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REVIEW ARTICLE

Global perspectives and future research directions for the phytoremediation of heavy metal-contaminated soil: A knowledge mapping analysis from 2001 to 2020

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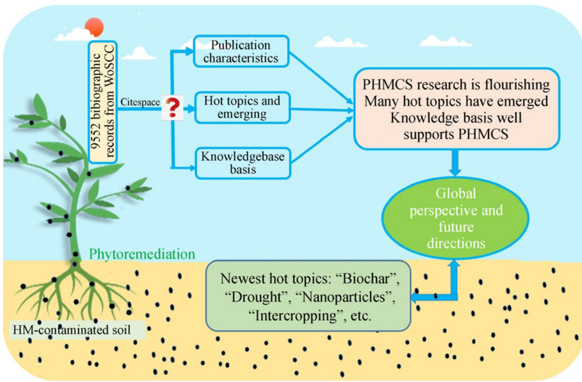
HIGHLIGHTS

- The overall global perspective of the PHMCS field was obtained.
- PHMCS research has flourished over the past two decades.
- In total, 8 clusters were obtained, and many new hot topics emerged.
- "Biochar," "Drought," "Nanoparticle," etc., may be future hot topics.
- Five future directions are proposed.

GRAPHIC ABSTRACT



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ABSTRACT

In total, 9,552 documents were extracted from the Web of Science Core Collection and subjected to knowledge mapping and visualization analysis for the field of phytoremediation of HM-contaminated soil (PHMCS) with CiteSpace 5.7 R3 software. The results showed that (1) the number of publications increased linearly over the studied period. The top 10 countries/regions, institutions and authors contributing to this field were exhibited. (2) Keyword co-occurrence cluster analysis revealed a total of 8 clusters, including "Bioremediation," "Arsenic," "Biochar," "Oxidative stress," "Hyperaccumulation," "EDTA," "Arbuscular mycorrhizal fungi," and "Environmental pollution" clusters (3) In total, 334 keyword bursts were obtained, and the 25 strongest, longest duration, and newest keyboard bursts were analyzed in depth. The strongest keyword burst test showed that the hottest keywords could be divided into 7 groups, i.e., "Plant bioremediation materials," "HM types," "Chelating amendments," "Other improved strategies," "Technical terminology," "Risk assessment," and "Other." Almost half of the newest topics had emerged in the past 3 years, including "biochar," "drought," "health risk assessment," "electrokinetic remediation," "nanoparticle," and "intercropping." (4) In total, 9 knowledge base clusters were obtained in this study. The studies of Ali et al. (2013), Blaylock et al. (1997), Huang et al. (1997), van der Ent et al. (2013), Salt et al. (1995), and Salt (1998), which had both high frequencies and the strongest burst scores, have had the most profound effects on PHMCS research. Finally, future research directions were proposed.

1 Introduction

The development of industry and agriculture, especially the mining industry, has resulted in severe soil contamination with heavy metals (HMs) worldwide. This

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contamination has become a critical global concern due to the high potential toxicity of HMs. In China, the overall rate of HMs in soil exceeding the standard is 16.1% (Ministry of Environmental Protection and Ministry of Land and Resources of China, 2014). In America, approximately 600,000 ha of brownfield sites have been polluted with HMs (Mahar et al., 2016). It has been reported that 200,000 sites are listed as HM-contaminated sites in France, Sweden, Slovakia, Hungary, and Austria, whereas 10,000 sites have been reported in Greece and Poland (Yadav et al., 2018). The sources of contamination are mainly sewage sludge, mining, sewage irrigation, etc. (Li et al., 2007; Mahar et al., 2016).

HMs in soil are difficult to clean because of their stable, durable, harmful, and nondegradable characteristics. Furthermore, they can be bioaccumulated and biomagnified along the food chain and ultimately have toxic effects on human health (Liu et al., 2018). Eliminating or reducing these hazards is essential to sustaining environmental health and the health of living organisms.

Among the various remediation methods, phytoremediation has likely received the greatest attention in the past few decades due to its cost efficiency and environmental friendliness, and it also requires relatively simple engineering procedures (Yadav et al., 2018). Previous researchers have focused mainly on the following aspects: (1) screening plant species for their ability to efficiently bioremediate soils contaminated by HMs (Liu et al., 2016a; Pan et al., 2019); (2) understanding the fundamentals of phytoremediation, including the different associated processes, mechanisms, and influencing factors (Yu et al., 2019); (3) ameliorating/modifying particular phytoremediation strategies to promote plant growth or HM accumulation (Li et al., 2020; Liu et al., 2020c; Yu et al., 2020a; Liu et al., 2021); and (4) combining different available technologies or phytoremediation techniques with modern chemical, biological, and genetic engineering tools to improve remediation efficiency (Yadav et al., 2018; Bukhat et al., 2020; Vieira et al., 2020). Furthermore, many excellent review articles summarizing this research have been published (Ali et al., 2013; Mahar et al., 2016; Yadav et al., 2018). However, researchers typically obtain the supporting material for these reviews by reading individual papers and then extracting the required information and reprocessing the materials based on their own knowledge. Furthermore, it is impossible for a single researcher to keep up with the rapidly growing amount of available literature; therefore, the information obtained by this method is limited, especially given the impossibility of reading and analyzing thousands of publications.

Knowledge mapping is defined as a tool for performing quantitative literature analysis using mathematical and statistical methods (Ji and Pei, 2019). It is a comprehensive system that integrates mathematics, philology, and statistics (Chen, 2017). CiteSpace, which is a powerful Java-based visualization software, is one of the most popular tools for knowledge mapping and was developed by Chen (2004). Bibliometric analysis combined with CiteSpace visualization provides a new, comprehensive perspective for understanding a certain field of study because this approach provides both overall and in-depth analyses (Chen et al., 2014; Guan et al., 2021). These analysis methods have been used mainly in the fields of psychology, informatics, medicine, pedagogy, and others (Chen, 2017). Currently, knowledge mapping analysis has gradually begun to enter the fields of ecological and environmental studies. For example, Ji and Pei (2019) analyzed geopolymer research and its application to HM immobilization. Li et al. (2020) used scientometrics to characterize As as a double-edged sword. Kamali et al. (2020) attempted to comprehensively discuss and understand scientific advances as well as the progress made in the application of biochar as a soil amendment. These papers applied knowledge mapping, i.e., bibliometric analysis combined with CiteSpace, to provide new, in-depth perspectives for scholars and recommendations for further study in these fields.

Since the beginning of the 21st century, publications on the phytoremediation of HM-contaminated soil (PHMCS) have proliferated. It is necessary to analyze these works both overall and in depth to obtain a more complete perspective and deeper insights to better understand the development of the PHMCS research field and forecast future popular research topics. Therefore, new methods should be introduced to identify global hotspots and perspectives in the field of PHMCS. However, a knowledge mapping analysis of the overall progress and emerging trends in global PHMCS hotspots and perspectives, especially those during the first two decades in the 21st century, has not been performed.

Hence, in the present study, relevant publications were extracted from the Web of Science Core Collection (WoSCC) to address the following questions regarding the PHMCS field. 1) What are the annual publication outputs? 2) Which countries/regions and institutions contribute the most to this field, and who are the most active researchers in this field? 3) Which journals publish most of these works or are suitable venues for their publication, and these publications mainly belong to which categories? 4) What are the current research hotspots and perspectives in this field? 5) Which research hotspots play a decisive role in determining the research direction of this field; which have been studied for the longest time; and which are likely to become new hotspots in the future? 6) Which important studies form the knowledge base that has supported studies in this field in the first two decades of the 21st century? 7) Finally, future research directions are suggested based on the analysis results and our understanding of PHMCS. The results of this study will help readers and scholars better understand this field both broadly and in depth.

2 Methods

2.1 Database and visualization software

The database used in this study was the WoSCC, which is a comprehensive research database that is the most frequently used for knowledge mapping analysis (Chen et al., 2014; Chen, 2017; Li et al., 2018). The WoSCC indexes "Science Citation Index-Expanded (SCI-E)," "Conference Proceedings Citation Index-Science (CPCI-S)," "Emerging Sources Citation Index (ESCI)," "Current Chemical Reactions (CCR-EXPANDED)," and "Index Chemicus (IC)."

The visualization software used to perform the knowledge mapping was CiteSpace (5.7 R3), which extensively analyzes collaborations among countries/regions, institutions, and authors. In addition, hot research topics and trends can both be obtained by use of the functions such as cocitation analysis, co-occurrence analysis, and burst analysis etc. (Chen et al., 2014; Chen, 2017; Li et al., 2018).

2.2 Research framework

Figure 1 shows the overall research framework, which included research theme determination, data extraction, and knowledge mapping analysis. The knowledge mapping analysis was further divided into three parts, i.e., "publication characteristics and scientific collaboration analysis," "hot topics and frontier trend analysis," and "knowledge base analysis." These results provide an overall research perspective in the field of PHMCS during the first two decades in the 21st century. Moreover, future research directions were forecasted based on these results and our understanding of the field.

2.2.1 Search strategy

According to the research objectives, three themes, "phytoremediation," "HMs," and "soil" were selected for this study. The details of the search strategy are as follows:

TS = (("Heavy metal*" OR Pb OR Lead OR "black lead" OR plumbum OR Cd OR Cadmium OR Zn OR Zinc OR Mn OR Manganese OR Cu OR Copper OR Au OR Gold OR TI OR Thallium OR Cr OR Chromium OR Chrome OR Co OR Cobalt OR Ni OR Nickel OR As OR Arsenic OR Hg OR Mercury OR "Hydrargyrum Quicksilver") AND (phytoremediat* OR phytoextract* OR phytostabilizat* OR phytodegradat* OR Phytostimulat* OR Phytovolatilizat* OR Rhizofiltrat* OR Phytodesalinat* OR Phytotransformat* OR Rhizodegradat* OR Rhizoattenuat* OR "Plant repair" OR "Plant restore" OR Hyperaccumulat* OR "Rhizosphere bioremediat*") AND (Soil*)). Relevant bibliographic records from the first two decades of the 21st century (Oct. 1, 2001–Nov. 31, 2020) were retrieved from the WoSCC database. In total, 9552 English-language records were obtained. The number of cited references in these publications was 176,782.

2.2.2 Framework for knowledge mapping analysis

We first analyzed the characteristics of the published studies, including the annual document output of the authors; their global distribution; the contributions of

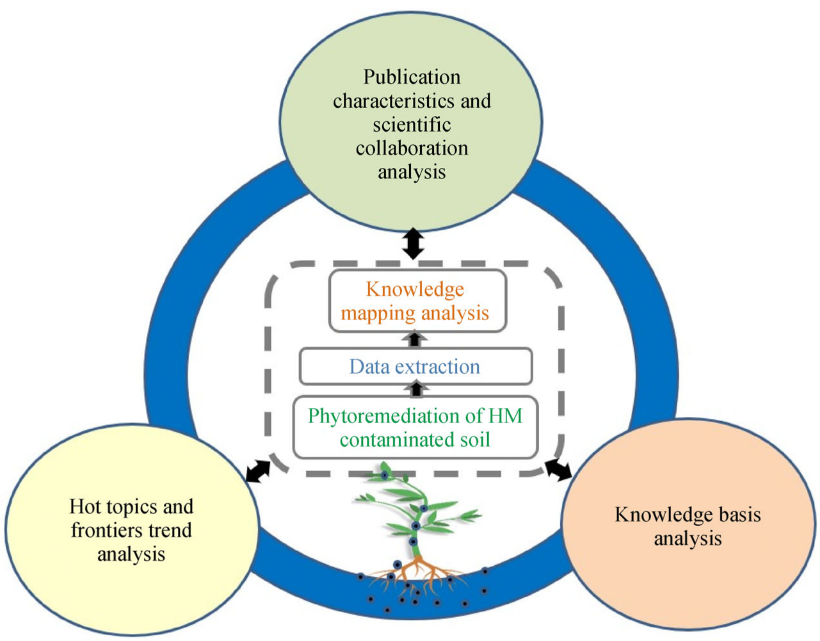

Fig. 1 Research framework.

different countries/regions, institutions, and authors; the subject categories; and the journals in which they were published, to determine which countries/regions and institutions are leaders in this field and which authors contribute the most. We determined the journals in which the studies were mainly published and to which main categories these publications belonged. Then, keyword co-occurrence analysis was carried out to determine which research topics were global hotspots. Based on the resultant co-occurrence map, a keyword cluster map was developed with the log-likelihood ratio test algorithm (LLR) to determine the current research status and the emerging trends in the PHMCS field. Then, a keyword burst test was carried out, to clarify which research topics had proliferated within a short period, how long these bursts lasted, and which topics are likely to continue to be studied in the following years. These results provide information about the newest topics that are emerging research trends. Finally, a cocitation map for the cited references was generated and analyzed to clarify which important studies form the knowledge base, and supports the study and development of this field. Documents with high values for both citation frequency (*CF*) and burst strength (*BS*) were discussed in depth.

2.2.3 Parameter setting and knowledge mapping reading

The parameters were set as follows. The time slice was set as one year. The top 50 keywords with the highest co-occurrence frequency (Top 50) were extracted from each time slice. The path-finding algorithm in CiteSpace (Pathfinder) was used for network pruning before knowledge map generation. The network maps for a specific object were generated by the *g*-index algorithm (k = 25, LRF = 3, LBY = – 1, and e = 1.0)1). *K*-core clustering was applied to generate clusters. Cluster labels were automatically extracted by the LLR and are shown in white in maps. The names of the high-frequency node types are shown in light yellow. In maps, one node represents an analysis object. The node size represents the frequency. A line connecting two nodes indicates that there is a certain relationship between the two nodes. A node with a high betweeness centrality (*BC*) is likely to sit in the middle of two large communities, or sub-network, hence the name betweenness, which surrounded by a purple circle has relatively high *BC* value (⩾ 0.1), indicating its vital role in map and extensively connections to other nodes (Chen, 2004; 2017; Yang and Meng, 2019; Zuanazzi et al., 2020).

3 Results and discussion

3.1 Publication characteristics and scientific collaboration analysis

3.1.1 Annual publication number and top 10 countries' publication contributions

The annual publication numbers and top 10 countries' publication contributions are shown in Fig. 2. The output of publications in a certain field demonstrates the

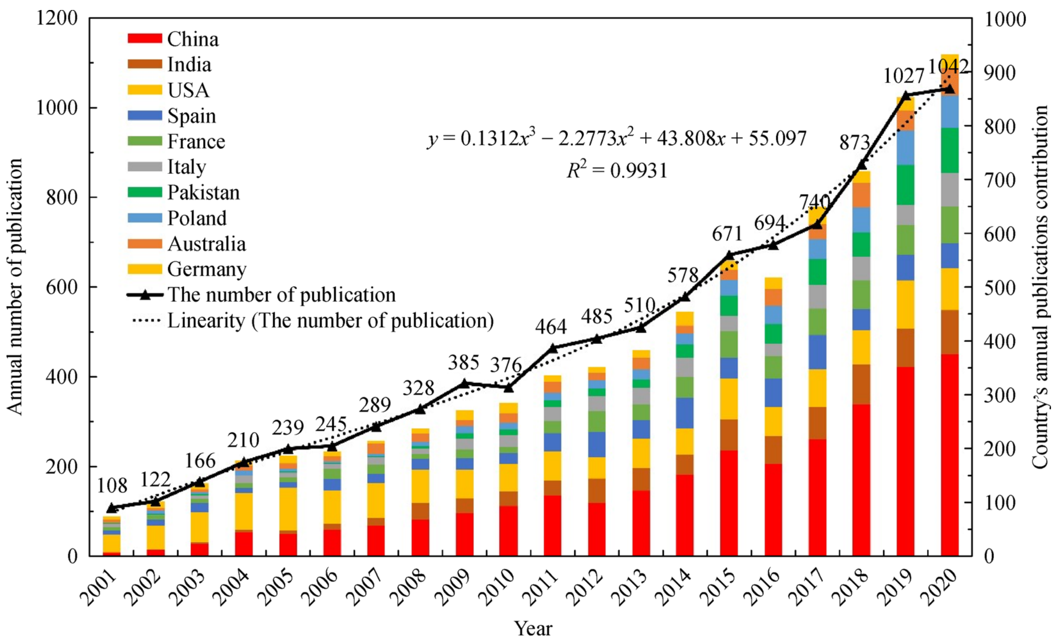

Fig. 2 Annual publication numbers and top 10 countries' publication contributions.

1) The values were automatically designated by the software of CiteSpace (5.7 R3).

development situation of that field. Although the first paper about PHMCS was published in 1945 (Robinson & Edgington, 1945), studies of PHMCS began to be published consistently only after the beginning of the 21st century; therefore, we analyzed the data in this period in present study. Figure 2 shows that the output of publications conformed to the growth of the cubic curve regression model ($y = 0.1312\ x^3 - 2.2773x^2 + 43.808x + 55.097$, $R^2 = 0.9931$) during the studied period, and that nearly half (45.81%) of the studies were published in the last five years, indicating highly attention has attracted in field of PHMCS in recent years. The publications mainly distributed in Asia, North America, and Europe, including in China, USA, and India.

3.1.2 Publication contribution analysis

The 10 countries/regions, institutions, authors, and journals that published the most PHMCS studies and the 10 most common categories of these studies are listed in Table 1. The frequency and percentage (%) values were used to analyze each contributor and category. As shown in Table 1, China was the country that made the highest contribution, with 2544 publications, (26.63% of the total). The USA and India contributed 1215 (12.62%) and 612 (7.07%) publications, respectively. Among the institutions, the Chinese Academy of Sciences (CAS) was by far the greatest contributor, with 637 publications (6.67% of the total). The second- and third-largest institutional contributors were Zhejiang University (216, 2.26%) and Consejo Superior de Investigaciones Científicas (CSIS) (179, 1.87%). The most active author in the field of PHMCS was Xiaoe Yang (with 66 publications). Guillaume Echevarria, Yongming Luo, and Lena Q Ma were similarly prolific, each publishing *c.* 55 studies. These publications appeared mainly in mainstream journals of ecology and environmental science, including the International Journal of Phytoremediation (8.66%), Environmental Science and Pollution Research (6.22%), Chemosphere (5.82%), Environmental Pollution (3.21%), and Science of the Total Environment (3.15%). More than half of the publications belonged to category of environmental science (61.45%). The others were mainly as plant science (13.91%), environmental engineering (9.56%), agronomy (6.39%), and toxicology (5.36%). As early as 1984, Reeves and Baker (1984) pointed out that the development of phytoremediation requires a multidisciplinary approach, spanning fields as diverse as plant biology, agronomy, agricultural engineering, soil science, microbiology, and genetic engineering. Currently, all these fields are involved in performing research on PHMCS.

3.1.3 Scientific collaboration analysis

Fig. S1 shows the scientific collaboration between countries/regions (a), institutions (b), and authors (c). A total of 129 countries/regions contributed to the related research. The countries of “USA,” “Germany,” “France,” “China,” “Spain,” and “Italy” nodes circled in purple and had high *BC*, with the value of 0.27, 0.23, 0.21, 0.20, 0.14, and 0.11, respectively, indicating these countries had extensive connections with other countries/regions. The number of contributing institutions was 775. The *BC* value of the CAS, CSIS, University of Melbourne, and University of Florida were 0.37, 0.24, 0.13, and 0.11, respectively, indicating that these institutions have extensive connections with others. A total of 1088 authors contributed studies to the PHMCS field, but the connection lines among authors were weak; furthermore, the *BC* values for all authors were < 0.1, indicating that a leading team in this field has not formed based on the bibliometric analysis. Global collaboration in this field should be strengthened to better address the problems of PHMCS.

3.2 Keyword co-occurrence network and cluster analysis

Keywords can be considered the soul of an article (Ouyang et al., 2018), as they concisely reflect the core content of the article. In total, 1108 nodes (keywords) and 13803 links were obtained in the keyword co-occurrence analysis (Fig. S2). The largest node was “phytoremediation,” with a frequency value of 5407, followed by “heavy metal,” “accumulation,” “plant,” and “soil,” with frequency values of 3822, 2711, 2485, and 2396, respectively.

Analyzing keyword clusters is an effective way to identify major research domains, emerging trends, and hot topics over time (Zhou et al., 2018). After analyzing the single-keyword co-occurrence map, co-occurrence clusters of the keywords were drawn using the LLR algorithm (Fig. 3). The co-occurrence clusters were arranged according to their size. In total, 8 clusters, including “Bioremediation” (#0), “Arsenic” (#1), “Biochar” (#2), “Oxidative stress” (#3), “Hyperaccumulation” (#4), “EDTA (ethylene diamine tetraacetic acid)” (#5), “Arbuscular mycorrhizal fungi” (#6), and “Environmental pollution” (#7), were obtained (Fig. 3 and Table S1). Each cluster is discussed in detail below to better characterize the hot topics in the PHMCS field over the study period.

Cluster #0: “Bioremediation”

The first cluster, labeled “Bioremediation,” was the largest cluster, containing 203 keywords, including “bioremediation,” “biodegradation,” “rhizosphere,” and “degradation.” The mean publication year for this cluster was 2008. The keywords with high frequency values related to phytoremediation, pollutant types, microorganisms, chelates, etc. grouped into this cluster. There are several different definitions of phytoremediation (Salt et al., 1995; Chen et al., 2012; Ali et al., 2013). The definition of phytoremediation that is currently generally

Table 1 The 10 countries/regions, institutions, authors, journals, and categories with the most PHMCS publications from 2001 to 2020

Rank	Country	Institution	Author	Journal source	Category
1	China (2544, 26.63)	Chinese Academy of Sciences (674, 7.06)	Xiaoe Yang (66, 0.69)	International Journal of Phytoremediation (827, 8.66)	Environmental Sciences (5870, 61.45)
2	USA (1205, 12.62)	INRAE (280, 2.93)	Guillaume Echevarria (57, 0.60)	Environmental Science and Pollution Research (594, 6.22)	Plant Sciences (1329, 13.91)
3	India (675, 7.07)	Centre National De La Recherche Scientifique Cnrs (266, 2.78)	Yongming Luo (56, 0.59)	Chemosphere (556, 5.82)	Soil Science (913, 9.56)
4	Spain (612, 6.41)	Consejo Superior De Investigaciones Cientificas Csic (247, 2.59)	Lena Q Ma (53, 0.55)	Environmental Pollution (307, 3.21)	Environmental Engineering (871, 9.12)
5	France (561, 5.87)	University of Chinese Academy of Sciences Cas (223, 2.33)	Shafaqat Ali (49, 0.51)	Science of the Total Environment (301, 3.15)	Agronomy (610, 6.39)
6	Italy (474, 4.96)	Zhejiang University (218, 2.28)	Muhammad Rizwan (45, 0.47)	Ecotoxicology and Environmental Safety (278, 2.91)	Toxicology (512, 5.36)
7	Pakistan (425, 4.45)	State University System of Florida (189, 1.98)	Antony Van Der Ent (43, 0.45)	Journal of Hazardous Materials (268, 2.81)	Water Resources (503, 5.27)
8	Poland (402, 4.21)	Universite De Lorraine (187, 1.96)	Qixing Zhou (41, 0.43)	Plant and Soil (267, 2.80)	Biotechnology/Applied Microbiology (442, 4.63)
9	Australia (388, 4.06)	University of Florida (175, 1.83)	Longhua Wu (38, 0.40)	Water, Air and Soil Pollution (222, 2.32)	Ecology (427, 4.47)
10	Germany (328, 343)	Institute of Soil Science Cas (169, 1.77)	Shuhe Wei (38, 0.40)	Journal of Environmental Management (142, 1.49)	Biochemistry/Molecular Biology (246, 2.58)

(1) The numbers in parentheses represent the number of studies and the percentage of all studies. (2) "Institution" represents "Expanded institution".

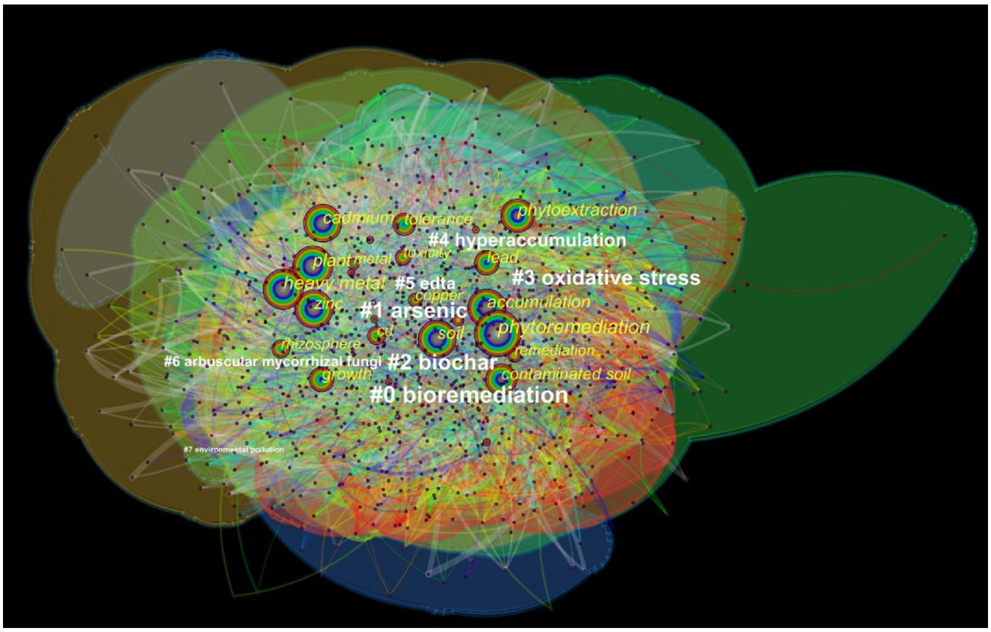

Fig. 3 Cluster map of co-occurring keywords in PHMCS studies published from 2001 to 2020.

accepted is "Phytoremediation basically refers to the use of plants and associated soil microbes to reduce the concentrations or toxic effects of contaminants in the environments" (Greipsson, 2011). It is a novel, cost-effective, efficient, solar-driven remediation strategy that is environmentally and ecologically friendly as well as applicable in situ (Salt et al., 1995; Ali et al., 2013; Gong et al., 2021). This approach is especially suitable for the phytoremediation of slightly, to moderately HM-contaminated soils. Because of its substantial advantages over physical and chemical methods, an increasing number of scholars are working in this field. As a result, the publication amount increased from 108 in 2001 to 1042 in 2020, showing a nearly 10-fold increase over 20 years of development (Table 1).

Cluster #1: "Arsenic"

A total of 194 keywords made up this cluster, and the most common were "arsenic" (As), "*Pteris vittata*," "speciation," "arsenate," and "phosphate." This is a relatively longstanding research field, and the mean year for this area was 2007. This cluster represents extensive concern about the hazards of As contamination, as it is a nonessential element for living organisms and poses a particular challenge for remediation (Li et al., 2015). Ferns, especially the species *Pteris vittata*, might be the most novel As phytoremediation species (Ma et al., 2001; Yang et al., 2020a). *Pteris vittata* has considerable biomass and is fast-growing, easy to propagate, and perennial (Ma et al., 2001). Ma and her collaborators first reported its As hyperextraction ability in the journal of Nature (Ma et al., 2001). Since then, many works have reported on As and phytoremediation (Visoottiviseth et al., 2002; Shoji et al., 2008; Yang et al., 2020a; Yang et al., 2020b). Some new genera have also been studied for As-contaminated soil remediation. For example, Kofroňová et al. (2019) reported that horseradish (*Armoracia rusticana*) showed high potential to tolerate As stress and that carbohydrates played a vital role in alleviating this kind of stress. Furthermore, Nie et al. (2002) first reported transgenic canola (*Brassica napa*) as an As phytoremediation plant, indicating that phytoremediation plant materials have expanded with the development of biotechnology, especially genetic engineering.

Arsenate can enter plants with phosphate transporters (Lee, 1982), and both phosphate and As are taken up by plants in this way (Straker and Mitchell, 1986). In addition, phosphate, when applied as a fertilizer, can promote plant growth and alleviate As stress during the phytoremediation process (Fayiga and Ma, 2006; Lessl and Ma, 2013; Yang et al., 2017). This may partly explain why "phosphate" was assigned to the same cluster as "As."

Cluster #2: "Biochar"

The third cluster, labeled "Biochar," consisted of 190 keywords, including "biochar," "phytostabilization," "compost," "bioavailability," and "immobilization." The mean publication year for this cluster was 2012, indicating that it is a relatively new research area. Biochar is defined as a porous carbonaceous material produced by the thermochemical decomposition of biomass under oxygen-free or oxygen-limited conditions (Ahmad et al., 2014). In recent years, it has been widely used in the PHMCS field. A meta-analysis by Hu et al. (2020) indicated that biochar is an effective amendment for remediating Cd-contaminated soils and that compost is a novel feedstock material for biochar. Our work supported this opinion, i.e., the inactivation of biochar for Cd, while the domestic residue-derived biochar was regarded as the most suitable biochar, which decreased the soil available Cd concentration and Cd uptake by plants by 36.04% and 53.17%, respectively (Liang et al., 2021). Biochar cannot only reduce the mobility and bioavailability of HMs in soil but can also provide beneficial nutrients for plant growth (Biederman and Harpole, 2013). Moreover, biochar can be applied simultaneously with agricultural activity; thus, it does not affect agricultural production and is easily accepted by farmers (Xie et al., 2018). The effects of biochar on HM immobilization and plant uptake also varied depending on the biochar feedstock material, application dosage, production conditions, target soil characteristics, HM type, and plant species (Chen et al., 2018; Norini et al., 2019; Simiele et al., 2020; Liang et al., 2021). Therefore, these factors should be comprehensively considered when using biochar for PHMCS. Considering the size of this node, the relatively late mean publication year, and the novel role of biochar in HM immobilization, more research attention will likely be paid to this area in the future. In China, a special journal named as "Biochar" was launched in March 2019, and has been included in many internationally renowned databases such as Scopus and SCI. As the first journal specifically focusing on biochar, the journal Biochar, beyond doubt that will serve as an efficient and professional platform for researchers and readers around world in the area of biochar on PHMCS.

Cluster #3: "Oxidative stress"

"Oxidative stress" was the fourth-largest cluster, with 165 keywords, including "oxidative stress," "antioxidant enzymes," "photosynthesis," and "antioxidants." Under HM stress, plants experience damage from reactive oxygen species (ROS) in the plant body, which retards plant growth and even causes plant death. ROS compounds are divided into two categories: (1) nonradical molecules, such as singlet oxygen (O_2) and hydrogen peroxide (H_2O_2), and (2) free radicals, including hydroxyl radicals (•OH), superoxide anions ($O_2•^-$), alkoxy radicals, perhydroxyl radicals (HO_2), reactive molecules, and ions (Emamverdian et al., 2020). Plants can maintain homeostasis by two different detoxification mechanisms involving nonenzymatic and enzymatic antioxidants (Kim et al., 2017). Enzymatic mechanisms mainly involve superoxidase (SOD), catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX), and nonenzymatic mechanisms mainly involve phytochelatins (PCs), sulfhydryl (-SH), glutathione (GSH), total proteins, and certain osmotica (Yu et al., 2013; Kofroňová et al., 2019; Zaid and Wani, 2019).

Primarily, SOD catalyzes the efficient removal of superoxide free radicals in chloroplasts, as they mainly generat in photosystem I during the light reaction (Kim et al., 2017). CAT is an oxidoreductase that directly alters ion valence and participates in the detoxification of HMs (Ma et al., 2021). CAT is located in the peroxisomes of plant cells, and its main role is the elimination of H_2O_2, which produced by the SOD reaction. It is a heme-containing enzyme located in the peroxisomes of plant cells that catalyzes the dismutation of H_2O_2 (produced by the SOD reaction) into oxygen and water. POD resists the peroxidation of membrane lipids and maintains the integrity of cellular membranes by eliminating malondialdehyde (MDA), and it catalyzes H_2O_2-dependent oxidation using guaiacol as a substrate (Adrees et al., 2015). APX is involved in the ASC/GSH cycle and can also remove H_2O_2; however, it is distributed in peroxisomes as well as chloroplasts, the cytosol, and mitochondria (Racchi, 2013). The ability to upregulate antioxidant enzyme activities (AEAs) is regarded as a universal strategy for plants to resist stress and has been reported under HM stress (Yu et al., 2013; Kofroňová et al., 2019; Zaid and Wani, 2019; El-Bahr et al., 2020; Guedes et al., 2021; Sharifi et al., 2021).

Plants can induce defense responses against oxidative stress by activating nonenzymatic antioxidants, which represent the second line of defense against ROS (Kim et al., 2017). Among them, thiols (-SH), glutathione (GSH), phytochelatins (PCs), and some other osmotic substances, including free proline, soluble protein (SP), and soluble sugar (SS), have aroused extensive concern. Thiols are a novel type of chelator and have been verified as the most important class of meta ligands in higher plants. This can be combined with HM in the plant body and then reduce HM hazards to plants. Glutathione is a low-relative molecular mass nonprotein compound with antioxidative properties and is the precursor of phytochelatins (PCs). Both-SH and GSH are universal scavengers of ROS in plants under HM stress (Yang et al., 2016; Speiser et al., 2018; Bai et al., 2021; Emamverdianet al., 2020; Sharifi et al., 2021). Moreover, in adaptations to reduce HM cell damage due to its various physiologic activities, cells may, through the use of more synthetic osmotic substances, increase the thickness of the cell wall or combine these substances with HM. Proline acts as a mediator of osmotic imbalance, as well as a free radical scavenger and source of reducing power in higher plants (Yang et al., 2016; Xie et al., 2019). Metabolomic studies have also revealed that proline acts as an indispensable osmotic adjustment substance in proline metabolism and can activate a variety of stress reactions as a signaling molecule (Wang et al., 2014). Furthermore, the increased SP and SS contents in plants under HM stress also play positive roles. For example, plants can strengthen the synthesis of Cd binding proteins/polypeptides to resist Cd toxicity in *Koelreuteria paniculata* (Yang et al., 2018), and the increased SS in *Broussonetia papyrifera* leaves was favorable to alleviate Mn stress (Huang et al., 2019). Therefore, the mechanisms by which plants alleviate HM stress are a constant theme in the PHMCS field, and we deduce that this theme will continue to be studied in the future.

Cluster #4: "Hyperaccumulation"

The "Hyperaccumulation" cluster contained 141 keywords and was the earliest research area, with a mean publication year of 2006. This indicates that the main research on the topics in this cluster was performed relatively early. The main keywords in this cluster were "hyperaccumulation," "nickel," "serpentine," "*Thlaspi caerulescens*," "*Alyssum murale*," "Brassicaceae," and "*Arabidopsis halleri*," indicating that the phytoremediation of Ni-contaminated soils by Ni accumulators was the main theme in this cluster.

This cluster contains many plants used in Ni phytoremediation, such as *Thlaspi caerulescens*, *Alyssum murale*, and *Arabidopsis halleri*. These results were also consistent with a previous report, i.e., among the hyperaccumulators, the majority were Ni hyperaccumulators (Cappa and Pilon-Smits, 2013). Nickel is an important trace metal and is also an essential microelement for normal plant growth and development. The annual production of Ni is over 130,000 tons. The release of Ni into the environment is of great concern. The threshold value set for hyperaccumulation Ni is$>$1000 mg/kg (Brooks et al., 1977). Most of them is consistently found in Ni-contaminated or serpentine soils.

In addition to Ni-hyperaccumulator, many other HM hyperaccumulators also founded. Hyperaccumulation is the uptake of one or more metal/metalloids to concentrations greater than 50–100 $\times$ those of the surrounding vegetation or 100–10000 mg/kg dry weight depending on the element, and there were more than 515 taxa of angiosperms (Cappa and Pilon-Smits, 2013). The phenomena of tolerance to high concentrations of specific elements and active uptake and accumulation to several percent of the dry mass of their aboveground parts were originally described by Sachs (1865), and since 1977 plants exhibiting these phenomena have been called hyperaccumulators (Brooks et al., 1977). A report from Stevens (2001 onwards) showed that there were more than 500 hyperaccumulators among the ~250000 angiosperm species, equating to ~0.2% of species. In addition, the analysis results from mapping the occurrence of hyperaccumulators onto the angiosperm phylogeny showed that hyperaccumulation has multiple origins across angiosperms. Even within a given order, family, or genus, there are typically multiple origins of hyperaccumulation for either the same or different elements (Cappa and Pilon-Smits, 2013). The field of PHMCS has shown flourishing development in the past 20 years, demanding an overall analysis of hyperaccumulators to provide new and complete data to readers. Therefore, how many hyperaccumulators are there so far; which of these hyperaccumulators are ready to uptake which HM(s); where are these hyperaccumulators mainly distributed where; to which families, genera and species do these hyperaccumulators belong; and what is the phylogeny of these hyperaccumulators are all questions that need to be studied and will be the focus of our following work.

Cluster #5: "EDTA"

The sixth cluster, labeled "EDTA," included 114 keywords. The main keywords were "EDTA," "phytoextraction," "lead," "EDD," and "cadmium." In addition, the keywords "organic acid," "EDTA-extractable Cd," "chelate," "EDTA derivatives," and "dihydrogen phosphate" also occurred in this cluster (Table S1), indicating that applying chelating agents as soil amendments in combination with phytoremediation is the related study domain in the PHMCS field. The unavailability of metals in the soil for plant uptake is one of the limitations on successful phytoremediation (Blaylock et al., 1997). Chelating agents can prevent HM precipitation and sorption, thereby maintaining their bioavailability for plant uptake (Salt et al., 1995). Therefore, amending the soil with chelating agents is an effective way to increase HM solubility, resulting in improved plant uptake. These studies are mainly concerned with how to use chemical chelation to improve phytoremediation efficiency in Cd- and Pb-contaminated soils. This cluster is a relatively early study area, in which the average publication year was 2007, but studies have continued to be published (Yu et al., 2019; Guo et al., 2020). It is reasonable to expect that research in this area will continue, as the availability of HMs in soils directly affects plant adsorption and is adjusted by chelating agents, such as ethylene diamine tetraacetic acid (EDTA), diethylene triamine penta acetate (DTPA), trans-1,2-cyclohexyene dinitriloter traacetic acid (CDTA), ethylene glycol tetraacetic acid (EGTA), and citric acid (Blaylock et al., 1997; Yu et al., 2019; Liu et al., 2021). The responses to these agents varied with the chelator type (Blaylock et al., 1997), HM type (Blaylock et al., 1997; Anning and Akoto, 2018), plant species (Tariq and Ashraf, 2016), soil (Liu et al., 2021), and even extent of artificial disturbance (Yu et al., 2019).

In addition, phytoremediation plant species were studied extensively in this cluster. For example, the genus *Brassica* is suitable for the remediation of Cd- or/and Pb-contaminated soil (Yu et al., 2020b), and *Sedum alfredii* (Guo et al., 2020) and *Brassica juncea* are novel hyperaccumulators for the phytoremediation of Zn- and Cd-contaminated soils. *Sebertia acuminata* (Jaffré et al., 1976) and Indian mustard (*Brassica juncea*) (Blaylock et al., 1997) are novel hyperaccumulators for Ni-contaminated soils. Moreover, some crops, including *Zea mays*, Helianthus, and chickpeas; ornamental plants, including *Globularia alypum* L. and *Fraxinus rotundifolia*; and some green manure plants can be used in PHMCS.

Cluster #6: "Arbuscular mycorrhizal fungi"

A total of 82 keywords constituted the seventh cluster. Some keywords related to microbes, such as "arbuscular mycorrhizal fungi," "arbuscular mycorrhiza," "*Glomus intraradices*," "*Glomus mosseae*," "*Glomus*," "saprobe fungi," "ectomycorrhizal fungi," and "symbiosis," were assigned to this cluster. Some keywords related to plants, such as "willow," "*Salix*," "poplar," "*Populus*," and "*Medicago truncatula*," were also included. Therefore, this cluster was concerned mainly with microbes known as plant growth-promoting rhizobacteria (PGPR) that assist in HM phytoremediation. PGPR are typically isolated from the rhizospheres of metallophytes growing in mining areas, and their inherent resistance to metals may be accompanied by exceptional plant growth-promoting (PGP) traits, including the production of phytohormones and siderophores and phosphorus solubilization (Benidire et al., 2021). Among all PGPR, arbuscular mycorrhizal fungi (AMF) have caused extensive concern because of their major roles affecting plant growth, nutrient uptake, and phytoremediation efficiency, which have been reported in association with a variety of plants from herbs to woody species.

In general, PGPR can modify the soil pH, increase the availability of soil HMs, improve soil properties, and use PGP traits to increase plant HM resistance or alleviate HM stress, and these benefits ultimately lead to increases in biomass and bioremediation efficiency (Meena et al., 2017; Asad et al., 2019; Li et al., 2020).

In addition, microorganisms can improve plant tolerance to HM stress by altering the influence of HMs. For example, *Hymenoscyphus ericae* isolated from the roots of *Calluna vulgaris* grown in soil contaminated with As and Cu showed increased accumulation of As, thus reducing As uptake by plants and improving the As tolerance of *C. vulgaris* (Sharples et al., 2000).

Although this research area emerged relatively early, it has also become a hot topic in the PHMCS field in recent years. This may be due to its novel role in phytoremediation. For example, our previous study results showed that *Enterobacter sp*. FM-1 is a potent bioaugmentation agent for both hyperaccumulators and vegetables (Li et al., 2020; Yu et al., 2020b); furthermore, it is suitable not only for Mn- and Cd-contaminated soils but also for Pb- and Zn-contaminated soils, indicating its strong inherent resistance to multiple HMs (Li et al., 2020; Yu et al., 2020b).

Cluster #7: "Environmental pollution"

There were only 22 keywords in the "Environmental pollution" cluster, which may be because it was the most recently emerged research area, with a mean publication year of 2015. The main keywords were "environmental pollution," "toxicology," "environmental science," "environmental toxicology," and "environmental chemistry." Some new keywords, such as "crop planting," "crop rotation," "chemistry," "environmental engineering," "soil science," and "simple uptake model," were also included in this cluster, indicating that research on PHMCS now spans more fields than ever before.

3.3 Keyword burst detection

Analyses based on keywords can provide details about the hot topics in a given field, but the results can't be used to analyze development trends, especially the newest trends in a field (Cui et al., 2019). Keyword occurrence bursts, which refer to sharp increases in the use of certain keywords within a specific period, can partially reflect the dynamics of and potential research questions in a certain field (Cui et al., 2019; de Castilhos Ghisi et al., 2020).

In total, 334 keywords were identified as having occurrence bursts throughout the study period (data not given). Of these, the 25 strongest, longest-duration[1)], and most recent[2)] keyword bursts were analyzed in depth, as these characteristics indicate strong attractiveness of the related topics to researchers (Fig. 4). The keywords with the strongest bursts were those related to the hottest topics or the most-studied research areas. The longest-duration keyword bursts were related to topics that have attracted long-term research interest from scholars. The most recent keyword bursts forecasted possible emerging research topics in the PHMCS field. Herein, we divided these three types of keyword bursts into several groups to further clarify to which research areas they corresponded (Table 2).

3.3.1 Analysis of the 25 strongest keyword bursts

As shown in Table 2, the 25 keywords with the strongest bursts were divided into 7 groups, i.e., "Plant bioremediation materials," "HM types," "Chelating amendments," "Other improvement strategies," "Bioremediation characteristics," "Risk assessment," and "Other." The remediation plant materials were mainly *Thlaspi caerulescens*, *Arabidopsis halleri*, and ferns. Among these species, Indian mustard is the most extensively studied plant species due to its high tolerance of and ability to accumulate multiple HMs, such as Pb, Cr, Cd, and Ni (Salt et al., 1995; Chaudhry et al., 2020; Zhu et al., 2020). The *Thlaspi* genus shows bioremediation potential for Zn, especially *Thlaspi caerulescens*. Furthermore, some members of this genus can accumulate multiple HMs. For example, *T. goesingense* can simultaneously accumulate

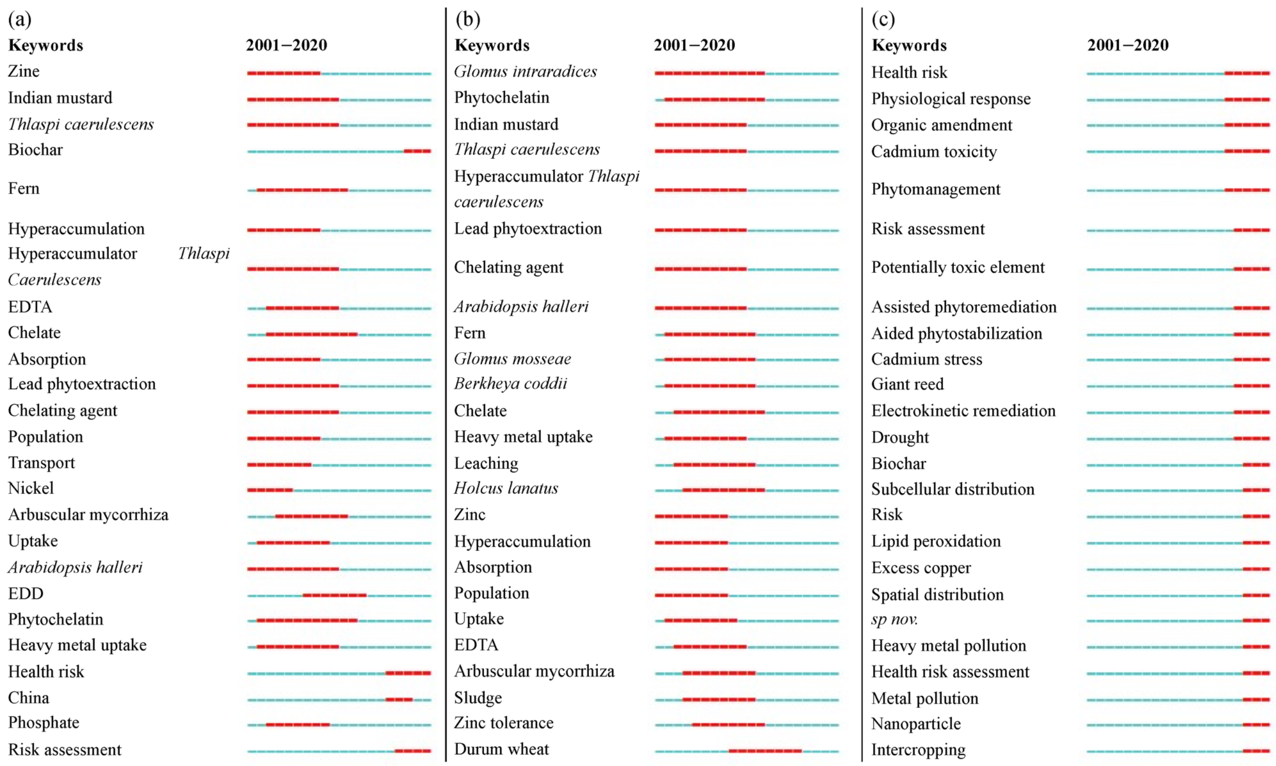

Fig. 4 The 25 strongest keyword bursts (a), longest-duration keyword bursts (b), and most recent keyword bursts (c) in PHMCS studies.

1) If two keyword bursts had the same duration time or ending time, the keywords were ranked according to their *BS* value.
2) Keyword bursts for which the burst time ended in 2020 were regarded as the most recent keyword bursts. Only the 25 strongest keyword bursts were considered in the analysis of the most recent keyword bursts.

Table 2 Group analysis of the 25 strongest, longest-duration, and most recent keyword bursts in PHMCS studies

Group labels	Highest keyword bursts	Longest duration keyword bursts	Most recent keyword bursts
(1) Remediation materials	Indian mustard (2001–2010, 46.9); *Thlaspi caerulescen* (2001–2010, 41.79); Hyperaccumulator *Thlaspi caerulescen* (2001–2010, 18.47); *Arabidopsis helleri* (2001–2010, 12.33); Fern (2002–2011, 19.6)	Durum wheat (2009–2016, 5.14); Indian mustard (2001–2010, 46.9); Thlaspi caerulescen (2001–2010, 41.79); Hyperaccumulator Thlaspi caerulescen (2001–2010, 18.47); Arabidopsis helleri (2001–2010, 12.33); Glomus intraradice (2001–2012, 4.77); Fern (2002–2011, 19.6); Berkheya coddii (2002–2011, 5.37); Holcus lanatus (2004–2011, 6.97)	Phytomanagement (2016–2020, 6.15); Assisted phytoremediation (2017–2020, 9.01); *Giant reed* (2017–2020, 6.95); Aided phytostabilization (2017–2020,8.48)
(2) HMs types	Nickel (2001–2005, 13.14); Zinc (2001–2008, 47.48); Lead phytoextraction (2001–2010, 14.56)	Zinc(2001–2008,47.48); Lead phytoextraction (2001–2010, 14.56); Zinc tolerance (2005–2012, 4.88);	Cadmium toxicity (2016–2020, 6.77); Potentially toxic element (2017–2020, 9.01); Cadmium stress (2017–2020, 8.29); Excess copper (2018–2020, 7.42)
(3) Chelates amendments	Chelating agent (2001–2010, 14.16); Phytochelatin (2002–2012, 11.7); EDTA (2003–2010, 15.46); Chelate (2003–2012, 15.07); EDD (2007–2013, 11.85)	Chelating agent (2001–2010,14.16); Phytochelatin (2002–2012, 11.7); EDTA (2003–2010, 15.46); Chelate (2003–2012, 15.07);	Organic amendment (2016–2020, 8.65)
(4) Other improve strategy	Phosphate (2003–2009, 10.5); Arbuscular mycorrhiza (2004–2011, 12.82); Biochar (2018–2020, 27.43)	*Glomus mossease* (2002–2011, 8.89); Arbuscular mycorrhiza (2004–2011,12.82); Sludge (2004–2011,7.19)	Biochar (218–2020, 27.43); *Sp nov* (2018–2020,7.05)
(5) Technical terminology	Transport (2001–2007, 13.85); Hyperaccumulation (2001–2008, 18.82); Absorption (2001–2008, 14.88); Uptake (2002–2009, 12.49); Heavy metal uptake (2002–2010, 11.58)	Hyperaccumulation (2001–2008, 18.82); Absorption (2001–2008, 14.88); Uptake (2002–2009, 12.49); Heavy metal uptake (2002–2010, 11.58); Leaching (2003–2011, 8.84);	Physiological response (2016–2020,9.52); Subcellar distribution (2018–2020, 10.05); Lipid peroxidation (2018–2020, 8.02); Spatial distribution (2018–2020, 7.05); Heavy metal pollution (2018–2020,6.68); Metal pollution (2018–2020, 6.3)
(6) Risk assessment	Health risk (2016–2020, 11.55); Risk assessment (2017–2020, 10.12)	–	Health risk (2016–2020, 11.55); Risk assessment (2017–2020, 10.12); Risk (2018–2020, 8.16); Health risk assessment (2018–2020, 6.67)
(7) Others	Population (2001–2008, 14.01); China (2016–2018, 11.21)	Population (2001–2008, 14.01)	Eletrokinetic remediation (2017–2020, 6.13); Drought (2017–2020, 6.1); Nanoparticle (2018–2020, 6.13); Intercropping (2018–2020,6.13)

Ni, Zn, Cd, Co, and Mn (Reeves & Baker, 1984). These plants are of particular significance for the phytoremediation of soils contaminated with multiple HMs. Moreover, ferns are another novel phytoremediation material, which is consistent with the keyword cluster analysis (Fig. 3).

Although the burst periods for "Chelate" and "EDD" related to improving phytoremediation efficiency lasted only from 2001 to 2013, they may represent an enduring theme, as much research has been done on these topics very recently (Yu et al., 2019; Guo et al., 2020). In addition, some other amendments, such as "phosphate" (2003–2009), "arbuscular mycorrhiza" (2004–2011), and "biochar" (2018–2020), also entered the PHMCS research field. Bioremediation characteristics were a hot topic in PHMCS in the first decade considered in this study. "Risk assessment" was the newest research area among the strongest keyword bursts (2016–2020).

The "Technical terminology" group, including "absorption," "(heavy metal) uptake," and "transport," represented earlier hot topics. The "Other" group included two keyword bursts, i.e., "population" and "China." The former, "population," is a relatively old research topic (2000–2008). When a species becomes established in HM-contaminated soil, some adjustments, such as phenotypic plasticity, will develop through adaptation or evolution at the population level over time (Schat, 1999; Pollard et al., 2002; Ernst, 2006; van der Ent et al., 2013). Moreover, the evolution of hosts and symbionts is fundamental to the colonization of polluted soils by key plant taxa (Sharples et al., 2000). The keyword "population" showed high burst values (13.92) that lasted for approximately eight years (Table 2). The second "Other" keyword, "China," had a newer keyword burst (2016–2018), indicating that an increasing number of studies are being performed related to Chinese issues. The publication contributions from different countries/regions, institutions, and authors also confirmed this result (Fig. 2 and Table 1).

3.3.2 Analysis of the 25 longest-duration keyword bursts

The analysis of the longest-duration keyword bursts showed that of these 25 keywords, 15 were similar to keywords identified as having the 25 strongest keyword bursts. This result indicates that the topics that were the most popular were also studied for a long duration. For example, the keyword bursts for "absorption" and "uptake," which are related to bioremediation characteristics, were among the strongest and longest-duration bursts identified in this study. This indicates that these parameters are important and have been extensively used to assess bioremediation efficiency in this field (van der Ent et al., 2013). Moreover, the "Plant bioremediation materials" group included 9 long-duration keyword bursts related to plants. This indicates that screening for suitable accumulators has received continuous attention in the field of PHMCS, as it is the prerequisite condition for phytoremediation implementation. Field investigations in highly HM-contaminated soils provide a potential way to screen for suitable accumulators (Robinson & Edgington, 1945; Ma et al., 2001; Li et al., 2007; Liu et al., 2016a; Liu et al., 2016b; Liu et al., 2020d). The longest-duration "HM type" keyword bursts were mainly for Pb and Zn. Considering the high degree of consistency in keywords between the LDKBT and SKBT results, we do not further expand this section.

3.3.3 Analysis of the 25 most recent keyword bursts

According to the keyword burst test, in total, 72 keyword bursts were ongoing until 2020, and these represent the most recent hot topics (Table S2). For the sake of limiting the paper length, only the 25 strongest of the most recent keyword bursts are analyzed in depth in this study. Compared to the results of the two keyword burst tests shown above, the results of the recency analysis were very different. This finding indicates that many new hot research topics emerged in the PHMCS field at the end of the studied period. Half (12) of the most recent keyword bursts emerged in the past 3 years of the studied period (2018–2020). All these results indicated that research on PHMCS is broadening in scope. The results regarding the categories of PHMCS analysis further supported this finding (Table 1).

The keyword burst for "biochar" ranked among both the 25 strongest (*BS* = 27.43) and most recent keyword bursts (from 2018 to 2020). This indicates that this topic is by far the most popular research theme to emerge in recent years. This result was corroborated well by keyword cluster analysis (Fig. 3). Considering its ability to reduce HM bioavailability, improve soil properties, supply nutrients for plants, and alleviate HM stress in HM accumulator species (Chen et al., 2018; Norini et al., 2019; Simiele et al., 2020), biochar will undoubtedly be one of the important directions for future research.

The second most attractive keyword was "health risk." Its *BS* was 11.55, which is lower than that of only "biochar" and placed it among the 25 strongest keyword bursts. However, this keyword has occurred for five years (2016–2020), indicating that much more attention has been given to this topic in recent years and that it has been a research focus for longer than biochar. For example, we assessed the nutrient status and pollution levels in five areas around a manganese mine in southern China and found that the total phosphorus was sufficient but that the total nitrogen and organic matter were insufficient in the explored mine area, tailings area and reclamation area. The tested areas around the Mn mine were considered heavily polluted and presented high ecological risk, and Mn and Cd were the dominant pollutants (Liu et al., 2020c). HM contamination in paddy soils and crops grown around mining-affected areas should be managed to mitigate human health risks (Liu et al., 2018). However, HM contamination in agricultural soils caused by the accidental collapse of tailings dams will require more risk and health assessments (Liu et al., 2020b). Therefore, this topic will continue to be essential before and after bioremediation application, alongside gaining increasing interest from the public regarding environmental awareness.

Another recent keyword burst was "electrokinetic remediation" (EKR), which is a restoration technique designed especially for the in situ treatment of contaminated soils. It is based on the application of a direct electric potential to contaminated soils by a series of electrodes (anodes and cathodes) (Cameselle et al., 2013). The use of EKRs in contaminated soil remediation has been researched over the last two decades (Cameselle et al., 2013). Currently, many studies have combined the methods of phytoremediation and EKR to address the limitations of phytoremediation alone that are related to HM availability, i.e., the long treatment time and the depth of treatment being limited to within the root zone (Siyar et al., 2020). Therefore, EKR represents part of a novel combined technique in the PHMCS field and may continue to be studied in the future.

"Nanoparticle" was one of newest keywords, occurring from 2018 to 2020, and had a *BS* of 6.13. Nanoparticles are considered "materials of the new millennium," with dimensions $\leqslant$100 nm and unique features such as high functionality, high reactivity, and large surface areas. Due to the efforts of many researchers, the combination of nanomaterials and phytoremediator plants has become an effective way to remediate polluted environments (Zhu et al., 2019). The review paper from Zhu et al. (2019) entitled "Nanomaterials and plants: Positive effects, toxicity and the remediation of metal and metalloid pollution in soil" proposes that nanomaterials, such as TiO^2, nano-Fe_3O_4, Ag, zero-valent iron, SnO_2, hydroxyapatite, carbon black, etc., can promote the germination of plant seeds and the growth of whole plants, resulting in improved HM bioremediation efficiency. Therefore, combining the advantages of these two methods is likely to be a future research topic.

Another new keyword is "intercropping," which had the same burst period and *BS* value as "nanoparticle." Intercropping is a useful agricultural cropping pattern and is now also used in the PH Some new keywords MCS field. Intercropping systems have been proposed to enhance phytoextraction and/or to reduce metal uptake by combining different species and taking advantage of their interactions. For example, when *Typha angustifolia* and *Limnocharis flava* were intercropped, the removal rates of multiple metals were higher than those obtained in monocultures (Syukor et al., 2016). Intercropping native plant species (*Setaria viridis*, *Echinochloa crus-galli*, and *Phragmites australis*) significantly enhanced the migration of HMs in polluted mining areas (Lu et al., 2019). Similar results were also found in cocropping systems with *Salix caprea* and *Arabidopsis* (Wieshammer et al., 2007); *Artemisia selengensis*, *Trifolium repens*, *Houttuynia cordata*, and *Medicago sativa* (Wang et al., 2018); and *Eleocharis acutangula*, *Cyperus papyrus*, and *Typha domingensis* (Carvalho et al., 2019). However, some studies have found that a combination of plant species may not improve the removal efficiency of any pollutant examined individually. Thus, the intercropping patterns used for remediation plants need to be studied further.

Notably, the keyword "drought" was one of the 25 most recent burst keywords, indicating that it is a popular research topic among scholars (Ma et al., 2017). The spatial and temporal redistribution of water resources may occur under global climate change, inducing dry places to become drier. On the one hand, climatic changes, particularly elevations in atmospheric CO_2, directly enhance biomass production and metal accumulation in plants. On the other hand, the indirect effects of climatic change could lead to altered metal bioavailability in soils and concomitantly affect plant growth by changing the rhizosphere microenvironment (Rajkumar et al., 2013). Ma et al. (2016; 2017) demonstrated that microorganisms have the potential to protect plants against drought stress, help plants thrive in semiarid ecosystems, and accelerate phytoremediation processes in HM-contaminated soils. Therefore, exploring how accumulators and their rhizosphere microenvironments change under the dual stresses of HM contamination and drought will be another interesting research topic in the future.

3.4 Knowledge base analysis

3.4.1 Overall determination of the knowledge base

Development in any field is based on previous research. In CiteSpace analysis, the cited references are considered the bases for the citing references and play a supporting role in citing reference research. Co-citation cluster mapping was also conducted in this study (Fig. 5). In total, 9 clusters were obtained from the knowledge map generated by the cocitation cluster analysis. The clusters were arranged by size from #0- #8 and labeled "phytostabilization," "hyperaccumulation," "EDTA," "endophytic bacteria," "oxidative stress," "polycyclic aromatic hydrocarbons," "arsenic," and "willow," respectively. From these cluster labels, we identified studies that corresponded well with these keywords (Fig. 5) and that therefore likely substantially supported the development of the PHMCS field.

3.4.2 Specific studies within the knowledge base

The cocitation map directly reflects which papers were cited the most. The co-occurrence map for PHMCS is

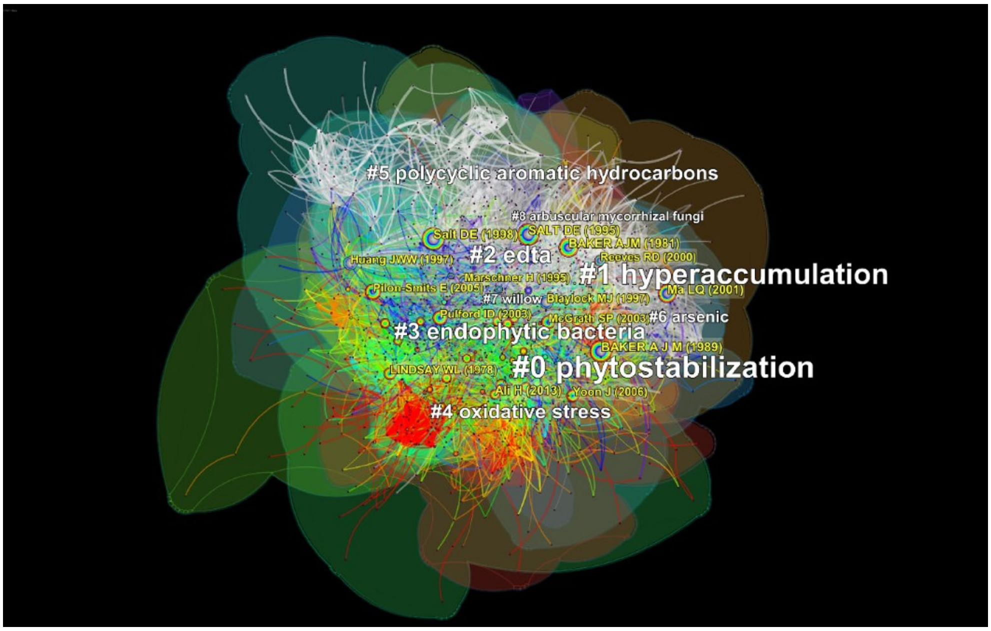

Fig. 5 Co-citation cluster mapping in the PHMCS field from 2001 to 2020.

Table 3 The most important cited references in the PHMCS field

No.	Author	Journal	Title	CF	BS	Begin- End	Range (2001–2020)
K01	Ali et al. (2013)	Chemosphere	Phytoremediation of heavy metals—Concepts and applications	582	103.54	2015–2020	
K02	Blaylock et al. (1997)	Environ Sci Technol	Enhanced accumulation of Pb in indian mustard by soil applied chelating agents	444	64.36	2001–2010	
K03	Huang et al. (1997)	Environ Sci Technol	Phytoremediation of lead-contaminated soils: Role of synthetic chelates in lead phytoextraction	412	63.52	2001–2008	
K04	Ent et al. (2013)	Plant Soil	Hyperaccumulators of metal and metalloid trace elements: Facts and fiction	350	47.95	2015–2020	
K05	Salt et al. (1995)	Bio-Technol	Phytoremediation: A novel strategy for the removal of toxic metals from the environment using plants	535	45.09	2001–2006	
K06	Salt et al. (1998)	Annu Rev Plant Phys	Phytoremediation	669	35.39	2001–2009	

CF and *BS* represent the citation frequency and burst strength, respectively.

shown in Fig. S3. The 3 most-cited papers were from Baker AJM et al. (1989), Salt DE et al. (1998), and Ali H et al. (2013), with citation frequency values of 702, 669, and 554, respectively. Considering the large amount of data for this field, only cited papers with both high *CF* and *BS* values (Huang et al., 2020), which indicated their fundamental and pivotal influence on the development of the PHMCS field, were analyzed in depth in this study. The citation frequency refers to the total number of times a certain document has been cited. Citation bursts, referring to sharp increases in the number of citations of a certain article, can partially reflect the dynamics and potential research questions in a certain area of a field (Cui et al., 2019; de Castilhos Ghisi et al., 2020). Among the 176,782 references cited by the research considered in this study, a total of 664 documents exhibited citation bursts from 2001 to 2020. These documents include the 25 most-cited documents, and the 25 citations with the strongest citation bursts were chosen for in-depth analysis. Six studies fell into both of these categories, and details about these studies are listed in Table 3. In general, the papers termed K02, K03, K05, and K06 played vital roles in supporting PHMCS research in the first decade of this century, while K01 and K04 played leading roles in supporting research in the PHMCS field in the subsequent decade, especially in the past 5 years.

The first paper identified in this analysis (K01) is a review paper from Ali et al. (2013) and had the highest BS value (103.54) and the third-highest *CF* value (582). This review fully introduces hazardous HMs, phytoremediation techniques/strategies; factors affecting phytoremediation efficiency; metallophyte categories; methods of quantifying phytoextraction efficiency; mechanisms of HM uptake, translocation, and tolerance; limitations of phytoremediation; and future trends in phytoremediation (Ali et al., 2013). It is nearly the ideal paper to enable both a neophyte and a senior researcher to fully understand and become familiar with the PHMCS field. The citation burst for this paper began in 2015 and continued until 2020, indicating that the paper has had a profound impact in the research field of PHMCS in recent years, especially in the past 5 years.

The second paper (K02) is a research paper entitled "Enhanced accumulation of Pb in Indian mustard by soil-applied chelating agents" (*CF* = 444, *BS* = 64.36) by Blaylock and his colleagues (Blaylock et al., 1997). This study demonstrates the effects of HM accumulation (Cd, Cu, Ni, Pb, and Zn), especially Pb accumulation, on Indian mustard (*Brassica juncea*), which is one of the most studied materials in the phytoremediation field, with and without EDTA amendment. In addition, the chelators EGTA, CDTA, DTPA, and citric and malic acid were assessed for their effects on plant growth and HM uptake. The results indicate that the accumulation of Pb in tissues is related to the soil Pb concentration and EDTA amendment concentration. In general, a chelating amendment of 5–10 mmol kg^{-1} resulted in several-fold higher HM concentrations in treated plants than in control plants. Treatment with a chelating amendment of 0.1 mmol kg^{-1} did not affect the plant dry biomass compared with that in the control, but the resulting biomass values were two times higher than those in a treatment with a chelating amendment of 10 mmol kg^{-1} (Blaylock et al., 1997). The third most important paper (K03) was a similar research work from Huang et al. (1997) entitled "Phytoremediation of lead-contaminated soils: Role of synthetic chelates in lead phytoextraction." This study had the same *CF* and *BS* values and the same publication year as K02. The results from these two papers show that chelation can activate HMs and thereby increase HM adsorption by plants. Our study results (Yu et al., 2019) and those of other researchers (Guo et al., 2020) also confirmed these findings. It is worth mentioning that the main keywords in these two papers ("Pb," "EDTA," "chelates," etc.) ranked among the 25 keywords with the strongest keyword bursts, making them hotspots among hotspots, and these bursts lasted for 8–10 years. These results indicate that both papers had similar profound impacts on the PHMCS field and have played a leading role in supporting the development of this field, especially with regard to the effects of chelating amendments on phytoremediation efficiency.

K04, entitled "Hyperaccumulators of metal and metalloid trace elements: Facts and fiction," was another prominent paper in PHMCS and was published in 2013 by van der Ent et al. (2013). This is a relatively new paper. Its burst began in 2015, lasted until 2020, and will most likely continue into the future, indicating that this paper has been critical for recent research in the PHMCS field. This paper clarifies the definition of a 'hyperaccumulator', (re)defines some of the field terminology, notes potential pitfalls, and summarizes and lists the threshold criteria for the main studied HMs (Pb, Zn, Cd, Cr, Cu, Mn, and Ni), metalloids (As and Se), and rare earth elements (Ce and La), as well as the corresponding bioconcentration factors (shoot-to-soil ratios) and translocation ratios (shoot-to-root ratios) (van der Ent et al., 2013). Many subsequent studies on hyperaccumulators, especially those confirming a new hyperaccumulator or assessing hyperaccumulation efficiency, cited or referred to this paper (Liu et al., 2016a; 2016b; Liu et al., 2020a; Yu et al., 2020b).

K05 is a review paper (*CF* = 535, *BS* = 45.09) entitled "Phytoremediation: a novel strategy for the removal of toxic metals from the environment using plants" (Salt et al., 1995). Due to its provision of an overall view of phytoremediation and suggestions of several field trials to confirm the feasibility of using plants for environmental remediation, as well as its relatively early publication time (i.e., it has had more chances to be cited), this paper ranked fifth according to its *CF* value (535). The citation burst for this paper began in 2001 and ended in 2005, lasting for 6 years. The definition of phytoremediation; its benefits, especially regarding its cost compared with that of traditional techniques; mechanisms for phytoremediation; and amendment strategies, especially the use of chelators and soil microorganisms to improve soil HM bioavailability, are fully discussed in this paper. Some of the opinions in this study are consistent with those in K02 and K03, and these three papers appear to have had a vital impact on the hot topics "Pb," "EDTA," "chelates," and others in the first decade of this century.

K06 is another review paper (*CF* = 669, *BS* = 35.39) with a very concise title, "Phytoremediation," by (Salt et al., 1998). It is a relatively old review paper in the PHMCS field. The paper summarizes the latest developments in phytoremediation technology and its biological mechanisms up to the year of publication (1998), but it is no longer current. The citation burst for this paper lasted only through the beginning of this century (2001-2009).

4 Future research directions

Based on the above analysis and our understanding of PHMCS, the following research directions are recommended for future studies:

1) Screening plant materials for their PHMCS potential. Phytoremediation materials are a prerequisite for phytoremediation. Therefore, the exploration of new germplasm resources, especially screening for multiple-HM accumulators, is likely to remain an attractive PHMCS research area in the future.

2) Strategies for PHMCS. The phytoremediation process is time-consuming, and even the strongest HM accumulator requires 13 to 14 years of continuous cultivation to remediate HM-contaminated soil (Salt et al., 1995). Therefore, improving phytoremediation efficiency with various amendments or other assistance methods to promote plant biomass and HM uptake is likely to be a main research topic in the PHMCS field in the future. Among these methods, biochar application, nanoparticle amendment, combining EKR with phytoremediation, and intercropping phytoremediators with other accumulators will likely become popular topics.

3) Microorganismal assistance for PHMCS. Plants in nature grow alongside microorganisms and form symbionts. Therefore, identifying new PGPR species with ideal PGP traits and determining their effects on phytoremediators and the possible mechanisms of these effects will likely be another emerging research area in the PHMCS field. In addition to using PGPR to promote phytoremediation under dual or multiple stresses, drought and HM stress are also likely to be new and interesting topics studied in the future.

4) Applying biotechnology to PHMCS. The development of biotechnology will greatly promote the development of PHMCs in terms of both their depth and breadth (Hassan & Aarts, 2011). Biotechnological approaches cannot only produce new phytoremediation plant materials but can also potentially increase plant biomass and HM uptake, resulting in improved phytoremediation efficiency. Furthermore, phytoremediation mechanisms can be fully studied at the protein, molecular, and genetic levels based on the development of new biotechnological techniques. The application of biotechnological principles and methods to the field of phytoremediation certainly represents a future research trend in this field.

5) Risk assessment and field application of PHMCS. With the increasing public attention paid to environmental issues, we speculate that risk assessment will become another hot topic in the following years, as will preliminary studies of in situ phytoremediation. This speculation is supported by the keyword burst analysis performed in this study. Moreover, soil HM contamination is a major environmental, social, and political issue. This problem must be resolved because of the limited cultivable land on Earth and the potential risks to living beings and the whole ecological system. After 20 years of rapid development in phytoremediation, many theories and methods have been generated in the laboratory, and some have been tested in long-term field experiments. This work has provided valuable experience for future in situ bioremediation efforts. Therefore, field applications and in situ phytoremediation are likely to be important future research areas in the field of PHMCS.

5 Conclusions

In this study, bibliometric analysis combined with visualization in CiteSpace software was applied to explore the publication characteristics, hot topics, change trends, and knowledge base of the PHMCS field. The number of related publications increased linearly over the last two decades, and nearly half of the total publications were published in the past 5 years, indicating that this field is attracting increasing attention. This field spans a wide range of research areas, including biology, agronomy, agricultural engineering, soil science, microbiology, and genetic engineering. However, scientific collaboration should be strengthened to enhance the development of PHMCS and to solve the global problem of HM-contaminated soils. The identified research domains were labeled “Bioremediation,” “Arsenic,” “Biochar,” “Oxidative stress,” “Hyperaccumulation,” “EDTA,” “Arbuscular mycorrhizal fungi,” and “Environmental pollution.” The keyword burst test showed that the keywords with the strongest bursts also had the longest burst durations, indicating that these hot topics had been studied for a comparatively long time. Many new keywords emerged during the past 5 years, and 60% emerged in the past 3 years, indicating that many new hot topics are emerging in recent years. These new keywords included “biochar,” “drought,” “health risk assessment,” “electrokinetic remediation,” “nanoparticle,” and “intercropping.” These newest hot topics may become future research directions. In general, this paper provides a comprehensive and systematic understanding of the field of PHMCS and proposes future research directions for the field.

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