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Research article

Farmland phytoremediation in bibliometric analysis

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ABSTRACT

Phytoremediation is an environmentally friendly, economical, and sustainable technique for restoring farmland. It can remove heavy metals and organic pollutants from the soil through the implementation of hyperaccumulator plants. In recent years, it has garnered significant interest from academic and industrial sectors. This article screened 368 research papers from the Web of Science core collection database related to farmland phytoremediation and conducted a bibliometric analysis of the domain based on CiteSpace. The paper intuitively demonstrates the most influential countries, the most productive institutions, the most contributing groups of authors, and the primary sources of farmland phytoremediation research domain. The findings additionally indicate that the research hotspots include: (1) mechanisms and principles of phytoremediation, (2) the improvement of restoration efficiency, (3) the economic, ecological, and sustainable development of phytoremediation. The exploration of plants with potential to accumulate heavy metals and produce large amounts of biomass is the research frontier within the field of farmland phytoremediation. Additionally, this bibliometric analysis can help scholars willing to work in this research field by concisely understanding the overall research field and frontiers. With the continuous improvement of phytoremediation and its combination with other remediation technologies, the future of farmland remediation will have a promising prospect.

1. Introduction

The quality of farmland is being seriously threatened by the continuous accumulation of persistent organics and heavy metals resulting from the overuse of pesticides or fertilizers and industrial pollution (Guan et al., 2019). This phenomenon, known as farmland pollution, has detrimental effects on crop growth, affecting the growth of crops, and reducing crop yields. Subsequently, these harmful substances have the capacity to amass within the organisms of animals and even human bodies through the progression of the food chain. Consequently, it might endanger animal and human health, increase pathogenic and lethal rates, and negatively impact food safety, the ecological environment, and human health.

Farmland pollution is a severe challenge that needs to be addressed immediately, and building a healthy farmland ecosystem has become a primary global goal. Several methods and techniques can be used to remediate farmland pollution, including physicochemical methods such as dig and fill, stabilization and solidification, and chemical elution (Wan et al., 2020; Xu et al., 2019); electrochemical methods such as electro-kinetic remediation (Lin et al., 2022); biological methods such as bioremediation and phytoremediation (Chen et al., 2023; Gao et al., 2023b); and combined restoration of multiple pathways (Kong et al., 2021; Ren et al., 2019). Conventional remediation methods exhibit several limitations, i.e., high labor intensity, expensive, time-consuming, less environmentally friendly, and make irreversible changes to the physicochemical properties of soil. In contrast to

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conventional remediation approaches, phytoremediation has been considered as an emerging technique, using plants to remove environmental pollutants. This technique is widely known for being a low-cost, non-invasive, eco-friendly alternative to conventional remediation methods (Lan et al., 2020). However, due to the limitations of the original phytoremediation method when implemented in a large-scale application, there is an urgent to employ a diverse array of methodologies to improve this strategy. By integrating the remediation approach, with modern biochemistry, artificial intelligence and transgenic species, phytoremediation efficiency can be significantly enhanced, yielding greater economic and ecological benefits.

Bibliometric analysis is one of the statistical analysis methods to elucidate the results and influence of literature research. Notably, scholars have extensively applied this analytical approach in different fields and disciplines, such as soil remediation (Ajibade et al., 2022), heavy metal pollution (Basmaci et al., 2023), groundwater contamination (Li et al., 2021a), energy production (Chen et al., 2021), and sustainable development (Gajdzik et al., 2020). Compared with conventional literature review, bibliometric analysis offers scholars the opportunity to comprehend the background expeditiously and directly, historical process, basic knowledge, current situation, development direction, shortcomings, and prospects of the discipline from the perspective of statistics. CiteSpace is a widely utilized tool in bibliometrics, which can perform diverse types of analysis encompassing but not limited to the number of articles, countries and institutions, authors, journals, references, and keywords clustering analysis. In addition, the data analyzed with CiteSpace can come from multiple databases such as Scopus, Web of Science, CNKI, etc.

At present, there are various excellent conventional literature reviews on the study of farmland phytoremediation. For examples, it was found Microbial-assisted phytoremediation has emerged as a promising in situ remediation method for contaminated soils, utilizing beneficial rhizobacteria and endophytes to promote plant growth and degrade contaminants (Song et al., 2020). The aforementioned briefly introduced the harm of heavy metals, the methods, processes, combination with molecular techniques (Bhattacharyya et al., 2023) and influencing factors of phytoremediation, and the current challenges and potential developments of phytoremediation (Matheson et al., 2023). These conventional literature reviews are significant for summarizing the previous research results, and discovering research shortcomings, and deficiencies to promote the development of farmland phytoremediation research. However, the content of these conventional reviews is often based on the expertise and comprehension of scholars within the respective field. Consequently, the analysis conducted in these reviews may inadvertently incorporate subjective viewpoints and personal opinions. In addition, these reviews tend to focus on a certain specific aspect, summarize the existing literature, and allocate only limited attention to the development process, research hotspots, and frontiers.

In the past few decades, researchers have increasingly directed their attention to the study of farmland phytoremediation, owing to the escalating severity of environmental problems. There is currently no bibliometric method for statistically analyzing the farmland phytoremediation from multiple perspectives and clearly understand the opportunities and challenges, a comprehensive bibliometric study is required. To this end, 368 articles from the Web of Science core collection database were selected for a bibliometric analysis to provide quantitative, intuitive, and systematic results. This paper undertakes an analysis of the following aspects: (1) describing and discussing trends in the number of literature; (2) investigating the collaboration of countries, institutions, and authors in the field, and the influence of journals and literature; (3) analyzing the research hotspots and frontiers in this field, while identifying inherent limitations and potential future research prospects.

2. Data sources and analytical methods

2.1. Data sources and screening

To collect the literature data, we selected the Core Collection of the WoS database. As a result of its comprehensive and multidisciplinary citation data, WoS has grown to become the main source of data for bibliometric analysis over other databases (Archambault et al., 2009; Li et al., 2020; Zhao, 2017). It allows researchers and scholars to acquire a large number of bibliographic data from several trustworthy and reputable journals. According to the research framework, the retrieval process was run, consisting of three steps. The initial phase involved the identification of the terms “phytoremediation”, “farmland” and other synonyms to identify the boundary of the research field. We chose “Advanced search” in the Web of Science Core Collection, used TS= ((phytoremediation) AND ((farmland*) OR (“agricultural land*“) OR (cropland*) OR (“cultivated land*“) OR (“farm field*“) OR (“cultivated field*“) OR (“agricultural farm*“) OR (“agricultural field*“) OR (“cultivated farm*“) OR (“agricultural area*“) OR (“cultivated area*“) OR (“crop field*“))) as the search content and the literature data search was conducted on March 1st, 2023, we obtained 443 publications. And we chose “Document Types” as “Article”, “Publication years” as “1997–2023” and “Languages” as “English”. Then the data was imported into the CiteSpace and the duplicate articles were removed using its duplicate checking function. As a result, 368 publications were identified. The bibliometric data from WoS contained lots of valuable and critical information, such as bibliographical information, keywords, author background, and cited references.

2.2. Analytical method

Collecting and analyzing the data are the most fundamental and crucial procedures to obtain reliable and valuable research results. The suitable tools are a prerequisite for a comprehensive and accurate analysis. The practical and powerful bibliometric analysis tool, namely CiteSpace designed and developed by Chen (2017), has been widely used to search for emerging tendencies and dynamic patterns in the scientific literature (Xu et al., 2022). CiteSpace endeavors to facilitate scholarly and research communities to expand their understanding of a particular research state of the art and future development. This software can be used to analyze some relevant research in the field of environment, such as water eutrophication (Hu et al., 2019), soil health (Liu et al., 2020), Atmospheric pollution (Li et al., 2017). We chose version 6.1. R6 of the CiteSpace as the primary bibliometric software. Four steps were taken in the subsequent data analysis to describe and highlight the knowledge landscape of farmland phytoremediation publications. Firstly, we analyzed the development of farmland phytoremediation using Origin by plotting the number of publications per year. Afterwards, in the co-occurrence analysis, the nodes (a point in the visualization map; the meaning of nodes is optional, different nodes represent different information) were set as country, institution, and author to gain valuable insights. In the co-citation analysis, we mainly analyzed the cited journals and references. Lastly, we performed a cluster (a bunch of close-knit nodes, it refers to a bunch of closely related keywords in this article) analysis of keywords and further analyzed the research hotspots and frontiers of farmland phytoremediation based on the timeline graphic. With the aid of these functions in the CiteSpace software, we gained insights into the content of the literature. We established conclusions and perspectives for the future based on the comprehensive bibliometric analysis.

3. Results of bibliometric analysis

3.1. Dynamics in the number of published papers

As a result, the publications on farmland phytoremediation analyzed in this study were 368, published from January 1st, 1997 to March 1st, 2023 (see Fig. 1). It was used Origin for the data processing. Overall, the number of articles presented an increasing trend. We have divided this period into three periods based on the number of articles per year. The articles during the 11 years from 1997 to 2008 accounted for only 6.5% of the total. No more than 5 papers were published in any year during this period. Although there was limited research on farmland phytoremediation during this period, the discussion on the methods of farmland restoration established a theoretical basis for later research (Mirck et al., 2005). Therefore, this period was called the "preparation period" for farmland phytoremediation research.

Since the year 2009, there has been a noticeable increase in farmland phytoremediation. From 2009 to 2016, the number of publications started to grow steadily, increasing to 15 times in comparison to the "preparation period" recorded in 2009. By the conclusion of this period, these publications constituted a substantial proportion, precisely 29.1%, of the total number of publications. This stage was called the "rise period", indicating that the research in this field did not remain depressed and developed a steady and positive trend. At this stage, many international scholars conducted case studies of farmland phytoremediation in various cities and regions worldwide (Cheng et al., 2016). Researchers have continuously experimented to select the plants with the most substantial remediation ability for farmland with different levels of pollution (Lord, 2015). Despite the relatively modest quantity of publications, it still effectively promoted the development of farmland phytoremediation.

Since 2017, the development of the field has entered in the "prosperity period". From 2017 to 2023, the number of papers multiplied and peaked in 2022. During this boom phase, 64.4% of all articles were published. Therefore, farmland phytoremediation has become an active research field for scholars to date. One of the most notable moments was in 2022, when the academic production reached 45, making 2022 a banner year for scholars studying the field. During this period, research became more extensive and emerging technologies that could assist in phytoremediation began to appear, such as genetic engineering (Nam and Han, 2020; Zhang et al., 2020b). As phytoremediation technology continued improving and maturing, it has been demonstrating a remarkable development. In addition, the number of publications in 2023 is limited as we only collected data up to March 1st.

3.2. Co-authorship analysis

This section uses CiteSpace to analyze the collaborative relationship between countries, institutions, and authors in farmland phytoremediation. The size of nodes represents the number of papers published by countries, institutions and authors, the line between two nodes represents the cooperation between them, and the color changes of the line represents different year of cooperation.

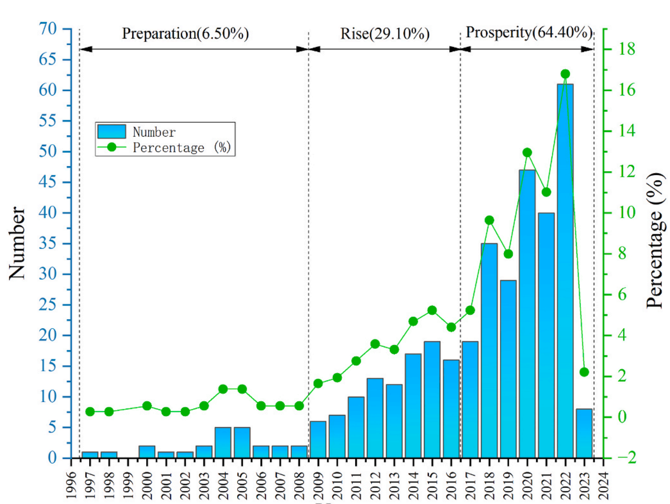

Fig. 1. Changes in the number of farmland phytoremediation publications from 1997 to 2023.

3.2.1. Countries and institutions co-authorship analysis

The map of collaborations in countries and institutions intuitively displays social relations and the degree of connection between countries or institutions in a specific field. This provides a new perspective for assessing the scientific research and academic strength of countries and institutions. It also assists agricultural scientific research countries or institutions worthy of attention. Based on the address information in the publications, we collected literature geographically distributed from 63 countries and 336 institutions. Tables 1 and 2 list the 15 highest-yielding countries and institutions, with 960 documents produced. It must be emphasized that scholars from multiple countries or institutions likely contributed to a document, so the number of papers is double counted. The number of publications and citations in each country or institution can show their influence in this research field.

All countries in Table 1 have published more than 5 documents. China ranks first with 163 articles, accounting for 44% of the papers. Followed by the USA, which published 37 articles (10.1%), which is 33.9% lower than China. Nevertheless, the United States of America was the first nation to actively participate in this field of study, indicating that it pioneered in this field. The majority of the institutions listed in Table 2 were Chinese, which also showed the dominance and influence of China in this field. The Chinese Academy of Sciences had the highest number of publications (count = 41), followed by the University of the Chinese Academy of Sciences (count = 15).

The bibliometric map of cooperation between countries and institutions is presented in Fig. 2, in which the node size represents the number of articles and node color means the average year of publication in every country or institution. Centrality is essential when describing cooperative relationships among countries or institutions. A higher centrality indicates that the node has more links with other nodes, the more influential the country or institution it represents in the field of research. China had the highest centrality (Centr = 0.81), followed by the United States (Centr = 0.48). The robust collaboration between China and the United States in the domain of farmland phytoremediation is evident. In the future, China and the United States will be the two largest developers of farmland phytoremediation in the world. Noteworthy advancements cannot be overstated, as they are poised to yield far-reaching benefits on a global scale. In addition, both countries have a close cooperative relationship with some developed countries such as Canada, Italy, Belgium, and Australia, etc., and some developing countries such as India and Pakistan, etc. In addition to the close cooperation between Chinese institutions, Chinese institutions have close relationships with certain foreign institutions, such as Hasselt

Table 1
Top-15 prolific countries in farmland phytoremediation.

Rank	Countries	Document	Centrality
1	China	163	0.81
2	USA	37	0.48
3	India	35	0.34
4	Canada	17	0.10
5	Pakistan	16	0.11
6	Italy	13	0.06
7	Belgium	10	0.04
8	Egypt	10	0.16
9	Austria	9	0.18
10	Germany	9	0.27
11	Japan	9	0.12
12	France	8	0.08
13	Sweden	7	0.03
14	Poland	7	0.04
15	Brazil	6	0.03

Table 2
Top-15 prolific institutions in farmland phytoremediation.

Rank	Institutions	Document	Centrality
1	Chinese Academy of Sciences	41	0.16
2	University of Chinese Academy of Sciences	15	0.06
3	Zhejiang University	11	0.04
4	Chinese Academy of Agricultural Sciences	9	0.08
5	Hasselt University	8	0.05
6	Sichuan Agricultural University	8	0.02
7	Hunan Agricultural University	8	0.06
8	China Agricultural University	6	0.01
9	Chaoyang University of Technology	5	0.01
10	Asia University	5	0.04
11	Nanjing Agricultural University	5	0.00
12	University of Manitoba	5	0.00
13	Swedish University of Agricultural Sciences	5	0.00
14	Babasaheb Bhimrao Ambedkar University	4	0.01
15	Sun Yat-Sen University	4	0.01

Table 3
Top 15 active authors of farmland phytoremediation.

Rank	Author	Documents	Year	Institution
1	Chen Tongbin	5	2018	Chinese Academy of Sciences
2	Lin Lijin	4	2014	Sichuan Agricultural University
3	Yang Jun	4	2021	Chinese Academy of Sciences
4	Cheng Shu-Fen	4	2015	Chaoyang University of Technology
5	Huang Chin-Yuan	4	2015	Asia University
6	Chen Kuo-Lin	4	2015	Chaoyang University of Technology
7	Liao Mingan	4	2014	Sichuan Agricultural University
8	Yang Xiaoe	4	2020	Zhejiang University
9	Zvomuya Francis	3	2018	University of Manitoba
10	Lei Mei	3	2013	Chinese Academy of Sciences
11	YangJunxing	3	2021	Chinese Academy of Sciences
12	Lin Sheng-Chien	3	2015	Chaoyang University of Technology
13	Wan Xiaoming	3	2021	Chinese Academy of Sciences
14	Cabral Cassia Michelle	3	2016	Federal University of Vales of Jequitinhonha and Mucuri
15	Lin Yung-Cheng	3	2015	Chaoyang University of Technology

University (Belgium), University of Manitoba (Canada), etc. Cooperation among different countries and institutions has brought economic benefits to people and promoted stability and new research lines worldwide for emerging pollutants. Due to the disposal of large amounts of contaminated farmlands, farmland phytoremediation has been the focus of a growing number of nations.

3.2.2. Author co-authorship analysis

The research of farmland phytoremediation is an expanding field, which has garnered considerable scholarly interest and engagement. The 368 publications analyzed this time were contributed by 485 authors who are “knowledge providers” in this field. The bibliometric analysis of author cooperation can be used to recognize the authors who contribute significantly to the research of farmland phytoremediation and the related cooperative relationship networks. The first to open the door to research in this field was G. S. Bafiue from USDA-ARS. In his article, it was posited the notion that the cultivation of plants with the capacity to accumulate and volatilize selenium from sediments and contaminated soil holds promise in mitigating soil selenium concentrations (Banuelos et al., 1997). This was an excellent starting point for the subsequent scholars to research in this field. Fig. 3 describes the author cooperation network of farmland phytoremediation, which includes authors with at least three papers. It can be seen from Fig. 3, that collaboration in this field presents overall cooperation and a small-world effect. Due to the dominance of China in this area, Chinese authors made up the majority of these cooperative groups. Fig. 3 a showed the cooperation of one of the small groups, represented by Chen Tongbin, Yang Jun, Lei Mei, etc. from the Chinese Academy of Sciences. Fig. 3 b described another representative cooperative group from the Chaoyang University of Technology, which included Cheng Shu-Fen, Chen Kuo-Lin, etc. Fig. 3 c showed that Afsheen Zehra from the Federal Urdu University of Arts in Pakistan had close collaborations with TangLin, YangXiaoe, etc. from Zhejiang University. The top 15 most influential authors were listed in Table 3 by the number of publications. These authors are mainly from China (count = 13), followed by the USA (count = 1), Canada (count = 1). It confirms that China has played a significant role in this field. Farmland phytoremediation research was also influenced by high-yield authors, such as Chen Tongbin from the Chinese Academy of Sciences, who contributed 5 articles from 2018 to 2021. One of the highly-cited articles proposed that misaligned intercropping between over-accumulation crops and low-accumulation cash crops was an ideal planting mode for remediating arsenic contamination in soil (Ma et al., 2018). Followed by Lijin Lin from Sichuan Agricultural University, that proposed that the best Cd hyperaccumulator could be screened out by a new method called artificially high soil Cd concentration, then it could be used for remediating Cd-contaminated cropland (Lin et al., 2014). The productivity and contribution of an author in a certain field is one of the important indicators to measure his influence in this area. The close connections among authors or author groups worldwide indicate that farmland phytoremediation is expanding.

3.3. Co-citation analysis

Co-citation analyzes the organization and representativeness of the literature and disciplines, the research object represents based on the co-citation relationship between literature. This section used CiteSpace to explore the citation relationship of journals and documents in farmland phytoremediation.

3.3.1. Journal co-citation analysis

Journal co-citation analysis can link many journals that may not possess an overtly discernible relationship. Analyzing journal co-citation can identify the core journal, determine the professionalism of the journal, as well as describe the discipline structure related to the journal. The journal is an important carrier for the dissemination of professional knowledge and the presentation of academic achievements. Bibliometrics analysis was used to describe and evaluate the role of journals in academic communication based on some indicators, like impact factor, citation frequency. Therefore, the higher the citation frequency of a journal, the greater its influence in this field, which also shows its strong professionalism (Jia et al., 2019). Establishing a co-citation relationship between two journals is contingent upon including at least one research paper from each journal within the cited articles. The bibliometric network of co-citation for journals is shown in Fig. 4, with a timeline. The size of the node indicates the number of citations for that journal. The more citations a journal receives, the greater its visibility, which is frequently referred to as the core journal, showing that these journals have an important impact in farmland phytoremediation. It can be seen from Fig. 4, Chemosphere, Environmental Pollution, Science of The Total Environment and Journal of Hazardous Materials all have a high citation frequency and a strong co-citation relationship among them. Table 4 lists the 15 journals with the most citations (more than 100) that have been in the spotlight. The analysis of journal co-citation enabled the differentiation of the connection and independence of cited articles published in the respective journals. Furthermore, the disciplines of the journals were examined by utilizing the strengths of the journals. Therefore, whether a journal was in the core or periphery was evaluated, providing valuable insights into their centrality and relevance to cropland phytoremediation.

Fig. 2. Countries and institutions research cooperation network on farmland phytoremediation.

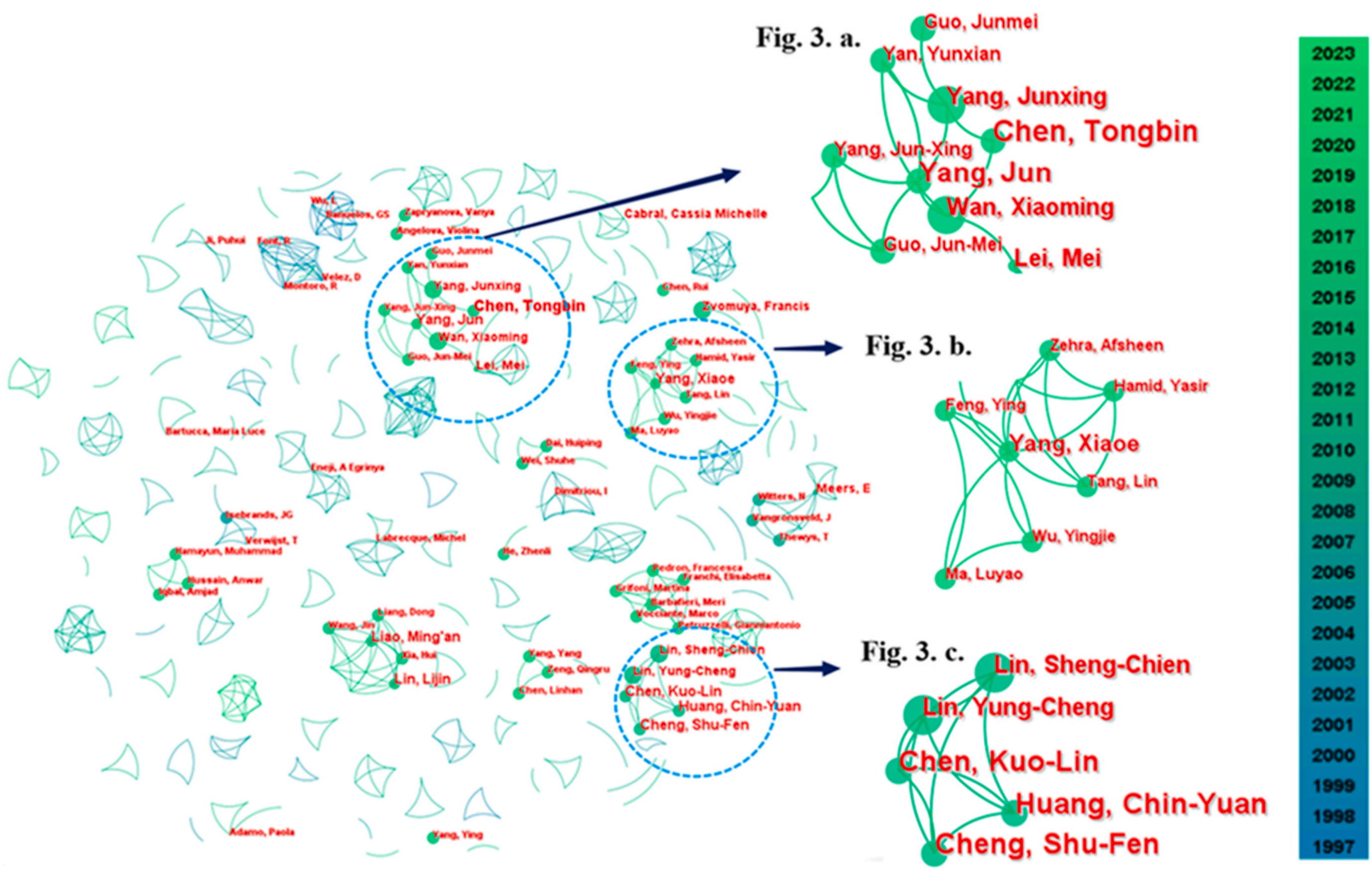

Fig. 3. Visualization map of the author collaborations analysis.

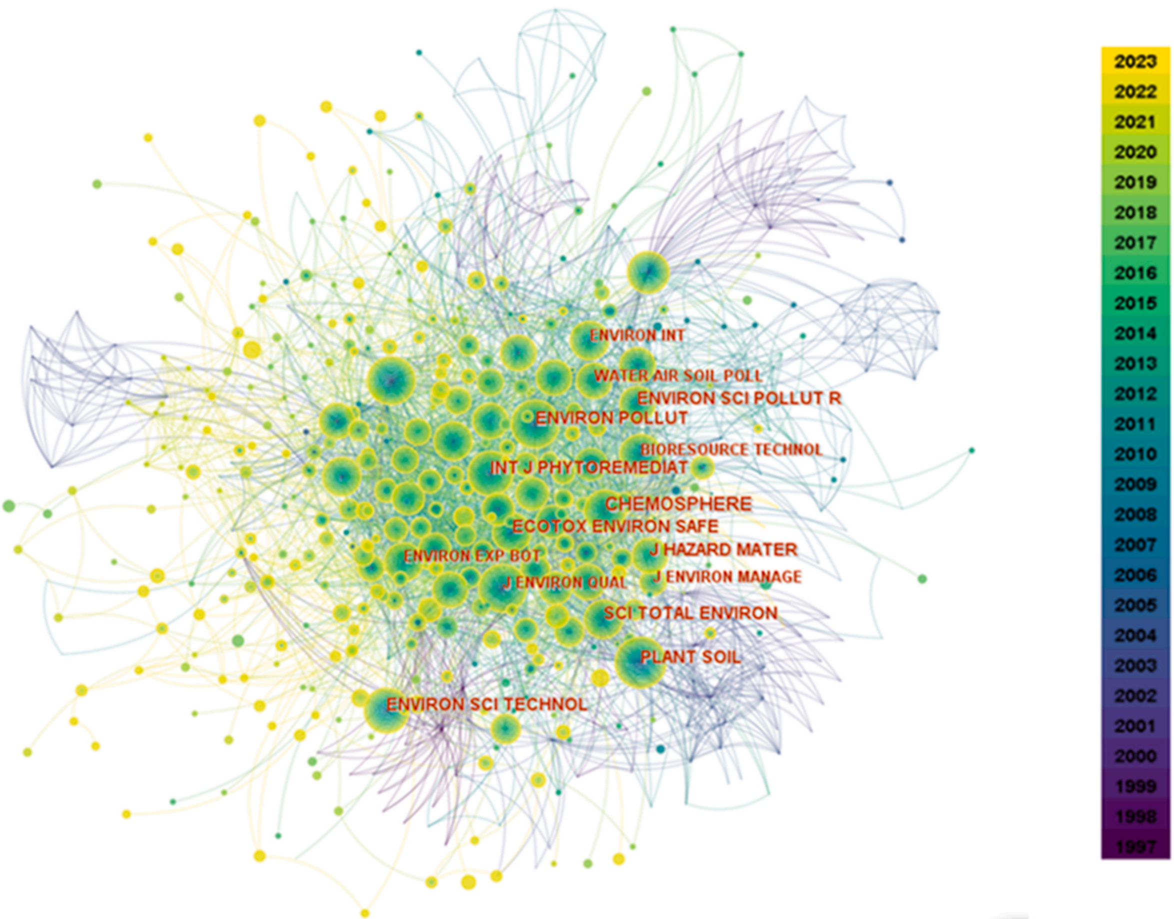

Fig. 4. Visualization picture of the journal co-citation analysis.

Table 4
Top 15 active core journals on farmland phytoremediation study.

Rank	Count	Year	Cited Journal
1	246	2006	Chemosphere
2	227	2004	Environmental Pollution
3	210	2000	Science of The Total Environment
4	187	2011	Journal of Hazardous Materials
5	177	2010	Environmental Science and Pollution Research
6	176	1997	Environmental Science & Technology
7	175	1997	Plant Soil
8	160	2004	The International Journal of Phytoremediation
9	152	1997	Ecotoxicology and Environmental Safety
10	127	2011	Water, Air, & Soil Pollution
11	111	2009	Bioresource Technology
12	103	1997	Journal of Environmental Quality
13	101	2014	Journal of Environmental Management
14	97	2010	Environmental and Experimental Botany
15	94	2006	Environment International

3.3.2. *Document co-citation analysis*

The references are a significant part of domain knowledge, and their quality reflects the overall level of research in the field. The co-citation analysis of documents can effectively determine and guide the direction of development in the research field. As can be seen from Fig. 5, co-cited connections between references can be described through connections between nodes. The greater the size of a node, the more significant the article it corresponds to. The color shades of the relations between the nodes represent the sooner or later connections between the articles. The node label marks the first author and the year of publication. We found 15 publications cited more than 5 times in the co-citation map. The top fifteen most frequently cited references are shown in Table 5. This map illustrated interdisciplinary collaboration, multifaceted research methods and models, and cross-influence in farmland phytoremediation research. Among the 15 most frequently cited documents, 40% of the literature was review articles, including personal views and ideas from multiple perspectives. These reviews summarized phytoremediation techniques and how to improve the efficiency of phytoextraction. Some of these reviews described widespread phytoremediation techniques, including phytostabilization, phytotransformation, phytostimulation, phytofiltration, and phytoextraction (Sarwar et al., 2017). It emphasized that using natural hyperaccumulators and the assistance of chemical chelating agents could improve phytoextraction efficiency (Liu et al., 2018). The results of these reviews through extensive data collection and experimental analysis are reliable and contribute to the accumulation of farmland phytoremediation knowledge base. The remaining articles focused on which plants had specific effects on which metals and some important influencing factors from three aspects: the cultivation of hyperaccumulators, adding amendments, and crop rotation. For example, it was proposed that the cultivation of energy maize played an important role in the removal of Zn and promoted the production of biomass (Meers et al., 2010). And some scholars introduced that adding different types of amendments would either promote the absorption of heavy metals in the soil, such as Cd would increase the yield of crops, such as wheat and rice (Rehman et al., 2017; Rizwan et al., 2018). It proposed three crop rotation methods to remediate soil contaminated with Pb and Cd or co-contaminated soil by Nitrate and Pb (Tang et al., 2017; Yang et al., 2017). Primarily, field trials and pot trials are commonly used experimental methods (Rodriguez et al., 2014). The models presented could be used to predict the relationship between biomass yield and plant metal content, such as exponential decay and

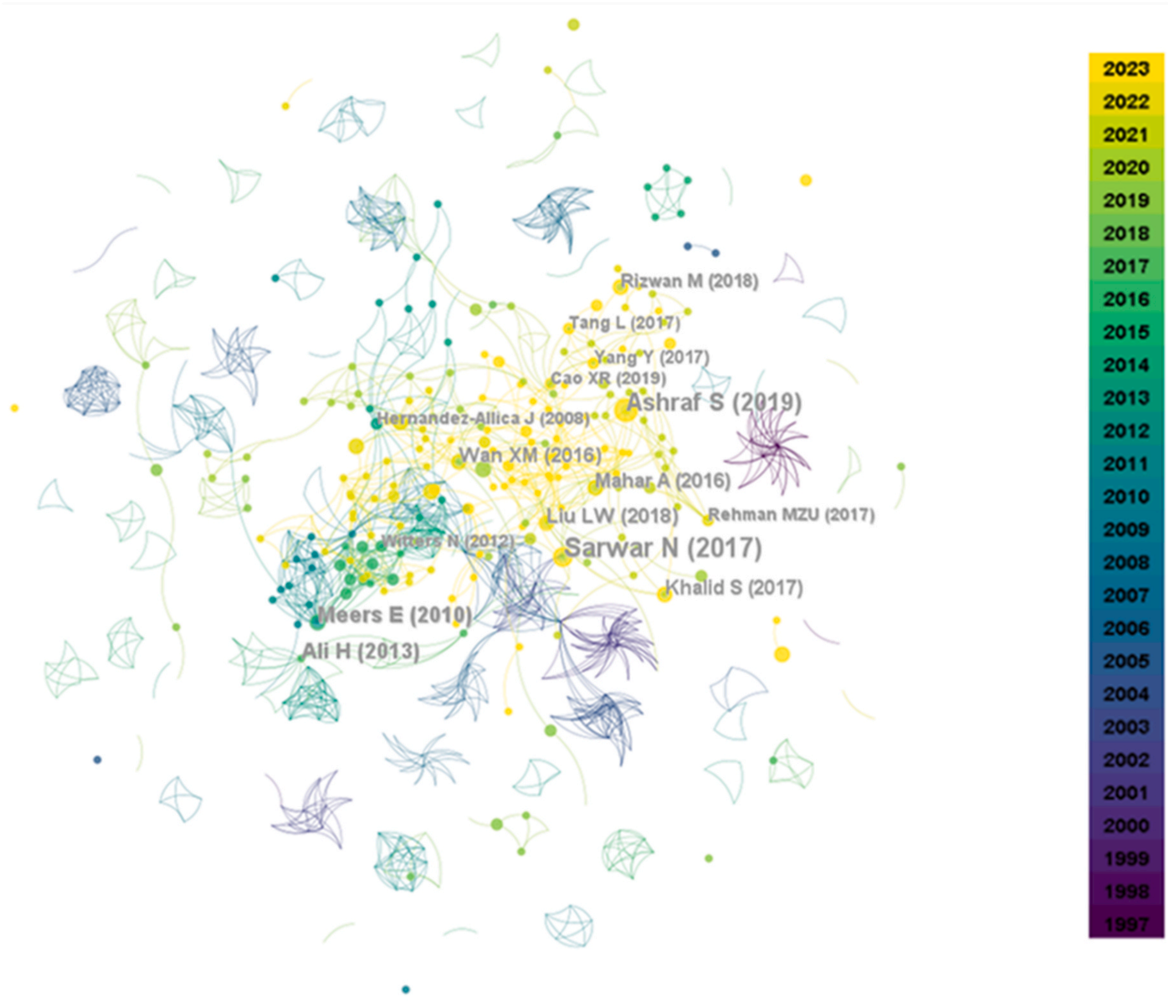

Fig. 5. Visualization of the document co-citation analysis.

Table 5
Top 15 references on farmland phytoremediation-related research.

Rank	Reference	Count	Year	DOI
1	Nadeem Sarwar et al.	16	2017	10.1016/j.chemosphere.2016.12.116
2	Sana Ashraf et al.	13	2019	10.1016/j.ecoenv.2019.02.068
3	Hazrat Ali et al.	10	2013	10.1016/j.chemosphere.2013.01.075
4	E. Meers et al.	9	2010	10.1016/j.chemosphere.2009.08.015
5	Liu Lianwen et al.	8	2018	10.1016/j.scitotenv.2018.03.161
6	Wan Xiaoming et al.	8	2016	10.1016/j.scitotenv.2015.12.080
7	Sana Khalid et al.	7	2017	10.1016/j.gexplo.2016.11.021
8	Amanullah Mahar et al.	7	2016	10.1016/j.ecoenv.2015.12.023
9	Muhammad Rizwan et al.	6	2018	10.1016/j.scitotenv.2018.03.104
10	Yang Yang et al.	6	2017	10.1016/j.chemosphere.2017.08.140
11	Tang Lin et al.	5	2017	10.1007/s11356-017-9146-7
12	N.Witters et al.	5	2012	10.1016/j.biombioe.2011.08.016
13	Javier Hernandez-Allica et al.	5	2008	10.1016/j.envpol.2007.06.002
14	Muhammad Zia ur Rehman et al.	5	2017	10.1016/j.envpol.2017.05.003
15	Cao Xuerui et al.	5	2019	10.1016/j.envpol.2019.05.147

linear models (Chen et al., 2012). Most of the articles (Khalid et al., 2017; Mahar et al., 2016) summarized the current shortcomings of phytoremediation and the future development prospects from economic benefits, agricultural creation, and environmental protection. The co-citation analysis is useful and pertinent for identifying the cited articles and essential documents that constitute the core knowledge system in a particular field.

3.4. Keywords clustering analysis

The keywords are obtained by the authors through the analysis and summary of the entire article, which can highly and concisely summarize the content and research focus. The distribution of keywords is based on their frequency of occurrence. According to the analysis of high-frequency keywords in the keyword co-occurrence map, the evolution and development trend of research hotspots and frontiers in farmland phytoremediation over time can be presented. Clustering keywords allows for a more comprehensive and accurate analysis of high-frequency keywords, given that many of them share certain connections by removing clusters that were not relevant to farmland phytoremediation and preserving clusters with high correlation, we got a total of nine clusters, as shown in Fig. 6. To further explore the order in which keywords appear and how they relate to each other, auxiliary analysis of the timeline map is fundamental, as shown in Fig. 7. Table 4 lists the 15 keywords which have strong explosiveness during 2006–2023, with the burst strength, and the beginning and ending years

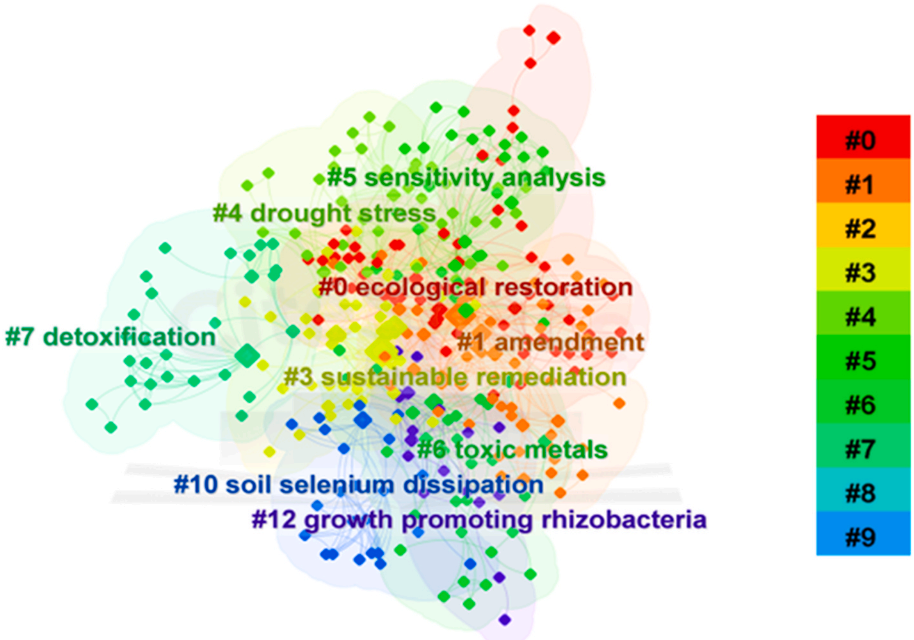

Fig. 6. Research hotspots clusters analysis of keywords.

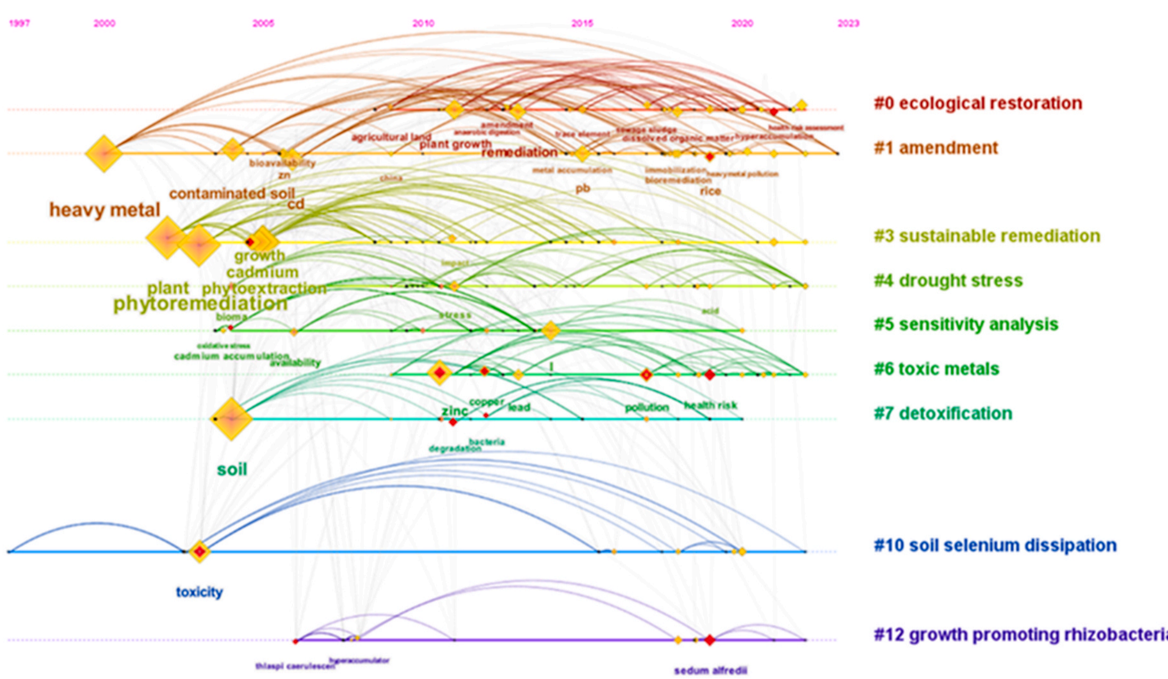

Fig. 7. Timeline visualization analysis of the important keyword clusters.

of keyword burst. It is necessary to use keyword burst detection to detect the frequency of keyword occurrence in a certain period, and the greater the burst intensity, indicating that the keyword is on the rise during that period, as well as showing that numerous related studies have appeared during this time.

3.4.1. Hot research topics

Research hotspots can be mainly divided into these three aspects: mechanisms and principles, restoration efficiency, and sustainable remediation. Then they can be further classified to describe the hotspots in more detail, "mechanisms and principles" includes "#4 drought stress", "# 6 toxic metals", "#7 detoxification" and "# 10 soil selenium dissipation"; "restoration efficiency" includes "#1 amendment" and "#12 growth promoting rhizobacteria"; "economic and ecological aspects" includes "#0 ecological restoration", "#3 sustainable remediation" and "#5 sensitivity analysis". According to Fig. 7 the research hotspots were first concentrated in three clusters, #1 and #10, then developed to #3, #4, #5, and #7, and finally deduced to #0, #6 and #12. In addition, the plot described the time nodes in which significant achievements occurred in each cluster, such as cluster #10 with the most prolonged duration, which spanned from 1997 to 2022. Cluster #6 was also a typical research hotspot with significant milestones between 2011 and 2022.

(1) In its infancy (#1 and #10), the following two types of keywords appeared in farmland phytoremediation research: "amendment" and "soil selenium dissipation".

The application of amendments can enhance the absorption of certain heavy metals or elements in the soil on the one hand and increase the biomass yield on the other hand. The addition of sulfur element increased the accumulation of Cd by hyperaccumulator Sedum plumbizincicola (Fan et al., 2019); Siderophore could mitigate the toxic effects of As on wheat through chelation (Kumari et al., 2019). The impact mechanism of different amendments on biomass is varied. For examples, biochar by improving soil fertility (Zhang et al., 2021a), Polyglycerol polyricinoleate (PGPR), by affecting gene expression in wheat roots (Ou et al., 2022), and N-fertilizers by inhibiting oxidative stress (Tang et al., 2022) could increase plant biomass.

Selenium is a trace element, small amounts are necessary for organisms, while large amounts are toxic. Considering the propensity for soil to accumulate excessive amounts Se within the food chain and as well as the potential contamination of drinking water systems through groundwater (Hasanuzzaman et al., 2020), the practice of phytoremediation has emerged as a viable alternative to accumulate and volatilize Se in the soil. For instance, phytoextraction may be a practical approach to remove Se from the soil (Salinitro et al., 2022). In areas with lower selenium content, hawthorn had more significant effect on selenium extraction (Dalla Vecchia et al., 2023). The identification of a plant species capable of accumulating significant amounts Se, coupled with its possession of abundant genetic resources, used genetic engineering to transform into high-biomass crops which also improved the accumulation, tolerance, and volatilization of selenium in plants to achieve sustainable environmental restoration (Kumar et al., 2022).

(2) In the mid-term phase (#3, #4, #5, and #7), the following four types of keywords appeared in farmland phytoremediation research: "sustainable remediation", "drought dress", "sensitivity analysis" and "detoxification".

Conventional restoration technology is compared to phytoremediation technology in terms of economy, environment, and society. The advantages of phytoremediation technology are low cost, less labor intensity, and no destruction of soil properties (Saxena et al., 2020). Sustainability indicators are mainly determined by the following parameters: (a) ecological parameters, (b) economic parameters, and (c) social parameters. Firstly, it could restore the availability of land and soil nutrients, allowing vegetation and wildlife to grow and survive again. Then diversified cultivation of plant types is more suitable for agricultural practices than monoculture, increasing soil productivity and farmers' incomes, and achieving sustainable agricultural development (Choudhary and Rijhwani, 2020). For example, Chicory-tobacco-peanut rotation not only enhanced the removal efficiency of cadmium but also improved the above-ground biomass and seed quality, bringing economic benefits to farmers (Chen et al., 2022). At the same time, it also brings some industrial benefits: On the one hand, kenaf-S. plumbizincicola rotation could remove many heavy metals, on the other hand, it also provided abundant raw materials for industrial development, including flax spinning industry, paper making industry, food processing industry, and medical industry (Gao et al., 2023a). Crop rotation combining phytoremediation with agricultural production and industrial development is a sustainable restoration strategy. On the one hand, phytoremediation improved the quality of drinking water, reduced food chain pollution, purified indoor air, and enhanced people's living standards (Mahfooz et al., 2020); on the other hand, it also reduced diseases and deaths caused by soil pollution, and protected people's health. Phytoremediation is the main driving force of ecological restoration and farmers' economic production and is listed as the main restoration method by many engineering restoration projects, bringing social benefits. Since phytoremediation meets the above three indicators, phytoremediation is an eco-friendly and sustainable mode of remediating soil pollution (Diarra et al., 2022). The following key findings and approaches have contributed to sustainable phytoremediation: inoculating plants with related microorganisms exhibiting multiple traits, applying genetic engineering in the hyperaccumulator, and combining energy crops with phytoremediation (Saxena et al., 2020).

Drought stress is an unfavorable growth condition that limits plant growth and biomass production by reducing the photosynthetic rate and photochemical efficiency. Researchers have proposed several solutions to protect plants from abiotic stresses, promote plant growth in arid ecosystems, and accelerate the remediation process of heavy metals in contaminated soils. The inoculation treatment of bacteria or strains effectively improved the remediation efficiency of plants, such as the inoculation of AMF (Li et al., 2023), and joint application of PGPR and NPs (Gulzar and Mazumder, 2022), which could improve the remediation potential of certain plants in water-scarce conditions by increasing chlorophyll, carotenoid and reducing antioxidant enzymes. In addition, magnetic field treatment could somewhat alleviate drought stress's adverse effects on plants (Yang et al., 2021). These methods laid the foundation for phytoremediation in arid areas.

To investigate the sustainability of phytoremediation of heavy metal-contaminated soils and whether these plants have the potential to combine agricultural energetics with positive environmental improvements, it is essential to perform sensitivity analysis. For example, sensitivity analysis was used to determine structural parameters of plant phytotoxicity and study mechanisms of plant degradation (Li et al., 2021b). Furthermore, sensitivity analysis of some influencing factors such as plant species and traits, soil properties, metal type, and pollution characteristics, was used to identify the most essential factors that improved the effectiveness of phytoremediation (Zhao et al., 2020). Sensitivity analysis could also be shown through models such as Structural Equation Modeling (SEM) (Mohebian et al., 2022). Sensitivity analysis is a practical approach to assess the remediation potential of a plant and its ability to accumulate certain metals (Wang et al., 2019).

Trace elements are necessary for plants and other organisms, but excessive amounts can have a toxic effect on organisms (Del Buono et al., 2020). Plants have typically evolved biological detoxification mechanisms, such as avoidance or rejection, excretion, and accumulation, to reduce the deleterious effects of heavy metal accumulation and exposure. For example, many plants decrease cadmium toxicity through a series of detoxification mechanisms such as cytoplasmic chelation (Luo and Zhang, 2021). The addition of certain amendments could promote the detoxification of plants on heavy metals, like PASP (polyaspartic acid, it is an amino acid polymer that occurs naturally in the shells of snails and molluscs, and PASP is a biodegradable, environmentally friendly chemical.) as an environmentally friendly chelating agent, which enhanced cadmium uptake by plants by improving the community structure of rhizosphere microorganisms and also increased aboveground biomass (Liu et al., 2023). In addition, in-depth study of the regulating effect of certain functional genes and special proteins could help to understand the metal detoxification effect of plants (Rono et al., 2022).

(3) In recent years (#0, #6, and #12), "ecological restoration", "toxic metals" and "growth promoting rhizobacteria" are the focus of research.

In recent years, the research focus still revolves around the sustainability of phytoremediation, but researchers pay more attention to its ecological effects than the economic benefits of phytoremediation. Plants mainly utilize their metabolism and interactions with microorganisms to restore the ecological environment. In the process of phytoremediation, soil performance would be improved, and the plants would be conducive to CO_2 emission reduction, which could bring significant improvement to the surrounding water quality, atmosphere, and ecological environment (Zhiqiang and Zhibiao, 2020). To further achieve the goal of ecological restoration, some researchers have begun to question the use of certain amendments, arguing that although they could promote the restoration of plants to the environment, they would have adverse effects at high doses, which need to be considered comprehensively (Wei et al., 2021).

Some heavy metals are highly toxic, highly persistent in nature, and can cause adverse effects at low concentrations, which directly manifest as affecting the physicochemical properties of soil, reducing yield and biomass of crops, and even entering the food chain, further causing toxic effects on the human body (Yan et al., 2020). The absorption, transport, and detoxification mechanisms of toxic metals by hyperaccumulating plants have always been research hotspots in this field. Phytoextraction is conducive to the enrichment of metals in the roots, the toxic metal is immobilized in the rhizosphere region through phytostabilisation, the toxic metal is transferred from the root to the ground part through rhizofiltration, and the metal is diffused into the atmosphere during the release process through phytovolatilization finally (Patra et al., 2019). Numerous new technologies, including the addition of chelating agents and biochar, have emerged to remove toxic metals more effectively, economically, and ecologically (Patra et al., 2020).

Considering that specific chelators may have toxic effects on plant and soil microbes, a feasible alternative is to use plant-microbe interactions which can alter the content, state, and bioavailability of metals in soil, improving phytoremediation efficiency. Plant growth-promoting rhizobacteria (PGPR) plays a crucial role in the phytoremediation of heavy metal-contaminated soils, overcoming its singularity and limitations in field application. The effect of PGPR may be manifested by directly affecting plant growth or altering the bioavailability of metals in plants to reduce toxicity. For example, PGPR promotes plant growth by synthesizing a variety of plant hormones and certain specific enzymes to induce a series of biochemical processes in plants (Ou et al., 2022). In addition, since PGPR had resistance to certain metals, it developed a series of mechanisms through which it can immobilize, move, or convert heavy metals (Narayanan et al., 2022). The application of PGPR will still be a research hotspot in the future, and it will bring significant benefits to phytoremediation.

3.4.2. Research frontiers

From 1997 to 2023, the top 15 keywords with strong bursts are listed in Fig. 8, which CiteSpace's burst detection recognizes. These keywords represented fast-growing topics in the farmland phytoremediation research domain. "Strength", the third column in Fig. 8, describes the degree to which a subject is studied. The greater the intensity, the more frequently the corresponding keyword appears, indicating that it will be cited more times in a period. "Year", the second column in Fig. 8, indicates when the keyword first emerges. "Begin" and "End" represent the start and end times of the keyword outbreak, respectively. In the last column, the blue stripe shows the time interval from the year the keyword first appears to 2023, and the red stripe indicates the period when the keyword is detected to have an outbreak and gains the most intense attention. These burst keywords reflect the research frontier of farmland phytoremediation to analyze the rise or decline of a discipline.

It can be seen from Fig. 8, "hyperaccumulation", "sedum alfredii" and "health risk" are research frontiers at this stage and in the future.

(1) Hyperaccumulator is the core of phytoremediation, which has the ability to accumulate exceptionally high concentrations of metals in its shoots. Presently, scientists are conducting intensive research on the plants with the highest hyperaccumulation capacity for a particular metal. Further exploration of the relationship between hyperaccumulation and metal tolerance is essential for implementing biofortification and phytoremediation techniques. However, due to the small size, slow growth, and low biomass production of some metal hyperaccumulators, effective agricultural practices are seriously limited, and the efficiency of phytoremediation is affected, so the search for plants with high biomass and strong ability to accumulate metals has become the frontier of research (Yuan et al., 2019). Changing the planting pattern of hyperaccumulators like determining the most suitable planting pattern (two harvests one year at the flowering phase) for Solanum nigrum L (Dou et al., 2022) and interplanting

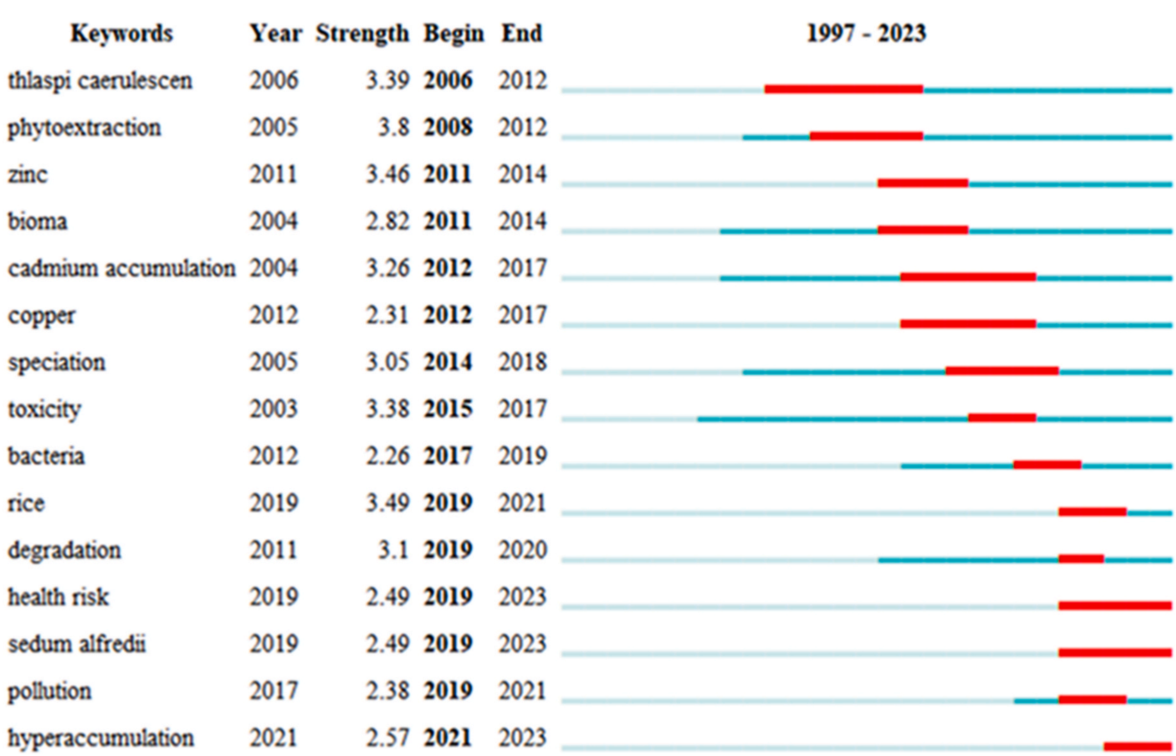

Fig. 8. Top 15 keywords with the strongest citation bursts.

hyperaccumulators with fruit trees like P. vittata- C. reticulata interplanting (Yan et al., 2022), which had positive effects on phytoremediation. These field experiments provide a reliable scientific basis and reference value for the practical application of phytoremediation, and some of them can be directly applied to practical agricultural production. In particular, some plants can be used as ideal biomass energy materials, such as sweet sorghum, miscanthus, poplar, etc., their application simultaneously realizes heavy metal contaminated soil remediation, resource treatment of later materials, and the generation of biomass diesel, which has great application potential (Xiao et al., 2022, 2023). In addition, in order to further improve the efficiency of phytoremediation, researchers began to use the acquisition of foreign substances, genetic breeding, hybridization technology, genetic engineering, and the comprehensive use of a variety of restoration technologies (Odoh et al., 2019). For example, poplar and willow hybrids not only improve tree survival but also facilitate phytoremediation (Simmer and Schnoor, 2022); there are twice as many chromosomes of genes related to kenaf fiber development because of the duplication of the genome, such as the cellulose synthase A gene, which contributes to the genetic improvement of fiber crops and accelerates breeding (Zhang et al., 2020a); some new techniques like in situ editing by the CRISPR/Cas9 gene, haploid induction, and gene silencing technology, can improve phytoremediation ability and enhance plants' ability to cope with HM stress (Kumar et al., 2022). Among them, understanding the genetic basis of heavy metal hyperaccumulation to achieve the development of genetically modified organisms is still in the primary stage and has always been an important goal of scholars' research.

(2) As a Zn and Cd hyperaccumulator, sedum alfredii has the advantages of rapid growth, easy reproduction, convenient mechanized harvesting, and multi-metal absorption characteristics (Wu et al., 2022). Most of the heavy metal remediation research of sedum alfredii is still in the stage of pot and field trials, and a set of agronomic management measures for large-scale commercial application is required from technology to practical application, so the strengthening of systematic field experimental research in this area has become the research frontier. The use of some amendments can improve the rhizosphere environment of sedum alfredii, which is conducive to the reproduction of microorganisms, and the growth of plants, and enhances its ability to accumulate metals (Dou et al., 2019). Therefore, the search for amendments that can maximize the remediation potential of sedum alfredii has become the goal of scholars. In addition, the most suitable cultivation method can be found by comparing the economic benefits of monocropping or rotation with other plants (Zhang et al., 2021b).

(3) Toxic heavy metals that penetrate the soil pose a range of health risks. The first is the risk of contamination in the food chain, some toxic metals may metastasize and accumulate in animals or humans through the food chain, which may cause DNA damage, and pathogenic or carcinogenic effects due to genetic mutations, greatly increasing health risks (Muro-González et al., 2020). The second is the risk of groundwater contamination, toxic heavy metals can penetrate from the soil into groundwater which is a source of drinking and domestic water, and further harm humans (Shikha and Singh, 2021). There are also many risks in the process of phytoremediation. Firstly, phytoremediation takes a long time to remediate contaminated farmland, during which the remediation efficiency may be reduced, and the restoration effect is not satisfactory, which is a remediation risk that currently exists. Then the risk of using amendments, because the low biodegradability and high environmental risk of some chelating agents can limit their application. Such as glutamic acid (GLDA) would lead Cd and Pb contamination in groundwater due to heavy rainfall and cause leaching risk during the phytoremediation (Liu et al., 2022). So the search for high-quality, low-risk amendments has been the research frontier in this field. To reduce these risks, many researchers try their best to get along with the most appropriate solutions.

4. Conclusions and prospects

This study uses scientific analysis, bibliometric search, and qualitative analysis to analyze the documents published in the farmland phytoremediation field in the past three decades. According to a bibliometric search, 368 articles published in the farmland phytoremediation domain from 1997 to 2023 were selected as literature analysis samples, and the trend of documents in the past three decades was obtained. Based on the scientific analysis, the following conclusions were shown:

(1) China, the United States, and India have made substantial contributions to the research community and maintain robust connections with one another. The majority of institutions that have made outstanding contributions to this field are in China; with Chinese Acad Sci, having the most publications. Chen Tongbin from China contributed the most articles. Chemosphere, Environmental Pollution, Science of The Total Environment ranked as the most influential journals.
(2) The top 15 citations with the highest frequency of citations were analyzed in terms of the accumulation potential of plants, the use of amendments, and planting and cultivation methods.
(3) In the cluster analysis of keywords, "amendment", "soil selenium dissipation", "sustainable remediation", "drought dress", "sensitivity analysis", "detoxification", "ecological restoration", "toxic metals" and "growth promoting rhizobacteria" are determined as research hotspots in this field. "hyperaccumulation", "sedum alfredii" and "health risk" were selected as research frontiers at this stage and in the future through the burst detection of keywords.

Based on qualitative analysis, the mainstream disciplines, research topics, and contents of farmland phytoremediation are summarized, the existing gaps and shortcomings are discussed, and future research directions are proposed.

The shortcomings include: (1) the application of phytoremediation technology is often restricted in practice, because most hyperaccumulators are regionally selective and their remediation period is long. (2) the restoration of some plants is single, remediate only for one contaminant; (3) the subsequent processing of phytoremediation is also necessary, otherwise the aboveground parts will return to the soil after withering; (4) phytoremediation can only be applied to shallow soil, and it is not suitable for areas with high pollutant concentration.

This comprehensive review provides a framework and direction for recent research and proposes some urgent challenges in the field of farmland phytoremediation, including:

(1) Consider the screening and cultivation of hyperaccumulating plants: It is essential to screen and cultivate plants with strong absorption capacity, which can accumulate a variety of heavy metal elements at the same time and have large biomass and short remediation cycle.
(2) Some chemicals applied to the soil have the risk of leaching and percolation, which may cause groundwater pollution. Develop some chemical reagents that are conducive to the enrichment of heavy metals in plants and have little risk of environmental pollution. It is conducive to the sustainable development of farmland phytoremediation.
(3) Focus on the applications of molecular biology and genetic engineering techniques: The hyperaccumulating plant genes and

microbial genes cultivated will be introduced into plants with large biomass, fast growth rate, and strong adaptability to improve the practicality of phytoremediation.

(4) Give careful consideration to the research on integrated bioremediation technology: traditional phytoremediation techniques, the addition of some chelating agents and amendments, the inoculation of specific microorganisms, the application of genetic engineering, rational agricultural techniques such as rational irrigation and optimal cultivation, etc. These measures improve the quality of the soil, increase the bioavailability of heavy metals in the soil, improve the tolerance and accumulation of heavy metals in plants, and are conducive to phytoremediation.

CRediT authorship contribution statement

Chaoqun Wang: Conceptualization, Data curation, Formal analysis, Writing - original draft. **Lirong Deng:** Data curation, Software, Visualization, Writing - original draft. **Yongxiang Zhang:** Investigation, Methodology. **Mingtao Zhao:** Methodology, Supervision. **Meiqi Liang:** Investigation, Validation. **Lien-Chieh Lee:** Supervision, Writing - review & editing. **Chicaiza-Ortiz Cristhian:** Validation, Writing - review & editing. **Long Yang:** Supervision, Writing - review & editing. **Tonghui He:** Funding acquisition, Project administration, Resources.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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