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Review

Application of Multi-Plant Symbiotic Systems in Phytoremediation: A Bibliometric Review

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Abstract: The bibliometric analysis technique was used to retrieve 232 relevant publications from the Web of Science core database published between 2002 and 2022. The basic characteristics of the literature were analyzed, and keyword co-occurrence analysis and literature co-citation analysis were performed. The results demonstrated the following: (1) The total number of publications on phytoremediation utilizing a multi-plant symbiosis system increased year by year, indicating that multi-plant symbiosis systems have garnered significant interest in the field of phytoremediation in recent years. (2) “Short rotation coppice” (#0), “straw” (#1), “heavy metal” (#2), “soil enzymes” (#3), “glomus caledonium” (#4), and “phenanthrene” (#5) comprise the research hotspots in this field both domestically and internationally, where the #0 clusters, #2 clusters, and #5 clusters indicate that the application of multi-plant combinations has not formed a new branch in the field of phytoremediation during 2007–2017. In addition, the #1 clusters, #3 clusters, and #4 clusters indicate that the safety of agricultural land, the mechanism of action of soil enzymes, and arbuscular mycorrhizal fungi comprise research hotspots in recent years. (3) “Heavy metal contamination” (#0), “agro-mining” (#1), “Leguminosae” (#2), “soil enzymes” (#3), “soil microbial community” (#4), and “*Salix caprea*” (#5) constitute the domestic and international knowledge base of this field, with a study of soil microbial communities regarded as the cutting-edge branch of this field. (4) The specific influencing factors of multi-plant symbiotic systems include plant diversity, interspecific relationships, and the gender of plant species, and the mechanisms of action include the plant–soil feedback mechanism, enhanced plant resistance mechanism, increased detoxification pathway, and plant–plant interaction mechanism. Finally, future research on phytoremediation using multi-plant symbiotic systems should focus on the following four aspects: exploring the applicable environment of multi-plant symbiotic systems as a remediation strategy; analyzing the remediation mechanism from multiple perspectives: atmosphere–plant–soil; combining physicochemical and biological technologies to improve remediation efficiency; and establishing a dynamic model to evaluate remediation effects.

Keywords: multi-plant symbiotic systems; phytoremediation; cite space; bibliometrics

1. Introduction

Phytoremediation is a bioremediation technique that employs green plants to transfer, absorb, or transform harmful pollutants into harmless byproducts. The remediation targets typically include heavy metals, organic matter, atmospheric pollutants, elements of radioactive objects, and microelements. Phytoremediation is inexpensive, produces little waste, and is not easily capable of causing “secondary pollution” [1]. However, there are still numerous aspects of this technology that could be improved, such as its lengthy remediation cycle, small biomass, and limited application sites [2,3]. Thus, how to improve the efficiency of phytoremediation and minimize the negative impact of environmental pollutants on the ecosystem and human health in a sustainable way is an urgent problem to be solved [4].

Phytoremediation techniques primarily include phytodegradation (phytotransformation), phytostabilization (phytoimmobilization), phytovolatilization, phytoextraction, phytofiltration, and phytostimulation [5]. External factors such as the level of pollution, soil physicochemical properties, bioavailability of pollutants, and planting density [6] and internal factors such as the growth and life cycle of plants, photosynthesis, respiration, root uptake capacity, and the ability of plants and their associated microorganisms to intercept, absorb, accumulate, and degrade pollutants [7,8] influence phytoremediation efficiency. Due to the limited remediation capacity of individual plant species, increasing plant species diversity can enhance pollutant removal [9–11] and positively influence plant resistance [12] and water use efficiency [13]. However, research findings on the response of multi-plant symbiotic systems to polluted environments and phytoremediation mechanisms appear to be scattered, and relevant studies that provide a unified conclusion are largely limited. For instance, Brisson et al. [14] discovered that wetland plant communities were not superior to monocultures for pollutant removal and that plant–plant complementarity was insignificant in highly productive, nutrient-rich wetlands.

Plant–plant interactions (such as facilitation [15], competition [16], nurse effect [17], and allelopathy [18]) play a crucial role in the response of plant communities to environmental changes [19]. Multi-plant systems in ecosystems frequently have different ecological niche requirements and nutrient uptake pathways, and different plant assemblages in polluted environments can enhance phytocoenosium by forming a number of complementary mechanisms to improve ecosystem services such as biomass, productivity, soil organic carbon content, and soil fertility [20–22]. However, the results of current research on the restoration of multi-plant assemblages are inconsistent, which may be attributable to plant life type (trees, shrubs, herbs), plant growth and development period (seedlings, adult plants), research methods (field trials, controlled trials), and research period.

Although many review articles on phytoremediation research have been published [23–25], most of these reviews have focused on the research progress of phytoremediation in different polluted environments, and studies focusing on the positive effects of multi-plant systems on phytoremediation have not yet been conducted. Thus, to clarify the intrinsic connections between various plant combinations, this study uses the information visualization and analysis software Cite Space (6.1.R6) [26], based on the core database of Web of Science (WoS), to conduct a bibliometric analysis of the relevant literature, in order to obtain the knowledge base, latest advances, and cutting-edge hotspots for the application of multi-plant systems in the field of phytoremediation, and then to explore the restoration mechanisms of different plant species combinations and future research trends. This study explores the phytoremediation strategy from the perspective of multi-plant assemblages, which can help to improve the diversity and stability of ecosystems in restored sites, and at the same time, enhance the richness of landscapes so as to satisfy people's aesthetic needs, and the conclusions of this study have practical application value.

2. Data and Methodology

2.1. Data Sources

In this study, the Social Sciences Citation Index (SSCI) database and the Science Citation Index Expanded (SCI-E) database in the Web of Science (WoS) core database were used. These databases were searched on 4 February 2023, and the search period was from the time of construction to 31 December 2022. The retrieval formula of this subject was TS = (Phytoremediation OR Phytodegradation OR Phytotransformation OR Phytostabilization OR Phytoimmobilization OR Phytovolatalization OR Phytoextraction OR Phytofiltration OR Phytostimulation) AND (Plant species mix OR plant diversity OR Plant–plant interaction OR plant combinations OR phytocoenosium OR plant configuration

OR intercrop OR mixed culture OR mixed cropping). The search objects are the title, abstract, and keywords of the literature. The first literature study on the application of multi-plant symbiotic systems in phytoremediation was published in 2002. Literature types include “Article, Review, Proceedings Paper and Early Access”, and a total of 2311 kinds of literature have been retrieved. After determining whether the title and abstract contained both phytoremediation and phytoassembly-related keywords, the 2311 kinds of literature were manually re-screened and introduced into Cite Space (6.1.R6) to remove duplicate references, and 232 papers were finally obtained [26].

2.2. Analysis Methodology

In this study, Cite Space (6.1.R6) software was first used to analyze the characteristics of literature countries, institutions, authors, subject categories, and journals to identify the countries, institutions, and authors with the most influence in this field in order to form a preliminary understanding of the application of multi-plant symbiotic systems in the field of phytoremediation [26]. Subsequently, keyword co-occurrence analysis and clustering were performed to identify research hotspots. Literature co-citation analysis was also performed, in which citation frequency (CF) and betweenness centrality (BC) are commonly used indicators of the importance of nodes, which can reflect the importance of a single document in a field. High values of both CF and BC indicate that they have a critical impact on the development of the field. Therefore, identifying the cited literature with the highest CF $\times$ BC value can help to explore the theoretical foundations and research frontiers [23,27]. The specific operations are as follows: the time interval is set to 1 year; the node type is then selected as a keyword or cited literature; subsequently, the threshold is set to TOP 50, which extracts the top 50 nodes with the highest co-occurrence frequency or citations; the results of the analysis are then clipped and combined using the Path Finder algorithm, and the log-likelihood ratio algorithm (LLR) is applied to the cluster analysis [28].

3. Research Results

3.1. Annual Changes in the Number of Articles Published and the Main Countries Studied

The annual distribution of publications on phytoremediation by multi-plant symbiotic systems from 2002 to 2022 is displayed in Figure 1. Although phytoremediation techniques were first proposed in the 1990s [1], studies incorporating multi-plant symbiotic systems started to be published at the beginning of the 21st century. In 2017 and before, plant–plant interactions accounted for 63.36% of all publications in the field of phytoremediation, indicating that they have garnered a great deal of interest in recent years. Relevant research results are distributed primarily in China, France, the United States, Spain, and other nations.

3.2. Publication Characteristics Analysis

The statistical analysis of the top 10 countries, research institutions, disciplinary categories, journal sources, and authors (Table 1) revealed that China, which had the most publications, ranked first with 138 publications, representing 59.48% of the total number of publications. With 21 (9.05%), 20 (8.60%), 14 (6.03%), and 11 (4.74%) articles, France, the United States, Spain, and Italy ranked second through fifth, respectively. Among domestic and international research institutions, the Chinese Academy of Sciences (CAS) published the most articles with 33 (14.22%), followed by the French National Institute of Agri-Food and Environment [17 (7.33%)] and the University of the Chinese Academy of Sciences [16 (6.90%)]. The relevant studies were primarily concentrated in the fields of environmental science [176 (75.86%)], soil science [32 (13.79%)], environmental engineering [24 (10.35%)], botany [19 (8.19%)], and ecology [18 (7.76%)], suggesting that phytoremediation of multi-plant assemblage systems received attention from multiple disciplines. The related research source journals focus primarily on environmental science and ecology, such as the International Journal of Phytoremediation [26 (11.21%)], Environmental Science and Pollution Research [22 (9.48%)], and Science of the Total Environment [22 (9.48%)].

Accordingly, the authors with a high publication contribution rate include Lin L.J., Li H.S., Tang Y., Wang J., and Wang X.

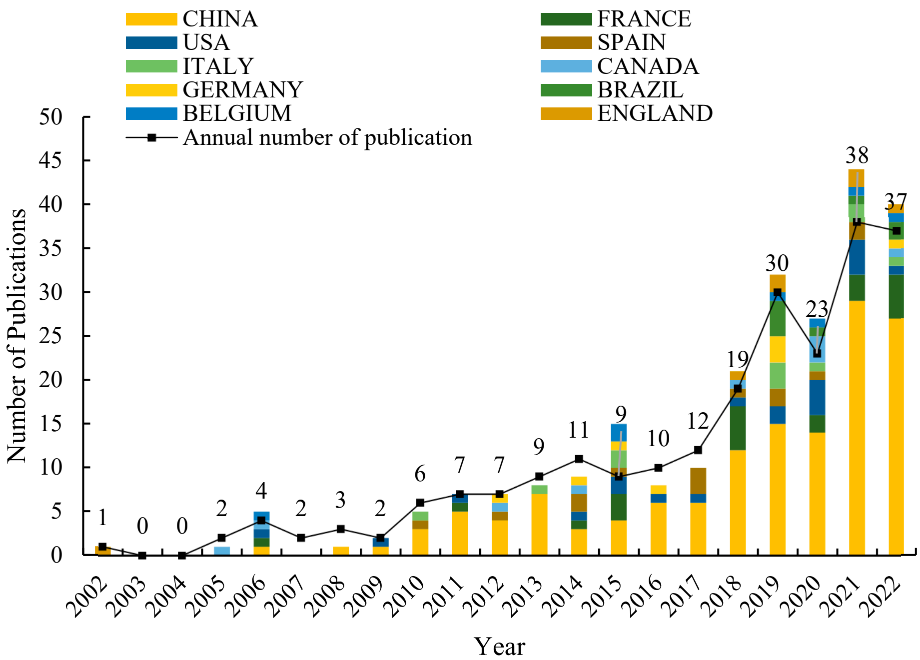

Figure 1. Annual change of publication volume and contribution rate of top 10 countries.

Table 1. The top 10 countries, institutions, categories, journals, and authors.

Rank	Country	Institution	Category	Journal Source	Author
1	China (138, 59.48%)	Chinese Academy of Sciences (33, 14.22%)	Environmental Sciences (176, 75.86%)	International Journal of Phytoremediation (26, 11.21%)	Lin LJ (12, 5.17%)
2	France (21, 9.05%)	Inrae (17, 7.33%)	Soil Science (32, 13.79%)	Environmental Science and Pollution Research (22, 9.48%)	Li HS (8, 3.45%)
3	USA (20, 8.62%)	University of Chinese Academy of Sciences Cas (16, 6.90%)	Engineering Environmental (24, 10.35%)	Science of the Total Environment (22, 9.48%)	Tang Y (8, 3.45%)
4	Spain (14, 6.03%)	Sichuan Agricultural University (15, 6.47%)	Plant Sciences (19, 8.19%)	Chemosphere (18, 7.76%)	Wang J (8, 3.45%)
5	Italy (11, 4.74%)	South China Agricultural University (14, 6.03%)	Ecology (18, 7.76%)	Environmental Pollution (9, 3.88%)	Wang X (8, 3.45%)
6	Canada (9, 3.88%)	Institute of Soil Science Cas (13, 5.60%)	Agronomy (13, 5.60%)	Journal of Soils and Sediments (9, 3.88%)	Christie P (7, 3.02%)
7	Germany (8, 3.45%)	Zhejiang University (13, 5.60%)	Toxicology (12, 5.17%)	Ecotoxicology and Environmental Safety (8, 3.45%)	Liang D (7, 3.02%)
8	Brazil (8, 3.45%)	Institute of Geographic Sciences Natural Resources Research Cas (12, 5.17%)	Water Resources (8, 3.45%)	Journal of Hazardous Materials (7, 3.02%)	Liao MA (7, 3.02%)

Table 1. *Cont.*

Rank	Country	Institution	Category	Journal Source	Author
9	Belgium (7, 3.02%)	Ministry of Agriculture Rural Affairs (11, 4.74%)	Meteorology Atmospheric Sciences (6, 2.59%)	Plant and Soil (7, 3.02%)	Luo J (7, 3.02%)
10	England (7, 3.02%)	Universite de Lorraine (10, 4.31%)	Green Sustainable Science Technology (5, 2.16%)	Ecological Engineering (6, 2.59%)	Luo YM (7, 3.02%)

Note: The numbers in parentheses represent the number of studies and the percentage of all studies.

3.3. Keyword Co-Occurrence Network and Clustering Analysis

Keyword co-occurrence analysis refers to the constant discovery of the same keywords from a large number of articles in a certain field, and the frequency of keyword co-occurrence, as a refined expression of academic research topics, is positively correlated with research heat. Moreover, cluster analysis generates the structure of connections between keywords based on keyword co-occurrence, which can, to some extent, reflects the research hotness direction of the field [28]. In the keyword co-occurrence cluster analysis atlas, Modularity (Q value) and Silhouette (S value) are the indicators for judging the effectiveness of the atlas. It is generally believed that $Q > 0.3$ and $S > 0.7$ indicate that the homogeneity of the graphs is high and the clustering results are significant and credible. According to the results of the clustering analysis, the Q value is 0.5952 (>0.3), and the S value is 0.8121 (>0.7), indicating that the clustering effect is significant and the keyword classification is reasonable [29]. As shown in Figure 2, the mapping consists of 395 keyword nodes and 1600 connecting lines, in which the node size indicates the level of keyword co-occurrence frequency; a larger node indicates a higher keyword co-occurrence frequency and the connection line indicates the co-occurrence relationship between keywords. Moreover, a node surrounded by a purple outer ring indicates that it has a higher BC value ($\geq$0.1), indicating the significance and high representativeness of the node during a particular time period in the subject area [30]. In addition to "phytoremediation (0.22)" and "phytoextraction (0.13)", other popular search terms for multi-plant assemblage restoration research include "accumulation (0.29)", "heavy metal (0.26)", "contaminated soil (0.22)", "cadmium (0.18)", "rhizosphere (0.16)", "growth (0.14)", "community (0.11)", and "remediation (0.10)".

The clustering of keywords was divided into six categories (Table 2): "short rotation coppice" (#0), "straw" (#1), "heavy metal" (#2), "soil enzymes" (#3), "glomus caledonium" (#4), and "phenanthrene" (#5). As shown in Table 2, the cluster size indicates the number of keywords contained in that cluster, and the size of the profile value reflects the density and degree of association of the nodes in that cluster [31]. Additionally, high-frequency keywords are displayed only for the top five co-occurrence frequency ranked subject terms, and keywords with a centrality greater than 0.1 are indicated. To clarify the research hotspots in the field, we will now examine these clusters in depth:

Table 2. Keywords high-frequency subject word information table in co-occurrence network.

Cluster	Size	Silhouette	Top Team (LLR)
#0 short rotation coppice	63	0.67	Remediation (0.1), *Pteris vittata* L., cadmium accumulation, microbial community, organic acid
#1 straw	50	0.73	Phytoremediation (0.22), Cd (0.13), Zn, maize, heavy metal pollution
#2 heavy metal	44	0.81	Phytoextraction (0.13), soil, cadmium (0.18), zinc, lead
#3 soil enzymes	41	0.83	heavy metal (0.26), biodiversity, enzyme activity, water

Table 2. *Cont.*

Cluster	Size	Silhouette	Top Team (LLR)
#4 glomus caledonium	38	0.83	Accumulation (0.29), plant, *Sedum alfredii*, Pb, Cu
#5 phenanthrene	37	0.93	Rhizosphere (0.16), degradation, bioremediation, polycyclic aromatic hydrocarbon, biodegradation

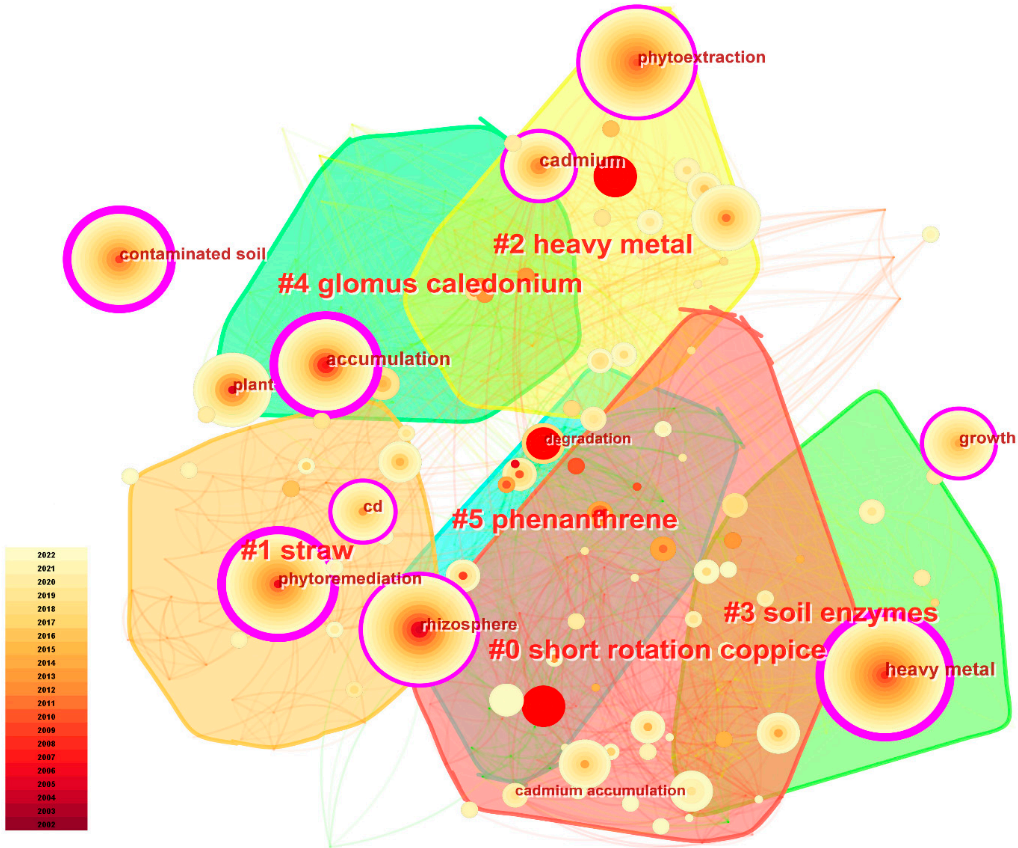

Figure 2. Cluster map of keywords co-occurrence.

#0 short rotation coppice: The #0 cluster investigates short rotation crop (SRC), intercrop, and mixed crop systems for the remediation of soil, water, and air polluted environments. Moreover, studies have demonstrated that multi-plant symbiotic systems can alter phytoremediation processes (e.g., phytoextraction, phytostabilization) [2] by influencing plant root exudates, microbial communities, soil enzyme activities, and soil pH (these have positive effects on phytoremediation efficiency), in addition to plant biomass, plant productivity, and plant resistance. Furthermore, other ecosystem services (e.g., increasing the biodiversity above and below ground, improving surface water and groundwater quality, carbon storage, mitigation of greenhouse gas emissions) are enhanced while also ensuring the provision of bioenergy feedstock (e.g., lignocellulose, starch, sugars) [32]. As shown in Table 2, the remediation targets of different types of multi-plant symbiotic systems were mainly dominated by heavy metals (Cd), and Li et al. [33] demonstrated that Cd-contaminated agricultural soil surfaces accounted for 16.67% of the total area of agricultural land in China, which led to a decrease in the quality and quantity of agricultural products such as rice and vegetables, and posed a serious threat to the health and economic income of the population. In the study of remediation mechanisms, the primary focus is on the role of microbial communities because the plant above the ground and the microbial communities below the ground are closely related. Additionally, plants can provide carbon (C) and other nutrients to the soil microbial community in the form of litter and root exudates (e.g., organic acids [34]), whereas the microbial community below the ground can decompose soil organic matter (SOM), stabilize soil structure, and by its role in the elemental cycle, release nutrients needed for plant growth, thereby influencing the vegetation structure [35]. Among the species used for multi-plant assemblage restoration, *Pteris vittata* has attracted widespread attention. Ma et al. [36] found as early as 2001 that *Pteris vittata* could efficiently extract arsenic (As) from soil and transfer it to biomass above the soil surface. Correspondingly, it was the first known plant for arsenic hyper-accumulation, and both domestic and international scholars focused on its association with agricultural crops [37,38], fruit trees [39], woody garden plants [40,41], and other intercropping phytoremediation effects.

#1 straw: The #1 cluster focuses on the phytoremediation of heavy metal-contaminated agricultural land. The remediation of contaminated agricultural soils is necessary to prevent the transfer of potentially toxic heavy metals through the food chain [6]. *Zea mays* is a globally significant crop with a high yield potential; consequently, it has attracted considerable interest in the remediation of heavy metal-contaminated soils by multi-plant symbiotic systems [42]. Although numerous studies have shown that intercropping with hyperaccumulator plants can increase *Zea mays* yield [43], studies demonstrating the opposite results have also been published. The underlying reason may be attributed to nutrient competition between species; thus, it must be considered comprehensively to eliminate unfavorable factors (e.g., screening for suitable intercropping species, adjusting planting density) according to the environment when applied in practice [16]. Straw incorporation is a common management practice in agricultural production. Straw is a precursor for the preparation of biochar, and its decomposition produces allelochemicals that can change the rhizospheric environment, reduce heavy metal elements in soil, as well as accumulate heavy metals in plant parts above the soil surface, thereby influencing plant growth [44]. Intercropping systems combined with management measures such as straw incorporation or biochar application are currently one of the research hotspots in the field of multi-plant combination remediation [2,45,46], where different plant species and different parts of the same plant straw can have varying effects. For instance, Huang et al. [2] discovered that the root straw of *Myriophyllum aquaticum* increased the biomass of *Nasturtium officinale*, whereas its biomass decreased after the application of straw from its stem and leaves.

#2 heavy metal: The #2 cluster addresses this area of research in remediation technologies for environments contaminated with heavy metals and illustrates the key components of multi-plant systems for remediation in environments contaminated with heavy metals. With the growth of industrialization and the disruption of biogeochemical cycles, the problem of heavy metal pollution has increased in severity. Moreover, heavy metals are typically non-degradable and toxic, and they can accumulate in soil and water, migrate, and enrich the food chain, posing a significant threat to ecosystems, human health, and food security [24]. Phytoextraction is the most important remediation technique for removing or reducing heavy metals and metalloids from the soil, water bodies, or sediments, primarily by enriching or hyper-enriching heavy metals in the biomass of plants above the ground, which are then harvested and disposed of in a particular manner [47,48]. Accordingly, Chaney et al. [1] suggested that hyper-accumulative or hyper-tolerant plants are more economically efficient than high biomass plants for phytoextraction. This is because hyperaccumulator plants are more efficiently extracted, and their biomass is usually smaller, making them easier to harvest after phytoremediation [25]. Thus, in order to improve the phytoextraction efficiency of multi-plant systems, researchers from both the United States and abroad have currently focused on plant species [49,50], chemical additives [42,51], microbial inoculation [52], and planting density [6,53]. Cadmium (Cd) and lead (Pb) elements are non-essential for humans and plants and are among the most toxic heavy metals [54]; additionally, although zinc (Zn) is an essential micronutrient for plant growth, excessive amounts can damage plant roots and slow their growth [55].

#3 soil enzymes: The #3 cluster is concerned with the soil enzyme activity response of multi-plant combination systems in remediating soil contamination. Assessment of phytoextraction should consider not only the rate of pollutant removal but also the remediation of soil health [56], a dynamic and complex functional structure that cannot be directly measured but can be quantified using soil quality indicators [57]. Soil enzyme activity plays an important role in soil nutrient cycling, accumulation, and decomposition, providing sufficient nitrogen (N) and phosphorus (P) for plant growth and development, primarily in the form of extracellular enzymes. Additionally, it is influenced by heavy metal content, plant species, plant species assemblage, soil microbial population, as well as the physical and chemical properties of the soil (water content, nutrients, pH, temperature), thereby comprising one of the most significant indicators of soil quality and biological activity [58–60]. Rhizosphere microorganisms use root secretions as carbon and nitrogen sources to sustain their growth and reproduction [34] and secrete a variety of soil enzymes to decompose and mineralize soil organic matter and increase the effective nutrient content of the soil [56], thus improving plant growth and phytoremediation efficiency. This has become one of the research hotspots for phytoremediation in multi-plant symbiotic systems [61]. In this regard, multi-plant symbiotic systems can significantly increase the activity of soil enzymes (dehydrogenases, urease, sucrase, and phosphatases [62]) due to the increased quantity and diversity of root exudates (polysaccharides, aromatic compounds, and ester compounds), which can serve as substrates for extracellular enzyme synthesis [40,63,64].

#4 glomus caledonium: The #4 cluster examines the impact of arbuscular mycorrhizal fungi (AMF) on the recovery of multi-plant systems. The plant–soil feedback effect mediated by arbuscular mycorrhizal fungi is one of the key mechanisms affecting plant community diversity and soil quality and is one of the research hotspots in this field [65,66]. This feedback effect can improve the ecosystem services provided by plant communities, including biodiversity, nutrient cycling, water flow regulation, water purification, and pollution control [67]. Furthermore, arbuscular mycorrhizal fungi increase the remediation efficiency of phytocommunities primarily through three mechanisms: (1) improving the nutrient status of host plants and increasing plant biomass by secreting soil enzymes to enhance pollutant accumulation [68]; (2) increasing the accumulation capacity of hyperaccumulated plants to reduce the accumulation of pollutants in adjacent plants [69,70]; and (3) increasing soil pH to reduce the bioavailability of heavy metals [71].

#5 phenanthrene: The #5 cluster is concerned with the remediation of polycyclic aromatic hydrocarbons (PAHs) in multi-plant systems. PAHs are hydrophobic organic compounds consisting of two or more fused benzene rings, which are predominantly found in environmental media such as soils, the atmosphere, water bodies, and surface sediments [72,73]. They cause severe damage to human health and the environment due to their toxicity (carcinogenicity, teratogenicity, and mutagenicity), bioaccumulation, and persistence [74]. Current research on PAHs by domestic and foreign researchers has centered on the primary pollutants phenanthrene, benzo [a] anthracene, and benzo [a] pyrene [75,76]. Furthermore, the mechanisms of PAH removal by multi-plant symbiotic systems include (1) the promotion of contaminant biodegradation via stimulation of soil microbial activity, soil enzyme activity, and co-metabolic pathways of root exudates; (2) the adsorption or movement of PAHs between roots via root surface and lipophilic root exudates; (3) direct plant uptake, accumulation, and metabolism; and (4) the reduction of PAHs by changing soil properties (increasing soil moisture and infiltration rate, reducing soil organic matter concentration) to enhance the volatilization and leaching of PAHs [77,78]. Meng et al. [79] discovered that the biodegradation pathway of plant communities could remove more than 99% of PAHs, while only a few PAHs (e.g., 2–4 ring dominated PAHs) were taken up by plants. Therefore, multi-plant assemblages are primarily used to increase phytoremediation efficiency by increasing the number of soil microorganisms, soil enzyme activity, and root exudates in order to optimize rhizosphere conditions and improve the biodegradation and bioavailability of pollutants as the primary pathway [78].

Combined with the analysis of keyword co-occurrence clustering maps, the following clusters are strongly related; clusters #0, #2, and #5 have a high overlap with the research hotspots in the field of phytoremediation [23], and the occurrences of the keyword nodes included occurred primarily between 2007 and 2017, indicating that the application of multi-plant combination forms in the field of phytoremediation has not formed a new branch during that time; in addition, the #1, #3, and keyword nodes included in cluster #4 appeared most frequently between 2018 and 2022, indicating that the safety of agricultural land, the mechanism of action of soil enzymes, and arbuscular mycorrhizal fungi have become research hotspots in recent years.

3.4. Literature Co-Citation Analysis

Literature co-citation means that two references are cited by the same document at the same time, which indicates that there is a co-citation relationship between these two documents. Literature with a high number of citations in scientific research makes up the knowledge base of current research, and the literature co-citation network shows the structure of the knowledge base, and cluster analysis of the knowledge base is the basis for identifying research frontiers [28]. The core literature is the foundation of the knowledge base and is characterized by a high citation count and a high degree of mediation. According to the results of the clustering analysis, the Q value of 0.8793 (>0.3) and an S value of 0.9359 (>0.7) indicate reasonable clustering results. As shown in Figure 3, the map contains 583 keyword nodes and 1704 linked lines, and the clusters are divided into six categories: "heavy metal pollution" (#0), "agromining" (#1), "Leguminosae" (#2), "soil enzymes" (#3), "soil microbial community" (#4), and "*Salix caprea*" (#5). The study network was more dispersed, and network overlap was low. Table 3 displays the cited literature with the highest CF $\times$ BC values in each cluster I.

Table 3. The most important cited references in the Co-citation cluster map.

Cluster	Author	Journal	Title	CF $\times$ BC	Time Horizon
#0 heavy metal pollution	Desjardins D [9]	Science of the Total Environment	Complementarity of three distinctive phytoremediation crops for multiple-trace element contaminated soil	0.39	2014–2018
#1 agromining	Bani A [86]	International Journal of Phytoremediation	Improving the Agronomy of Alyssum murale for Extensive Phytomining: A Five-Year Field Study	0.72	2010–2018
#2 Leguminosae	An LY [87]	Plant Soil	Heavy metal absorption status of five plant species in monoculture and intercropping	0.99	2004–2012
#3 soil enzymes	Wei SQ [88]	J Soils Sediments	Phytoremediation for soils contaminated by phenanthrene and pyrene with multiple plant species	0.80	2005–2011
#4 soil microbial community	Zeng P [80]	Science of the Total Environment	Phytoextraction potential of *Pteris vittata* L. co-planted with woody species for As, Cd, Pb, and Zn in contaminated soil	3.42	2014–2021
#5 *Salix caprea*	Marschner H [89]	Academic press	Marschner's Mineral Nutrition of Higher Plants	0.27	2003–2012

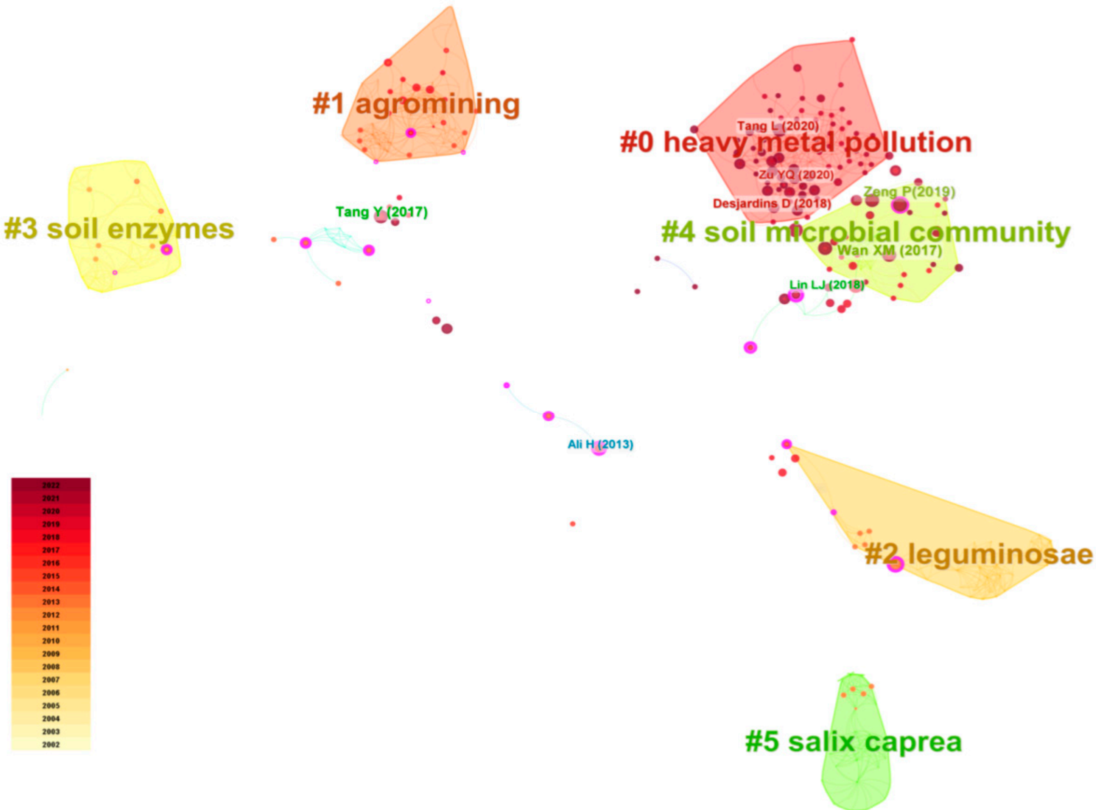

Figure 3. Co-citation cluster map [9,24,80–85].

Clusters #0, #1, and #4 constitute the knowledge base of the field over the past decade, with a strong correlation between heavy metal contamination and soil microbial community clusters. In addition, the #0 heavy metal contamination knowledge cluster is represented in the literature from a study published by Desjardins et al. [9] in 2018, which examined the growth and remediation efficiency of *Festuca arundinacea*, *Medicago sativa*, and *Salix miyabeana* in soils contaminated with a mixture of multiple heavy metals through monoculture and combination cultures. The mixed planting of *Festuca arundinacea* + *Medicago sativa* (F + M), *Festuca arundinacea* + *Salix miyabeana* (F + S), and *Festuca arundinacea* + *Medicago sativa* + *Salix miyabeana* (F + M + S) occupied the largest total biomass above ground, as well as the total biomass below the ground and root surface area. Among these, the best planting method for *Festuca arundinacea* comprised its combination with *Salix miyabeana* in terms of plant accumulation. In contrast, the best choice in terms of phytoextraction varied according to the heavy metal elements. This leads to the conclusion that in the practical application of multi-plant symbiotic system remediation, the biomass allocation pattern, remediation capacity, nutrient utilization, and other aspects have to be considered comprehensively to clarify the remediation aims. A research paper published by Bani et al. in 2015 [86] represented the #1 agromining knowledge base. Phytomining (Agromining) refers to the additional combustion and smelting of harvested plant parts above the ground to extract the heavy metals they contain, based on phytoremediation [90]. This study compared the effects of fertilization, harvesting period, weeding, and planting techniques (autotrophic and sowing) on the remediation of contaminated soil by the super-enriched plant *Alyssum murale*. The results indicated that the proper application of nitrogen fertilizer significantly increased the biomass of *Alyssum murale* without decreasing the extraction efficiency and that nutrient stress may be the main limiting factor for species coexistence and plant productivity in autotrophic planting systems. The #4 soil microbial community knowledge base is represented by a paper from Zeng et al. [80] published in 2019, which demonstrated the effect of the super-enriched plant *Pteris vittata* on plant accumulation capacity in mixed cultivation with woody plants, with the results indicating that after 270 days of mixed cultivation with *Morus alba* and *Broussonetia*, the accumulation of soil arsenic by *Pteris vittata* increased by 80.0% and 64.2%, respectively ($p < 0.05$). However, the mixed planting did not significantly contribute to the accumulation capacity of woody plants.

The #2, #3, and #5 clusters formed the basis of early research in the field. The #2 legume knowledge cluster is represented by a study published by An et al. [87] in 2011, which is similar to the core literature studies of the #0 and #4 legume knowledge clusters, which used the crops *Zea mays*, *Solanum lycopersicum*, *Brassica rapa* var. *chinensis*, *Brassica oleracea*, and the legume companion *Kummerowia striata* to compare the phytoremediation efficiency of different plant species and cropping patterns. Accordingly, the results showed that *Zea mays* and *Solanum lycopersicum* could improve the phytoaccumulation capacity of the intercropping system. Among these, the heavy metal content in the portion of *Zea mays* above the ground was below the edible safety threshold. Representative of the #3 soil enzyme knowledge group is a research paper published by Wei et al. [88] in 2010, in which a mixture of *Medicago sativa*, *Brassica rapa* var. *oleifera*, and *Trifolium repens* was cultivated to study the contribution of different remediation pathways to the remediation of PAH-contaminated soil by multiple plant combinations. The results indicated that multi-plant combinations enhanced plant–microbial interactions, and the combined plant–microbial remediation pathway contributed 44.69–48.86% to the removal of PAHs, which was the dominant role, whereas the plant uptake and accumulation pathways did not significantly contribute to the removal of PAHs. Since its initial publication in 1986, the international plant nutrition community has regarded *Marschner's Mineral Nutrition of Higher Plants*, edited by Marschner [89], as a classic of the highest academic caliber, and the authors have continuously revised and supplemented it, and republished it again in 2012, which lays a theoretical foundation for the study of phytoremediation mechanisms, and provides a theoretical basis for the application of multi-plant symbiotic systems in the field of phytoremediation. It also provides a theoretical basis for the application of multi-plant symbiotic systems in phytoremediation. The aforementioned literature has provided the theoretical foundation for the study of "Phytoextraction", "soil", "heavy metal", and "Accumulation", as well as other research hotspots, providing successful cases and the theoretical foundation for subsequent studies and playing a leading role in the development of multi-plant systems for phytoremediation research.

Combined with the analysis of co-citation mapping, the research branches in this field prior to 2012 are the #2 clusters, #3 clusters, and #5 clusters, all of which exhibit a high degree of independence. The #0 clustering, #1 clustering, and #4 clustering are the research branches of the last decade, with the #0 clustering and #4 clustering being highly correlated. The #0 knowledge cluster is the theoretical foundation of the #4 knowledge cluster, and the #4 knowledge cluster is the theoretical extension of the #0 knowledge cluster, which can be considered the frontier branch in this field.

4. Discussion

4.1. Factors Influencing the Restoration of Multi-Plant Symbiotic Systems

Plant–plant interactions are one of the core contents of community ecology [91] and one of the hotspots of research in the field of phytoremediation, which primarily includes both facilitation and competition, and the analysis of a sample of the literature in this field reveals that facilitation typically predominates in stressful environments. Callaway et al. [92] considered that plant–plant interactions are a dynamic process of change determined by multiple factors. Plant species, the bioavailability of pollutants, pollutant concentration, and the physicochemical properties of the environment are the primary influences on phytoremediation [6]. The specific factors that affect phytoremediation include:

(1) Plant diversity. Generally, plant diversity increases plant community productivity, community stability, and biomass and decreases the toxicity of pollutants to plants via multiple plant–soil feedback mechanisms, thereby enhancing phytoremediation [21,93]. Furthermore, plant diversity is comprised primarily of species diversity and functional diversity. Studies have demonstrated that plant diversity is influenced

by soil heterogeneity [94], habitat heterogeneity [95], and spatial heterogeneity [96]. Species diversity has a significant positive effect on plant biomass above the ground and microbial communities below the ground [97,98]. Nevertheless, some scholars contend that functional diversity is more important than species diversity [99,100]. That functional trait diversity can be enhanced by promoting ecological niche complementarity to modify mutual competitive effects and reduce interspecific competition among plants [101]. It has also been discovered that increasing the number of genotypes in plant populations can enhance the functional diversity of communities and indirectly promote resource complementarity and ecological niche differentiation among different genotypes in order to increase resource use efficiency [102].

(2) Interspecific relationships. Appropriate species combinations, planting ratios, planting densities, and planting patterns can enhance the facilitative relationships between plant assemblages by increasing the resource use efficiency of plants. Studies have shown that nutrients may be a major limiting factor for species coexistence and plant productivity in polluted environments [86,103]. However, plant assemblages can increase the ability of each species to obtain key elements from the soil nutrient pool [104]. Thus, when ecological niche overlap among plants is high (e.g., *Zea mays* and *Suaeda saltbush* I [16], *Solanum melongena* and *Sedum alfredii* [52]), it will increase nutrient competition among species and weaken the facilitative effect of plant combination cropping systems. This can be enhanced through fertilization, microorganism inoculation, and the addition of exogenous substances [52].

(3) Sex of plant species. According to studies, dioecious plants exhibit sex differences in response to environmental stress, with female plants tending to allocate more resources to reproductive growth and male plants tending to increase their own tolerance [105]. Mixed plantings of plants of different sexes can increase the abundance of microbial communities such as actinomycetes and β-amastigotes to improve the rhizosphere environment, thereby affecting the remediation capacity of plant assemblages and tolerance to polluted environments [106]. Plants of different sexes can also enhance plant community promotion through the complementary effect of ecological niches, such as a study by Bu Chunlan et al. [107], who discovered that when *Morus alba* of different sexes was mixed in cultivation, the transfer of nutrients elements between males and females was achieved through hyphal links, which improved the photosynthetic capacity of the plants, thereby promoting the biomass of mulberry in the mixed female–male planting.

4.2. Mechanisms for the Restoration of Multi-Plant Symbiotic Systems

According to the keyword co-occurrence clustering analysis, studies on the restoration mechanisms of multi-plant symbiotic systems are primarily concentrated in the subsurface portion. However, the mechanisms of plant interactions vary in different environments and different combinations and can be roughly divided into the three sections below:

(1) Plant–soil feedback (PSF) mechanisms, which primarily consist of plant–pathogenic fungi, plant–mycorrhizal fungi, and plant–soil enzymes, in which different plant species drive different changes in soil properties, and these changes, in turn, affect aspects of plant remediation efficiency, resilience, and competitiveness [108,109]. Studies have shown that plant species composition is the dominant factor influencing microbial community composition at the soil surface (0–10 cm), but microbial community changes are more sensitive to plant height responses in deeper soil layers (11–20 cm) [110]. Plant–soil feedbacks primarily promote the restoration of multi-plant systems by promoting the secretion of root exudates, the diversity and abundance of rhizosphere microorganisms, and the formation of symbiotic networks of clumping mycorrhizal fungi, which alter soil physicochemical properties and provide a favorable environment for plant growth. Mycorrhizal fungi that form clumps are the primary mechanism for the plant–soil feedback effect that drives phytoremediation [111]. Multi-plant co-cropping can increase microbial population diversity and

activity of phosphatases, dehydrogenases, and especially urease [97] while reducing soil fungal pathogen abundance, thereby increasing plant productivity, because soil bacteria can produce disease-resistance-related defense enzymes such as chitinases to degrade the cell walls of fungal pathogens [21]. However, although plant–soil feedback mechanisms are a hot topic of research in this field [63,112,113], studies on their interactions with plants must still be conducted due to their small size and complex habitat heterogeneity.

(2) The majority of plants have their own resistance mechanisms, and multi-plant symbiotic systems can enhance the resistance mechanisms of plants in the system or increase detoxification pathways, thereby decreasing the bioavailability and toxicity of pollutants. For instance, the tolerance and detoxification mechanisms of plants to heavy metals are related to their subcellular distribution; plants primarily use cell wall fixation or vesicle storage of heavy metal elements to reduce the degree of stress; and different forms of heavy metal elements have different migration abilities and produce different levels of toxicity in plants. In addition, Yue et al. [114] discovered that the *Syngonium podophyllum-Peperomia tetraphylla* co-planting system inhibited the reduction of metallic uranium (U) by the root system of *Peperomia tetraphylla*, facilitated the transport of U from roots to the plant parts above the ground, and enhanced the barrier effect of cell walls and vesicles on U, thereby reducing its toxic effects on plants. It effectively increased the biomass of both plants, as well as significantly increasing the bioaccumulation (BA), transport factor (TF), and bioaccumulation factor (BCF) of U in plants. The multi-plant combination system can also reduce oxidative stress while accelerating pollutant metabolism by increasing antioxidant substances in plants and antioxidant enzyme activity and detoxification enzyme activities, such as cytochrome P450 reductase (CPR), glutathione sulfhydryl transferase (GST), and glycosyl transferase (GT) [115].

(3) Through plant–plant interactions, multi-plant symbiotic systems can enhance the overall remediation capacity of plant communities. According to the stress gradient hypothesis (SGH), competition dominates plant–plant interactions in benign or low-stress environments, whereas competition typically decreases and facilitation increases as environmental stress increases [19]. In addition, additional studies have demonstrated that facilitation is more likely to benefit plant species with low tolerance but high competitive ability [116]. It has also been demonstrated that litter decomposition and chemosensory effects in plant communities can increase the competitive advantage of hyperaccumulating plants, thereby decreasing the toxic effects of pollutants on neighboring plants [117]. Koelbener et al. [118] discovered, for instance, that competitive interactions between *Salix caprea* and *Carex flava* promoted the uptake of Zn by *Salix caprea*, thereby mitigating the negative effects of heavy metals on *Carex flava*. Consequently, a suitable phytocommunity composition can enhance plant–plant interactions to maximize a phytocommunity's ability to degrade pollutants, thereby enhancing phytoremediation efficiency.

5. Future Research Directions

(1) According to the results of the keyword co-occurrence analysis, phytoremediation of multi-plant symbiotic systems is primarily concentrated in the field of soil pollution, and the number of studies on the remediation of polluted environments such as water bodies and air by plant combinations has increased gradually since 2008. Among them, the field of multi-plant combinations for purifying air pollution is dominated by indoor pollutant gases [119,120], while research on major air pollution gases such as nitrogen oxides (NO_x), ozone (O_3), and volatile organic compounds (VOCs) lacks theoretical studies and practical applications; therefore, future research on phytoremediation of multi-plant combinations in water bodies, air, and other environments should be intensified. (2) Current research on the potential mechanisms of multi-plant assemblages for phytoremediation has primarily focused on the portion below the ground; however, it has been demonstrated

that microorganisms in the plant leaf ring (i.e., the portion of the plant above ground) can increase host resistance to biotic and abiotic stresses and improve phytoremediation efficiency by degrading pollutants such as fine particulate matter, black carbon, and atmospheric hydrocarbons [121]. Therefore, future phytoremediation mechanisms must be examined from multiple perspectives in both the above and belowground portions. (3) Future trends include the use of additives [e.g., plant growth regulators (PGR) [122], organic improvers [123], inorganic improvers [124], chelating agents [125], microorganisms [arbuscular mycorrhizal fungi (AMF), plant-growth-promoting rhizobacteria (PGPR)] [126–128], and other means to assist multi-plant combination restoration techniques. (4) Molecular, breeding, and biotechnology are also important ways to improve the efficiency of multi-plant assemblages for remediation, reduce remediation time, and speed up ecosystem recovery by targeting transgenic plants that improve plant–microbe interactions or rhizosphere microbial activity, thereby promoting positive plant–plant benefits. For example, transgenic plants capable of secreting heavy metal-selective ligands that solubilize elements used for phytoremediation have been created [129,130]. (5) To better evaluate the remediation effects of multi-plant species systems, phytoremediation kinetic models for different plant combination patterns can be developed in the future based on an in-depth examination of the restoration mechanisms of multi-plant combinations [131].

In conclusion, future research on phytoremediation using multi-plant symbiotic systems should focus on the following aspects: (1) exploring the applicable environments for using multi-plant symbiotic systems as a remediation strategy; (2) analyzing the remediation mechanism from multiple perspectives of atmosphere–plant–soil; (3) combining physicochemical and biological techniques to improve the remediation efficiency; and (4) establishing a dynamic model to assess remediation effects.

6. Conclusions

This study presents a comprehensive review of the research on the application of multi-plant symbiotic systems in the field of phytoremediation in the last 20 years. The results showed that plant–plant interactions have attracted great attention in the field of phytoremediation in recent years. From 2007 to 2017, no new research branches were formed for the application of multi-plant symbiotic systems in phytoremediation; farmland safety, soil enzyme action mechanism, and arbuscular mycorrhizal fungi were the research hotspots from 2018 to 2022. Before 2012, the research branches for the application of multi-plant symbiotic systems were Leguminosae, soil enzyme, and *Salix caprea*. Heavy metal pollution, agromining, and soil microbial communities have been the research branches in the last decade, of which soil microbial communities are the frontier branch for phytoremediation with the application of multi-plant symbiotic systems. Finally, the influencing factors and action mechanisms of phytoremediation in multi-plant symbiotic systems were systematically summarized, and future research directions in this field were proposed.

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