosives, chlorophenols, pesticides, wood preservatives, and polycyclic aromatic hydrocarbons in aerobic and anaerobic processes (Rivera-Espinoza and Dendooven, 2004).

Another specific technique applied is mycoremediation by the use of fungi to degrade or remove toxic agents from the environment. In contaminated soils, its practice involves the sowing of mycelia, its introduction of a support material of vegetable origin, the selective stimulation of the development of native species or the combination of these strategies. Microbially assisted phytoremediation is a promising strategy to hyperaccumulate, detoxify, or remediate soil contaminants (Khalid et al., 2021).

The vermiremediation technique is classified as an "emerging ecotechnology" and is part of the new processes that are being applied to efforts aimed at resolving environmental situations associated with the treatment of waste from a factory or a productive enterprise (Fu et al., 2021). Many European countries consider it as an economic technology, friendly to the environment because it does not require many resources or high expenses to be able to efficiently treat an effluent or a substrate that tends to pollute the environment (Fu et al., 2021). Earthworms are organisms with great potential, not only because they act as a valid tool to evaluate and monitor soil quality, but also because earthworms are applicable in the field of bioremediation as a methodological alternative (vermicomposting as vermiremediation for the treatment of polluting organic waste) to remedy environmental problems (Fu et al., 2021).

Bioleaching has been little studied; however, due to its simplicity of operation and low cost, it is a promising technology for the decontamination of PTE-contaminated soils. Microbes and their metabolites directly or indirectly mobilize insoluble contaminants from solid media such as PTEs during bioleaching, which is done by oxidation, reduction, complexation, adsorption, or dissolution (Gao et al., 2021; Kumar et al., 2022). Eight articles alluded to bioleaching in WoS and 13 in Scopus.

### 3.16. Physical and chemical technique

Regarding traditional techniques (physical and chemical and their combinations), the measurement results indicated occurrences for WoS in the following order: soil washing (49) > electrochemical-electrokinetic (25), while for Scopus they were: adsorption (70) > sorption (70) > immobilization (38) > dissipation (23).

The soil washing technique to remove organic contaminants is a common method of remediation and different chelating agents and inorganic and organic surfactants have been used with diverse effects and mechanisms, because their efficiency depends on the washing conditions: type of agent, concentration, pH, contact time, and the solid-liquid relationship (Liu et al., 2022). In the case of PHs, PAHs and PCBs or chlorinated agents, researchers have insisted not only on eliminating the contaminants but also recovering the extraction agents for reuse and for this reason, technical combinations such as advanced oxidation processes (AOP) in situ for the formation of OH radicals are being applied, which constitute a good option; in addition, anodic oxidation processes have been highlighted to selectively degrade target contaminants (Trellu et al., 2021). If the contaminant is more toxic or risky, then the intermediate volatile components that result from the process are of special concern and cause for future research (Tran et al., 2022), together with the development of washing agents that respect the environment, optimization of washing conditions, cost reduction avoiding the destruction of soil function and groundwater contamination (Liu et al., 2022).

It is also observed that electrochemical techniques are used to eliminate synthetic herbicides from agricultural soils, such as triazine, chlorophenoiacetic acid, urea, among others, highly biorecalcitrant and stable. It is also usual to find reports of the combination with other techniques such as simple and combined electrochemical advanced oxidation (published with greater emphasis in 2010). In the bibliometric study carried out by Brillas (2021) on the remediation of soils published in the Scopus database (2010–2020), single and combined treatments such as: anodic oxidation and electrogenerated $H_2O_2$, homogeneous and heterogeneous electro-Fenton, photo-electro-Fenton, solar photo-electro-Fenton and photo-electrocatalysis, among others are highlighted; for example, Trellu et al. (2019) applied boron-doped diamond electrodes to remove pesticides in soils.

Unresolved trade-offs still exist when it comes to removing volatile organic pollutants (VOCs) and gas streams produced during large-scale treatment. The researchers have not been aware of discussing why the mechanism corresponds to ground heating and not to electrokinetic heating as reported at the laboratory level (Miller de Melo Henrique et al., 2021; Muñoz-Morales et al., 2021); In addition, the technique is not totally comprehensive, because it does not always include the treatment of the produced gases. There are also certain combinations between solid electrolyte cells (direct treatment) with adsorption and absorption processes, whose results are promising to recover gases such as chlorine or volatile species generated in the electrochemical process of the soil (Andrade and Vieira dos Santos, 2020; Miller de Melo Henrique et al., 2021); however, the high consumption of electrical energy and its replacement by renewable energy has become a challenge for researchers (Ganiyu et al., 2020).

In relation to the elimination of organic and inorganic contaminants from the soil, in situ electrokinetics on porous matrices of low permeability is beneficial; but, the pH must be regulated to maintain the solubility of the contaminant and if higher voltages are applied in the presence of carbonates or gravel, the temperature of the soil increases, thus reducing the efficiency of the process (Virkutyte et al., 2002). Certain emerging in-situ electrokinetic technologies (Lasagna™, Elektro-Klean™, and electro-bioremediation) require further research to improve their large-scale commercial applicability (Wen et al., 2021).

Another of the most used techniques is the dissipation of soil contaminants and solar heating in soil covered with high-density polyethylene film has been highlighted because this application causes a significant increase of 2 to 6 °C with respect to soil temperature (direct hydrothermal effect); in addition, it has been applied to degrade herbicides, but again the combinations with other components such as biological ones, in cases of modifications with animal manure (biosolarization) can be considered as a useful ecological tool for the dissipation of soil contaminants (Pérez-Lucas et al., 2021). Another option is the transformation of vegetable or animal residues used as pollutant adsorbents.

Regarding adsorbents, Wu et al. (2021) developed a scientometric analysis on the application of biochar described in 3671 Web of Science publications in 2020 showed China and the US as leading countries investigating degradation of organic contaminants, immobilization of heavy metals, and bioremediation as critical points of the studies. Bioremediation with functional bacteria resistant to heavy metals and degraders of organic pollutants immobilized in biochar are current issues, because it combines the immobilization and metabolism of microbial cells with the efficient physical chemistry of biochar. The relevance of the use of biochar in soil treatment goes beyond the immobilization of contaminants; also, improvements in the physical, chemical, and biological properties of the soil have been reported, as well as the removal of organic and inorganic contaminants from groundwater and therefore, a lower bioavailability of these contaminants in the soil (Bolan et al., 2022a).

Li et al. (2020) points out that future trends in the application of biochar for the sorption of organic compounds and heavy metals focus on the mechanism of sorption, desorption, and kinetics, added to the thermochemical conversion of the precursor material and the characterization of biochar, depending on the method applied (slow or fast pyrolysis, gasification, torrefaction, or hydrothermal carbonization).

In situ thermal techniques used to evaporate emerging volatile organic contaminants from the soil, also require future research, because they seek to avoid excavation and use direct or alternating current to convert electricity into heat, thus facilitating the flow of the contaminant in the soil (low conductivity) and it is recommended to use low temperatures to avoid loss of fertility and save energy (Lanzalaco and Sirés, 2021). The simultaneous technical combinations of in situ chemical oxidation for increasing the degradation of pollutants are not always optimal (Lanzalaco and Sirés, 2021), and further research is required to reduce the use of washing solvents; in addition, perfluoroalkyl substances (PFAS) and perfluorooctane sulfonates (PFOS and PFOA) require a longer treatment time and temperatures (close to 1200 °C) to break the molecules of the secondary gases formed in the treatment (Mahinroosta and Senevirathna, 2020). In recent years, steam power generator concepts at 1100 °C have been highlighted to destroy PFAS with gas desorption in the vapor phase (Mahinroosta and Senevirathna, 2020), including infrared heat treatment with a similar function (Ross et al., 2018).

Although the term “microplastics” does not appear in the search carried out, this is a phenomenon derived from the high use of plastic products in society, which could have a long-term negative effect on ecosystems. The most alarming fact is that experts estimate that soil contamination by microplastics could be between 4 and 23 times greater than that of the ocean, depending on the region studied (Yang et al., 2021). However, the progress of research on microplastics in soil is restricted by inherent technological inconsistencies and difficulties in the analysis of particles in complex matrices, and studies on the presence and distribution of microplastics in soils remain very scarce (Kim et al., 2021). Limited research has shown that the combination and interaction of microplastics with the contaminants that they have absorbed can affect soil health and function and even migration through the food chain. The appearance and impact of microplastics in the soil depend on the morphology, chemical components, and natural factors; in addition, the existence of large research gaps in the quantification and estimation of regional emissions of microplastics in the soil also limit investigations of their remediation (Yang et al., 2021).

### 3.17. *Combination of chemical, physical and biological techniques*

In recent years, a combination of techniques has been developed, not only physicochemical ones, but also biological ones. Nano remediation is a combined and novel technique linked to the biological processes of the soil, plants, and microorganisms; in addition, nanoparticles improve the bioremediation process, with a potential for high microbial activity, low cost, and low toxicity (Jiang et al., 2018). However, an adverse effect could be generated and further studies on the interactions of nanoparticles with microorganisms or plants involved in soil remediation are required to determine their final fate (Gong et al., 2018).

The mechanisms of accumulation and degradation of the process are not exactly known and it could reach the groundwater due to its environmental release and the by-products of transformation; therefore, it is necessary to study its potential toxicity and pathology in the ecosystem through theoretical models that allow predicting the risks of its application, which for now is only done at the laboratory level (Gong et al., 2018). In addition, the application of genetic engineering also contributes to improving the tolerance of plants and promotes their growth (Liu et al., 2020). While the application of chemically modified bio sorbents and the combination of biomass with chemical materials and multiple complex biomass systems are novel techniques, research is focused on their configuration, performance, synthesis, regeneration, and reuse; but, it is necessary to deepen its application and future development together with intracellular autogenous nanomaterials also used as bio sorbents, constituting an attractive treatment alternative (Qin et al., 2020).

## 4. Conclusions

The scientometric study on contaminated soil treatment technologies between 2010 and 2021 in two of the main academic databases (WoS and Scopus) worldwide allowed to identify a growing annual trend of publications in this field. Among the relevant results, Scopus presented the highest number of publications compared to WoS, with 15 % of the documents published in both academic databases (overlapping). In addition, the majority number of journals indexed in Scopus demonstrates the greatest contribution of this academic base in publications on this topic. Additionally, the subject area with the highest number of publications in both databases is “Environmental Science”, highlighting the limited contribution of the subject areas “Soil Science” and “Agriculture and Biological Science” in WoS and Scopus, respectively. Additionally, China is consolidated with the largest number of publications related to the subject, supported by funding from various public and private institutions. Other countries with a high number of publications were the USA, India, Italy, and Spain. It should be noted that The Chinese Academy of Sciences of Beijing in China stood out for its greatest contribution in this field of research, followed by the University of Chinese Academy of Sciences and Zhejiang University.

The most cited article in this last decade was “A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment”, which had 1289 citations and was published in the journal “Science of the total environment”. Another article with a high citation rate was “Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil” with 765 citations and was published in the journal “Environmental Pollution”. In addition, the journal that had the greatest contribution in the number of publications in WoS was “Environmental science and Pollution Research”. Meanwhile, “Science of the total environmental” was the journal with the highest number of publications in Scopus. Eight of each 10 journals with the highest citations are indexed in both databases, which guarantees compliance with high quality criteria and greater visibility. Chinese journals do not appear in the top ten journals with the most citations despite the fact that China is the first country producing articles in this field.

In respect to the author's keywords, the highest frequencies were in the following: phytoremediation, bioremediation, heavy metals, biodegradation, soil, and cadmium. Research in the last decade has leaned towards phytoremediation, bioremediation, and biodegradation as treatment technologies. Meanwhile, the most studied inorganic contaminants were the following: Cd, Pb, As, Cu, and Zn. In addition, among the most investigated organic pollutants, PAHs, pesticides, PH, crude oil and phenanthrene stand out. Cooperative research also has intensified with a trend towards multidisciplinary and multi-technological integration in the last decade.

Recent research (from 2020 onwards) points to the study of pesticides and particularly herbicides, including Chlorimuron-ethyl. In addition, a substantial increase in research on microplastics in the soil is estimated. On the other hand, due to its great versatility in the treatment of various pollutants, bioremediation is the technique that leads to the treatment of contaminated soils. Regarding emerging contaminants, the remediation of soils contaminated with PFAS stands out as a challenge due to the fact that the traditional methods such as immobilization or washing are not efficient, requiring future research. In addition, the thermal technique and its combinations require lower energy consumption and/or the change to renewable energy and lower temperatures. Also, it is important to study how to control the emission of secondary gases and avoid the impact on biodiversity, looking for its feasibility and profitability in situ.

Raw plastic waste that generates microplastics contains chemical additives such as phthalates, bisphenol A, and polybrominated diphenyl ethers, which are part of the emerging pollutants and can induce toxic effects when ingested by living organisms. In addition, there are still no standardized protocols for their identification and quantification, which in a certain way has limited the investigations for their removal from the soil matrix. Finally, the current trend of combinations of techniques is very attractive because it is aimed at improving soil remediation processes, showing that the application of nanoparticles in bioremediation with microorganisms has been giving excellent results at the laboratory level; however, more research is required to measure the potential risk and adverse effects on the environment due to its final disposal.

## 5. Suggestion to future research

According to the results of the investigations, the effects of soil contamination on human health suggest the urgent need to remedy contaminated soils and there is a diversity of inorganic contaminants (heavy metals), organic, emerging and especially persistent, so which researchers must optimize conventional technologies that sometimes are not enough to achieve a significant removal of the desired contaminant, so more research is required on combinations, assistance or hybridizations with other techniques to achieve a synergistic effect in the removal of contaminants and above all that they are friendly to the environment.

It is important to identify and characterize the source of contamination in order to use the most appropriate technique for soil remediation, considering removal efficiency, less impact on biodiversity, and low operating costs. Among them, bioremediation is the technique that will continue to lead the treatment of contaminated soils, due to its cost and opportunities to find new alternatives for the use of microorganisms. On the other hand, the remediation of emerging contaminants such as microplastics will demand continuous interest from researchers; consequently, research about the identification, physical and chemical characterization, treatment, and their impacts on the soil will be increased.

The combination of techniques has been developing successfully in the elimination of contaminants; However, more research is still required on the mechanisms of the processes on toxicity in biodiversity, the routes and their final disposal because the laboratory conditions could present certain biases in relation to their application in the field, due to that not only it tries to reduce the consumption of materials and costs but to predict the environmental risk, as well as the risk to human health and biodiversity. Likewise, it is advisable to promote the transfer of knowledge acquired in studies on a laboratory or pilot scale to a real scale.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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