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Hyperaccumulators for Potentially Toxic Elements: A Scientometric Analysis

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Abstract: Phytoremediation is an effective and low-cost method for the remediation of soil contaminated by potentially toxic elements (metals and metalloids) with hyperaccumulating plants. This study analyzed hyperaccumulator publications using data from the Web of Science Core Collection (WoSCC) (1992–2020). We explored the research status on this topic by creating a series of scientific maps using VOSviewer, HistCite Pro, and CiteSpace. The results showed that the total number of publications in this field shows an upward trend. Dr. Xiaoe Yang is the most productive researcher on hyperaccumulators and has the broadest international collaboration network. The Chinese Academy of Sciences (China), Zhejiang University (China), and the University of Florida (USA) are the top three most productive institutions in the field. China, the USA, and India are the top three most productive countries. The most widely used journals were the *International Journal of Phytoremediation*, *Environmental Science and Pollution Research*, and *Chemosphere*. Co-occurrence and citation analysis were used to identify the most influential publications in this field. In addition, possible knowledge gaps and perspectives for future studies are also presented.

Keywords: scientometrics; science mapping; VOSviewer; HistCite Pro; heavy metals; arsenic; cadmium; mercury; lead

Citation: Zhang, D.; Dyck, M.; Filipović, L.; Filipović, V.; Lv, J.; He, H. Hyperaccumulators for Potentially Toxic Elements: A Scientometric Analysis. *Agronomy* **2021**, *11*, 1729. https://doi.org/10.3390/agronomy11091729

Academic Editors: Maria Pilar Bernal and Paula Alvarenga

Received: 13 July 2021
Accepted: 26 August 2021
Published: 29 August 2021

1. Introduction

Potentially toxic elements (PTEs), including metals and metalloids, are important pollutants originating from the mineralization of parent materials (geogenic origin) or human activities (anthropogenic origin), and their concentration in the environment increases year by year [1]. Increased concentrations of PTEs in the environment pose a severe threat to human, animal, and plant health. For example, the frequently reported "blood lead incident" [2], "cadmium rice" [3], and "heavy metal contaminated vegetables" [4] are all associated with PTE pollution. In addition, PTEs may pollute the air through wind erosion [5,6] as well as surface and underground water bodies through surface runoff or deep percolation [7]. Phytoremediation is an efficient and environmentally friendly remediation strategy for PTEs pollution [8,9], which can be used for the reclamation of contaminated soils without disturbing soil fertility and biodiversity [10,11]. Hyperaccumulators can generally accumulate large amounts of PTEs at concentrations 10 to 100 times higher than non-hyperaccumulating plants can tolerate [12]. In addition, Macnair [13] stated that the shoot-to-root quotient of concentrations for PTEs in super-enriched plants is usually >1. Besides using plants in situ, other ex-situ strategies, such as excavation of polluted soil followed by a certain treatment, are also possible, although they are much more labor- and cost-demanding. Therefore, hyperaccumulators are considered a green alternative to solve the issue of PTEs pollution and are a more practical approach for large-scale applications.

Hyperaccumulating plants of PTEs have developed certain adaptation mechanisms that enable them to tolerate high concentrations in their tissues [14–20]. These tolerance mechanisms may include (1) organometallic complexes with donor ligands, including organic acids [21,22], cysteine [23,24], nicotinamide [25,26], histidine [27–30], and other thiols with low molecular weight [31]; (2) transportation capability [32], e.g., it is thought that arsenic (As) uptake by *Pteris vittata* is achieved through a high-affinity phosphate transport system [33]; (3) compartmentation potential [34,35], e.g., Asemaneh et al. [34] proposed that cellular and subcellular compartmentation are both possible mechanisms for nickel (Ni) tolerance employed by the *serpentine Alyssum murale* and *Alyssum bracteatum*; and (4) the ability to store these complexes in the vacuoles of leaf storage cells [36]. Tolerance is a key prerequisite for the accumulation and phytoremediation of PTEs [37,38]. Plants are not considered to be hyperaccumulators or super-enriched if they cannot tolerate high concentrations of PTEs in their tissues and complete their life cycle. However, for a successful hyperaccumulating plant, the ability to produce high biomass is also important, in addition to their ability to uptake high concentrations of PTEs without having a negative impact on their physiological processes. For instance, Chen and Cutright [39] found that ethylene diamine tetraacetic acid (EDTA) could increase the concentration of cadmium (Cd) in the stem of sunflower, but the total biomass of plants decreased sharply. Ent et al. [40] described that a hyperaccumulator should include extreme tolerance and have a very high bioconcentration factor.

As the emission of PTEs into the environment by continuously expanding urbanization and agriculturalization is increasing worldwide, it is expected that the topic of PTEs-hyperaccumulating plants and their potential for removing these PTEs from the contaminated soils will keep increasing in the future. Scientometric analysis of hyperaccumulators for remediating contaminated soils is thus a useful tool for identifying and summarizing the main research points relevant to expanding, publishing, and applying up-to-date knowledge on this topic. Previous studies have reviewed the applications and future trends in phytoremediation [8,36,41]. There are also bibliometric studies that map the overall research status of PTEs in the environment [42–45]. However, there is no such study focusing on the research status of the topic of hyperaccumulators that have the potential for PTE removal from contaminated soils. The objective of this study was therefore to reveal the development history of research focused on hyperaccumulators from the bibliometric perspective and provide useful information for scientists working in this research area.

2. Materials and Methods

The Science Citation Index Expanded (SCI-EXPANDED) database of the Web of Science Core Collection (WoSCC) contains literature data since 1992. The data between January 1992 and December 2020 were downloaded from the WoSCC on 10 February 2021 for analysis. The query sets used for the literature search were: “TS = (hyperaccumulating plants OR hyperaccumulat* OR “accumulator plants” OR phytoremediation OR hyperaccumulation OR Phytoextraction) AND TS = (heavy metal OR lead (Pb) OR cadmium OR copper OR Zinc OR mercury OR arsenic OR chromium OR nickel OR antimony OR aluminum OR contaminated OR polluted)”. Document types of articles, letters, notes, books/book chapters, data papers, database reviews, proceedings papers, and reviews written in English were retained. The search was then saved as a text file containing “full record and citation data” for bibliometric analysis.

VOSviewer v1.6.15 [46], HistCite Pro (history of cite) [47], and CiteSpace v5.7.R5 [48] were used to analyze the retrieved literature. VOSviewer uses co-citation [49] and bibliographic coupling to generate a visual atlas for the analysis of journals, authors, countries, institutions, and keywords [46]. Research hotspots in specific fields are generally explored through keyword analysis. HistCite Pro is a more concise and convenient version of the out-of-service HistCite modified by Wang Qing from the Chinese Academy of Sciences. Citation analysis in Histcite Pro can identify highly cited papers and references. CiteSpace is a citation network analysis tool developed by Professor Chen Chaomei, and it was used to develop the strongest citation bursts map of keywords.

3. Results and Discussion

3.1. Annual Publication Trend

A total of 13,239 publications were retrieved from the WoSCC database. Figure 1a shows an increasing trend in the number of publications in phytoremediation during the period from 1992 to 2020. It is expected that there will be more publications in the future. In addition, the majority of the papers were articles (93.22%), followed by reviews (6.68%), book chapters (0.22%), letters (0.09%), and notes (0.01%). The top ten Web of Science categories are shown in Figure 1b. Among them, environmental sciences was the subject area with the greatest volume of publications on hyperaccumulators, accounting for 58.15% of the total papers, followed by plant sciences (17.57%), engineering environmental (8.94%), soil science (7.39%), toxicology (5.57%), biotechnology applied microbiology (5.56%), agronomy (5.25%), water resources (5.08%), ecology (4.24%), and biochemistry and molecular biology (3.78%).

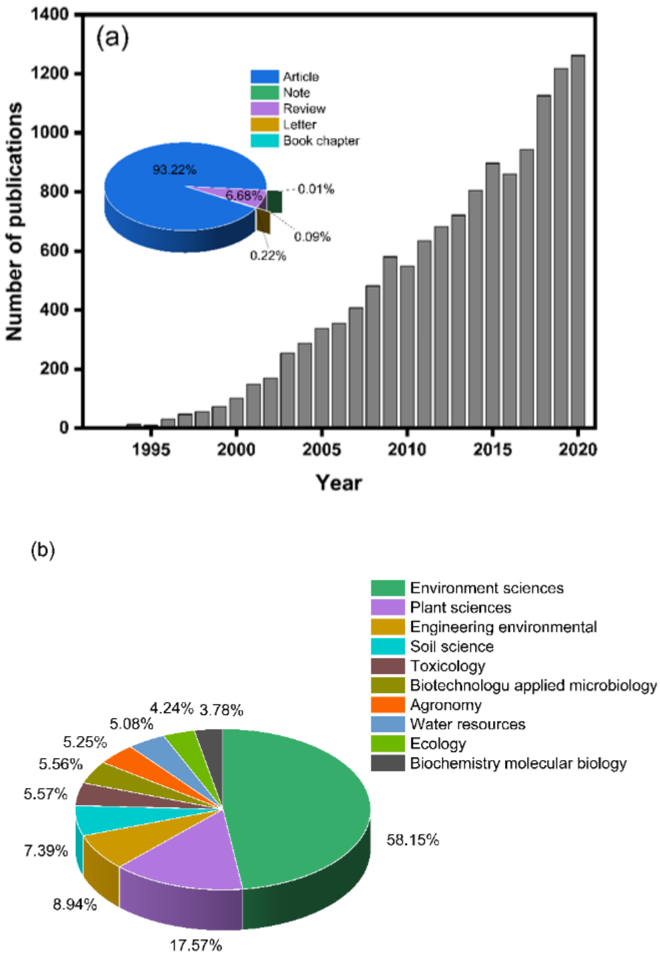

Figure 1. (**a**) Annual publications on the topic of hyperaccumulators remediation of potential toxic element (PTE) pollution based on data from Science Citation Index Expanded (Sci-Expanded) database of the Web of Science Core Collection (WoSCC) and document types; (**b**) percentages of publications for Web of Science categories.

3.2. Citation Network of Authors, Organizations, and Countries

A total of 457 authors met the threshold of a minimum of 10 publications per author. They consisted of 31 clusters in different colors (Figure 2), which indicates that there are 31 closely related groups working on hyperaccumulators for PTE pollution. Among them, Dr. Xiaoe Yang from Zhejiang University (Zhejiang, China) had more international collaborations than the other authors, as indicated by the greatest value of total links (TLS) of 294, followed by Dr. Xun Wang from Sichuan Agricultural University (Sichuan, China) (TLS = 247) and Dr. Yongming Luo from the Chinese Academy of Sciences (Beijing, China) (TLS = 211).

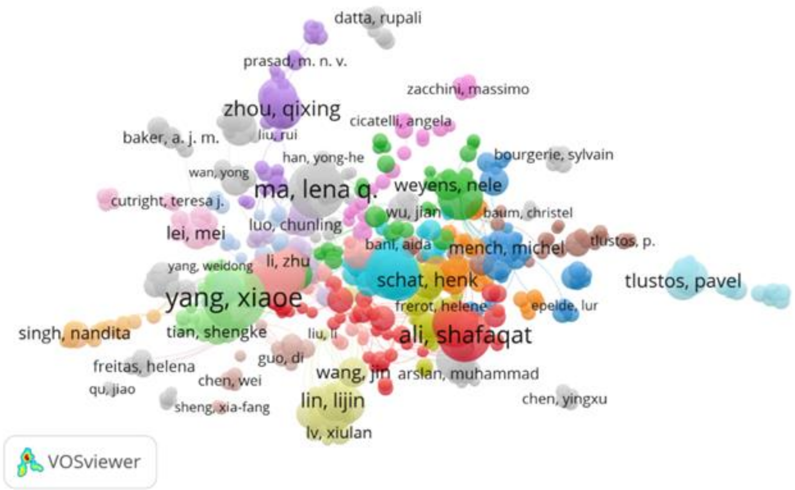

Figure 2. Co-authorship network map of authors. There are 31 clusters with a total of 1634 links and a total link strength (TLS) of 8122.Larger nodes indicate that the researcher has more publications. Lines connecting clusters indicate a collaboration between the researchers, which is stronger when the line is thicker. Note that this is produced by VOSviewer and the content cannot be modified.

Some of the most productive authors with over 100 publications on this topic include Dr. Xiaoe Yang (*N* = 131), Dr. Alan J.M. Baker (*N* = 108) from the University of Melbourne (Melbourne, Australia), Dr. Ma Lena Q (*N* = 103) from Zhejiang University (Zhejiang, China), Dr. Yongming Luo (*N* = 101) and Dr. Jaco Vangronsveld (*N* = 101) from University of Hasselt (Diepenbeek, Belgium). It is interesting to note that Dr. Xiaoe Yang has conducted much research on *Sedum alfredii Hance* (a Zn-hyperaccumulator plant species) [50–54], including the phytoremediation of combined contamination with zinc (Zn), copper (Cu), and other PTEs [55–58]. Dr. Alan J.M. Baker investigated the effects of a variety of hyperaccumulators [59–61] on pollution of PTEs, including nickel (Ni) [62], manganese (Mn) [63], and cadmium (Cd) [64], among other metals and metalloids. These studies from Dr. Alan J.M. Baker were highly cited by studies related to hyperaccumulator research retrieved from the Web of Science, as indicated by the greatest total local citation score (TLCS) of 6262. They were also highly cited by other related research as indicated by the greatest total global citation score (TGCS) of 10,248.

The top 10 organizations and countries are shown in Table 1 and Figure 3. Six of the top 10 institutions were from China, which makes China the most productive country on hyperaccumulator research, with *N* = 3554 (Table 1). China was followed by the USA (*N* = 1772) and India (*N* = 1052). Fewer studies were found from Africa, the Middle East, and South America (Figure 3), but the underlying reason remains unknown. It was noted that the per-article citations (TGCS/N = 51) of the USA were much higher than the other countries. This is also true for the University of Florida (Gainesville, FL, USA), whose TGCS/N (54) was higher than the other top 10 productive organizations.

Table 1. The top 10 organizations and countries in overall strength of publications related to phytoremediation. The number of publications (N), total local citation score (TLCS), total global citation score (TGCS), total number of links (L), and total link strength (TLS) were obtained from the VOSviewer. TGCS/N is the per-article citations.

No.	Items	*N*	TLCS	TGCS	L	TLS	TGCS/N
	Top 10 organizations						
1	Chinese Academy of Sciences (China)	855	10,651	24,491	182	927	29
2	Zhejiang University (China)	344	5143	10,573	82	274	31
3	University of Florida (USA)	226	6391	12,142	69	266	54
4	Nanjing Agricultural University (China)	207	3122	6484	55	180	31
5	Consejo Superior de Investigaciones Científicas (Spain)	205	1982	7769	87	215	38
6	University of Chinese Academy of Sciences (China)	182	884	2510	58	278	14
7	University of Lorraine (France)	159	1039	2399	69	252	15
8	Sichuan Agricultural University (China)	147	846	1823	28	71	12
9	The University of Melbourne (Australia)	141	3226	6936	74	209	49
10	Sun Yat-sen University (China)	128	1655	3534	52	143	28
	Top 10 countries						
1	China	3554	32,535	79,946	61	1397	22
2	USA	1772	37,501	90,176	65	1133	51
3	India	1052	11,223	33,446	48	384	32
4	France	745	10,502	25,694	62	789	34
5	Spain	694	6091	20,788	53	444	30
6	Italy	619	7379	18,489	53	336	30
7	Pakistan	562	6212	14,449	40	559	26
8	Poland	543	2958	9168	48	314	17
9	Australia	539	7826	20,881	56	617	39
10	United Kingdom	539	18,318	38,660	55	442	72

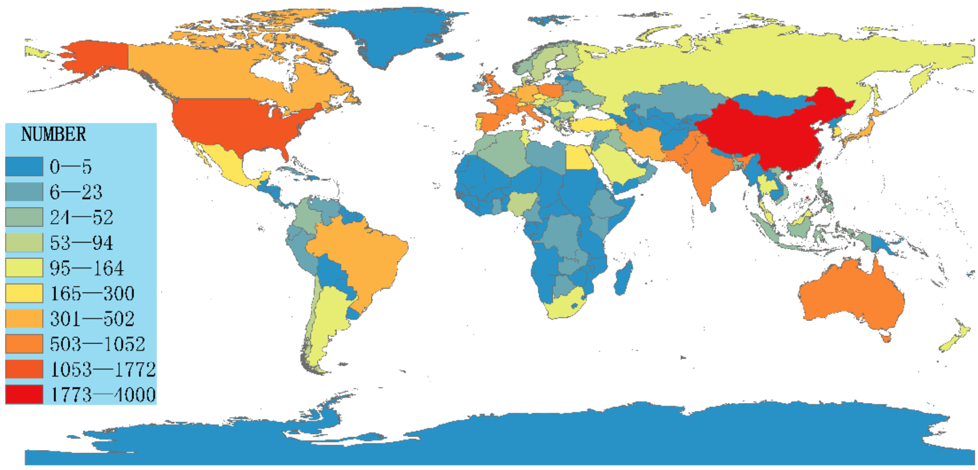

Figure 3. World map of publication distribution by country.

3.3. Most Recognized Journals

The 13,239 studies on hyperaccumulators were published in 1126 journals, with the top 10 most utilized journals listed in Figure 4. It is understood that most of these journals are related to phytoremediation and environmental pollution. The *International Journal of Phytoremediation* was ranked No. 1, publishing over 1000 papers on this topic, followed by *Environmental Science and Pollution Research* (*N* = 813) and *Chemosphere* (*N* = 705).

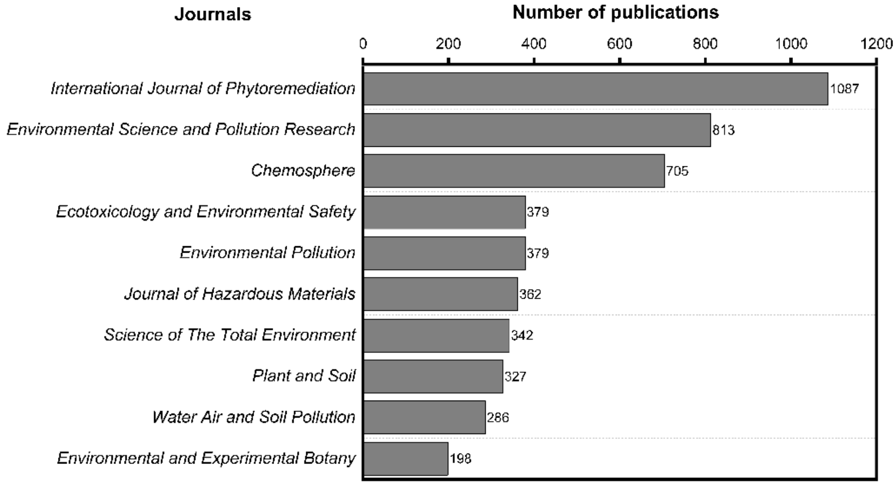

Figure 4. Top 10 journals publishing research on phytoremediation.

3.4. Highly Impacted Studies

Citation analysis with HistCite Pro showed that papers numbered 135 [60], 138 [65], 144 [66], 145 [67], and 149 [68] were highly cited, as indicated by the larger circles and more surrounding arrows (Figure 5). These studies have greatly contributed to the promotion of the application of phytoremediation. The papers numbered 135 [60], 411 [69], 516 [70], and 2998 [71] explained molecular mechanisms of plant tolerance and homeostasis. The papers 138 [65], 3063 [72], 4246 [16], and 5661 [8] highlighted the applications of phytoremediation and more possibilities for the future. The paper numbered 508 [73] reported an As-hyperaccumulator plant species, *Pteris vittate*. The paper numbered 1128 [74] reported for the first time a new Cd-hyperaccumulator plant (*Sedum alfredii Hance*). Paper 457 [75] demonstrated that the mesophyll cells in the leaves of plants are the major storage sites for Zn and Cd. Paper 522 [76] introduced the phytoextraction of PTEs and considered it an economical and effective method [77–79].

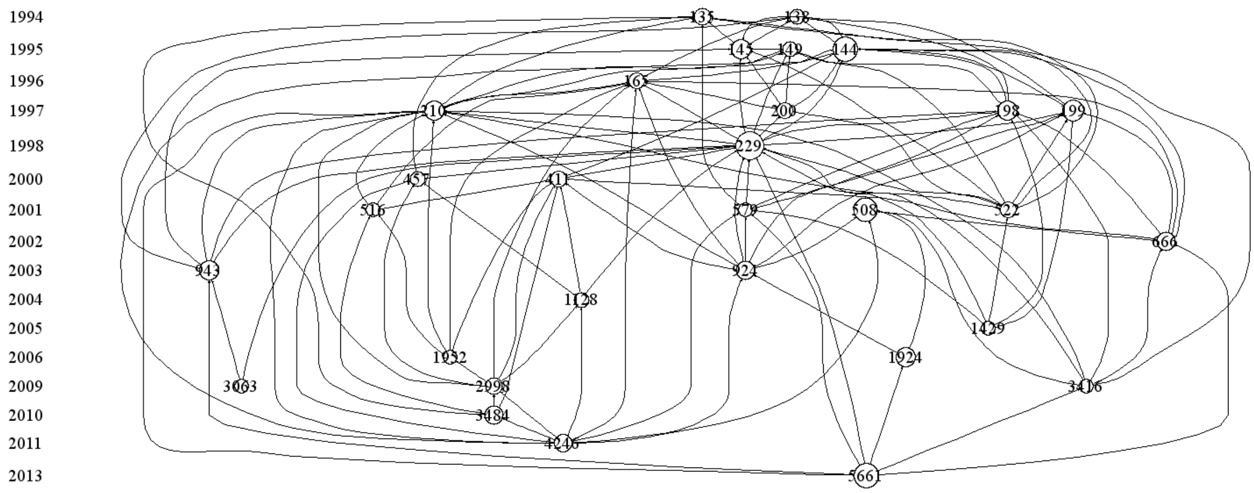

Figure 5. A citation analysis network of the top 30 publications on phytoremediation using HistCite Pro, based on data obtained from the Web of Science Core Collection (WoSCC). On the left is the year, and on the right are publications for the corresponding year. Each circle represents a publication, and the larger the circle, the more citations. The numbers in the circles were given by HistCite Pro. The numbers in the circles and their publications are: 135 [60], 138 [65], 144 [66], 145 [67], 149 [68], 165 [80], 198 [81], 199 [82], 200 [83], 210 [84], 229 [85], 411 [69], 457 [75], 508 [73], 516 [70], 522 [76], 579 [86], 666 [87], 924 [88], 943 [89], 1128 [74], 1429 [90], 1924 [91], 1952 [92], 2998 [71], 3063 [72], 3416 [93], 3484 [94], 4246 [16], and 5661 [8].

3.5. Co-Occurrence Analysis of Keywords

Keywords are generally the core of a study and can reveal the research topic in a particular field. The VOSviewer software was used to draw the keyword co-occurrence density map of the 13,239 publications (Figure 6). Phytoremediation was undoubtedly the most frequently used keyword, with over 1000 occurrences. It is not surprising that the terms "phytoremediation", "phytoextraction", and "accumulation" stand out in Figure 6, as they are commonly used keywords. Phytoremediation is used to describe the ability of hyperaccumulators to remove PTEs from soil; therefore, terms such as "tolerance", "removal", "antioxidant enzymes", and "rhizosphere" are mentioned repeatedly [75,95,96]. The use of terms for PTE, such as "zinc" [97,98], "cadmium" [74,99], and "copper" [100–103], as well as hyperaccumulators, such as "*thlaspi-caerulescens*" [14,104,105], indicates that the phytoremediation of particular metal (i.e., zinc (Zn), cadmium (Cd), and copper (Cu))-contaminated soils has been extensively studied. It should be noted that the keyword co-occurrence density map can only show the hotspots of phytoremediation research in a qualitative way, and it cannot reflect the temporal change, which will be further resolved in the next section.

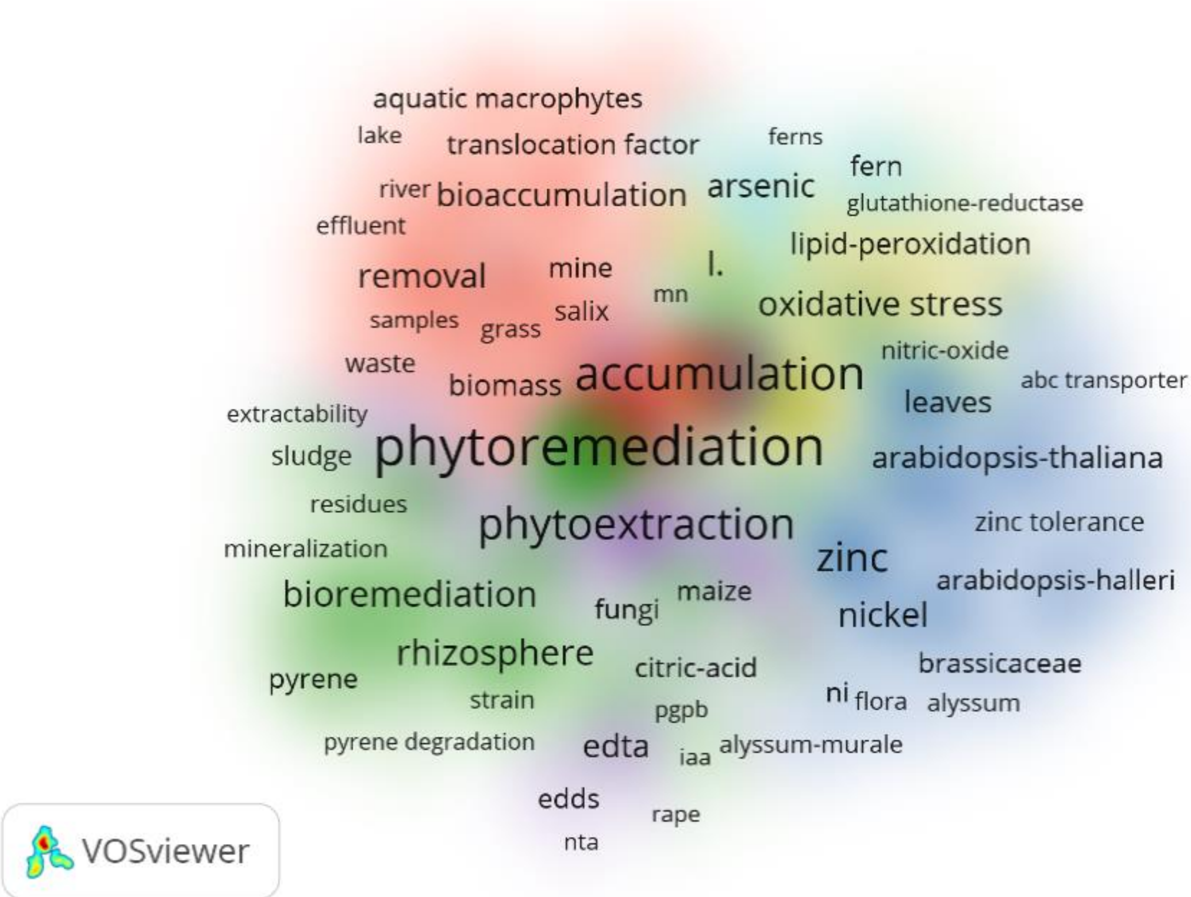

Figure 6. The density view of keyword co-occurrence. Note that a larger font for a keyword indicates a greater total link strength (TLS). The closer the keywords are to each other, the better the relevance of these topics. Note that this is produced by Vosviewer and the content cannot be modified.

3.6. Keywords with the Strongest Citation Bursts

Figure 7 shows the temporal change of frequently appearing keywords or research hotspots with the strongest citation bursts analysis using CiteSpace. The red lines represent the time periods for a keyword with a strong burst. "Nickel", "zinc", and "cadmium" were the most-studied PTEs from the 1990s to 2000s. "Metal tolerance" in "plant", such as "*brassicaceae*" received widespread attention from 1994 to 2007. The hot topic from 1996 to 1999 was the "uptake" and "transport" of PTEs by "*brassicaceae*" plants, such as "*thlaspi* *caerulescen*" and "*Indian mustard*". New hyperaccumulators continued to be discovered, as indicated by "*fern*" and "*arabidopsis halleri*" in the 2000s. The concern of PTEs on "health risk" and the applications of "biochar" to remediate soil heavy metal pollution was a hot topic in 2018–2020.

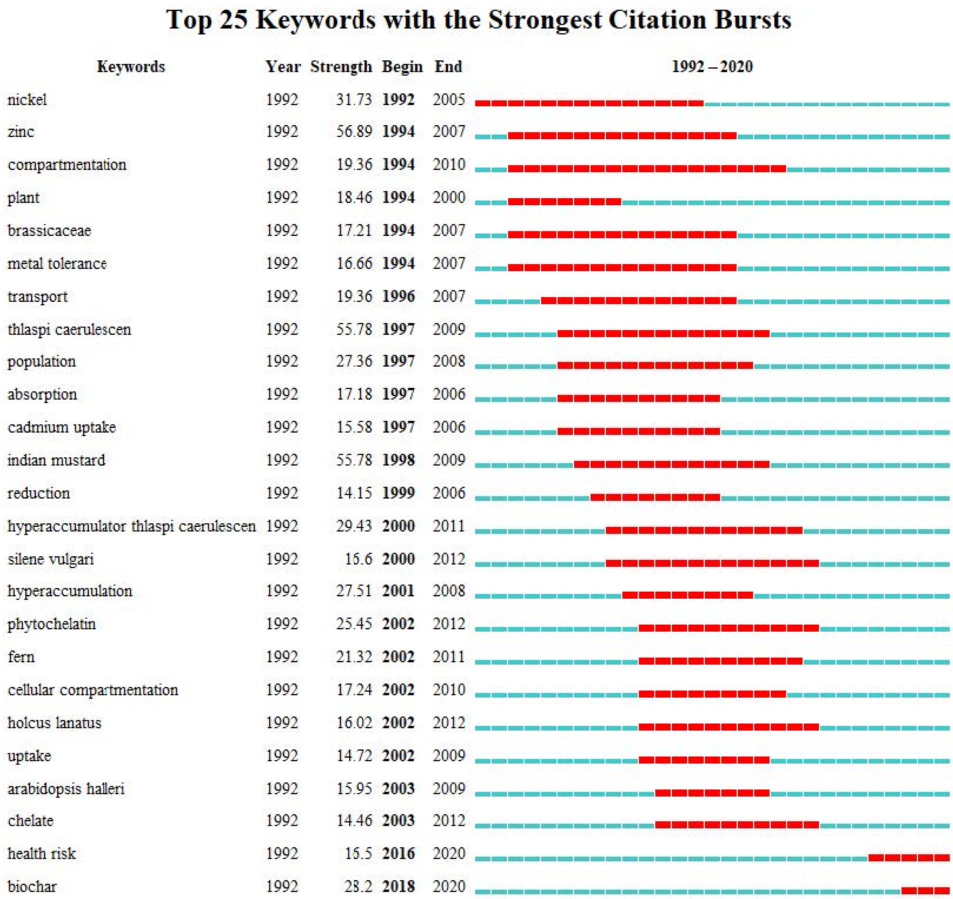

Figure 7. Keywords with the strongest citation bursts developed by CiteSpace. Blue indicates the time when keywords appear, and red indicates the time when keywords burst.

4. Conclusions and Perspectives

In this study, bibliometrics were used to analyze the research status of the topic of hyperaccumulators for remediating PTE-contaminated soil from 1992 to 2020. The results show that the number of publications in this field increased steadily and rapidly over the past three decades. The most productive authors, organizations, and countries were identified with co-authorship network analysis. Dr. Yang Xiaoe from Zhejiang University (Zhejiang, China), Dr. Alan J.M. Baker from the University of Melbourne (Melbourne, Australia), and Dr. Ma Lena Qi from Zhejiang University (Zhejiang, China) were the three most productive researchers. The Chinese Academy of Sciences (Beijing, China), Zhejiang University (Zhejiang, China), and the University of Florida (Gainesville, USA) were the top three institutions in the field. China, the USA, and India were the top three contributing countries. *International Journal of Phytoremediation*, *Environmental Science and Pollution Research*, and *Chemosphere* were the most influential periodicals. The co-occurrence and strong burst analysis of keywords identified the research hotspots and their evolution with time and provided useful information for invoice and experts alike to better understand the research status of hyperaccumulators.

Hyperaccumulators are of great significance for the phytoremediation of soil contaminated by PTEs, and numerous studies have been conducted over the past decades. However, it was noted that there is still a lack of comprehensive databases collating the currently available hyperaccumulators, their characteristics (e.g., description, classification, distribution, collection of records, and analysis of data), and applications, examples, or demos [106]. In addition, there is a lack of methods that can visualize the transport and accumulation of PTEs in plants; thus, the use of computed tomography is a promising technique. Although numerous studies have investigated the transport and accumulation of PTEs in plants, they are mainly based on destructive sampling methods and cannot be used to monitor the spatio-temporal change of these characteristics in live plants. Cost-effective tools that are suited for in situ and continuous measurement are required.

Because of the limitations of VOSViewer itself, such as synonyms that cannot be intelligently merged and the effect of search methods, this study does not include all the results of PTEs and hyperaccumulators. In recent years, with the continuous optimization of software and the continuous improvement of analysis methods, we will overcome these deficiencies in the future to obtain more detailed and accurate research conclusions.

Author Contributions: Conceptualization, H.H.; methodology, H.H.; software, D.Z.; resources, M.D.; data curation, D.Z.; writing—original draft preparation, D.Z. and H.H.; writing—review and editing, J.L., M.D., L.F., V.F. and H.H.; supervision, H.H.; funding acquisition, J.L. and H.H. All authors have read and agreed to the published version of the manuscript.

Funding: Funding for this research was provided in part by the Natural Science Foundation of China (NSFC, Grant No. 42077135), the Fundamental Research Funds for the Central Universities at the Northwest A&F University (No. 2452015287), and the 111 project (No. B12007).

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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