Frontiers in Environmental Research
Print ISSN: 2960-0251
Online ISSN: 2960-026X
DOI: https://doi.org/10.61784/fer3035

THE ROLE OF MICROORGANISMS IN SOIL SALINIZATION REMEDIATION

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Abstract: Saline soil is one of the main forms of soil degradation, covering approximately 1 billion hectares globally. It is mainly found in Russia, the United States and China. Climate warming and improper irrigation practices have accelerated the salinization of the soil, posing a threat to crop productivity. In recent years, microorganisms, as an important part of the natural cycle, have been playing an increasingly significant role in the restoration of soil salinization. However, a comprehensive bibliometric analysis of this field has not yet been performed. Here CiteSpace, VOSviewer and the Bibliometrix R package were used to predict future trends in this field. The results showed numbers of published papers on the role of microorganisms in soil salinization remediation is increasing year by year. Functional microorganisms play a crucial role in restoring saline-alkali wetlands by regulating the expression of plant salt-tolerance genes and improving the soil microenvironment. Future research will focus on designing synthetic microbial communities, analyzing multi-omics interaction networks, and jointly enhancing the efficacy of ecological restoration and carbon sequestration, providing innovative solutions for the sustainable management of saline-alkali wetlands.
Keywords: Salinization; Microorganisms; CiteSpace; VOSviewer; Bibliometrix

1 INTRODUCTION

Soil is an indispensable resource for human production and life. Healthy soil and arable land play a crucial role in food security and human survival[1]. With the accelerated pace of global urbanization and the continuous expansion of industrial and agricultural sectors, soil pollution and degradation problems have become increasingly severe[2]. Among them, soil salinization, as a prominent issue of soil degradation, poses a threat to the soil health and food security of our country[3]. The cultivated soil layer in saline-alkali areas suffers from high salt content, low soil fertility, unbalanced nutrients, low agricultural productivity and low production efficiency, which severely restricts the high-quality development of efficient ecological agriculture[4]. Currently, there are many measures for the improvement of saline-alkali land. According to the nature of the improvement measures for saline-alkali land, they can be classified into three major categories: physical improvement measures, chemical improvement measures, and biological improvement measures[5]. Compared with other improvement measures, using microbial agents prepared by functional microorganisms to improve saline-alkali land can achieve better improvement effects while having the advantages of ecological protection, no pollution, and long-lasting improvement effects[6]. The beneficial functional microorganisms in microbial agents can not only activate nutrients such as phosphorus and potassium in saline-alkali soil, but also secrete auxins (IAA) and other promoting substances to promote crop growth and increase crop yield[7]. Currently, using microorganisms to improve saline-alkali land has become one of the important measures for the improvement of saline-alkali land.

Functional microorganisms refer to microbial communities that play a significant role in specific environments or ecosystems. They participate in specific biogeochemical processes, material cycles, or ecological functions through physiological metabolic activities to maintain or improve environmental conditions[8]. These microorganisms include bacteria, fungi, and archaea. The application of functional microorganisms can improve the nutrient status of saline-alkali soils, enhance soil fertility and crop yields, and promote sustainable agricultural development[9]. There are many sources of functional microorganisms, such as natural ecosystems, within plants and animals, plant rhizospheres, and extreme environments. Due to the potential disturbance that the addition of exogenous microorganisms may cause to the diversity and stability of the indigenous microbial community, current research mostly involves screening functional microorganisms from the original soil, preparing them into microbial agents, and then applying them to the original soil, achieving the goal of "taking from the soil and using it in the soil"[10].

To comprehensively understand the research status and cutting-edge trends of the role of microorganisms in soil salinization remediation at home and abroad, the research in this field was conducted by bibliometric analysis. And for this article, R software alongside VOSviewer and CiteSpace were used to extensively analyze the literature concerning microorganisms in the context of soil salinization remediation. The primary objective was to investigate the evolution and emerging research trends in the application of microorganisms in soil salinization remediation between 2000 and 2025. By fostering a deeper understanding of the current landscape and future potential of this filed, this research seeks to contribute to the sustainable advancement of this field, ultimately enhancing the efficacy and application of microorganisms in soil salinization remediation.

2 MATERIAL AND METHODS

2.1 Data Sources and Retrieval Strategies

All the data in this article were collected from the Web of Science Core Collection Database (WOSCC) on August 25, 2025. We adopted the following search strategy: "TS=("soil salinization") OR TS=("halophytes") AND TS=("rhizosphere microorganisms")". Using the time slicing function, the time period was set from January 1, 2010 to May 25, 2025. The selected included literature types were "Article" and "Review". Then, complete records and reference citations were extracted from all the retrieved results and saved in plain text format for further analysis. After removing duplicates and irrelevant items, a total of 4986 articles were retrieved. Subsequently, bibliometric analysis and visualization were conducted using CiteSpace, VOSviewer, and the Bibliometrix R package.

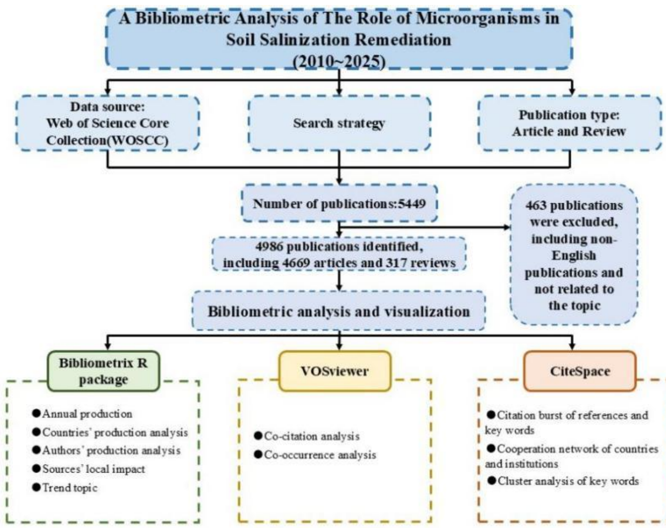

Figure 1 Flowchart Depicting the Article Selection Process

2.2 Data Analysis

CiteSpace 6.3.R1 software was used to citation bursts in references and keywords, visualize the cooperation network of countries and institutions, and perform cluster analysis of keywords. VOSviewer 1.6.20 software was used to perform co-citation and co-occurrence analyses, with co-citation analysis focusing mainly on cited journals and references. The Bibliometrix R package 3.2.1 was mainly used for analyzing annual production, country-wise production, authors' contributions over time, local impacts of sources based on the H-index, and trending topics.

3 RESULTS

3.1 General Landscapes of Global Publications

According to the search strategy, 5,449 publications were collected from WOS without any duplicates. Eventually, after excluding the irrelevant literature, a total of 4,986 articles were selected, including 4,669 "Articles" and 317 "Reviews" (Figure 1). Regarding the research on the role of halophyte-root-associated soil microorganisms in saline-alkali land restoration, the related research papers generally showed an increasing trend year by year (Figure 2). From 2010 to 2017, the number of published papers remained relatively stable, with an average annual publication volume of 132, and the growth rate was not significant. This phenomenon reflects that the research at this stage is still in the stage of basic accumulation. After 2017, with the development of biological technologies such as 16sRNA, metagenomics, and metabolomics, the overall number of research publications significantly increased, with the annual publication volume increasing from 223 to 717. In addition, the annual total number of citations (SOTC) also showed a gradually increasing trend over time, while the H-index of paper publication years showed a relatively stable trend. This indicates that the research on the role of halophytes-root-associated soil microorganisms in saline-alkali land restoration has received more attention and achieved more results compared to the previous stage.

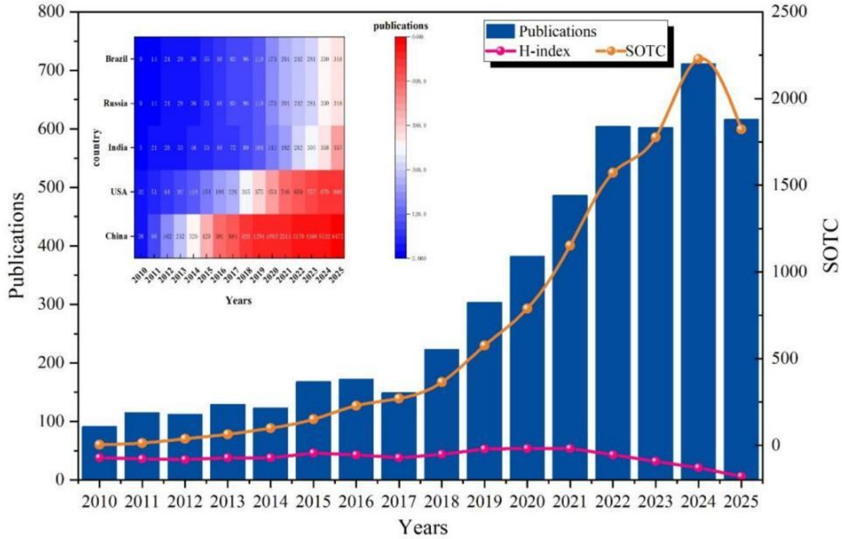

Figure 2 The Annual Number of Publications Related to Microorganisms in Soil Salinization Remediation

3.2 Analysis of Collaboration in Countries and Regions

According to the analysis conducted by the Bibliometrix R software package, it was found that a total of 96 countries participated in the research on the role of halophyte-root-associated soil microorganisms in the restoration of saline-alkali land. The top 10 countries and institutions with the largest number of publications are shown in Figure 3B. Among them, China had the highest number of publications (n = 2288), accounting for 45.9% of the total number of publications. The United States (n = 243, 4.9%), India (n = 168, 3.4%), Russia (n = 168, 3.4%), and Brazil (n = 135, 2.7%) followed closely. The centrality is positively correlated with the influence of the corresponding countries/regions, that is, the closer the centrality value is to 1, the higher the influence of the related research results of that country/region. Therefore, the research results of the United States, China, and India are leading in this field. Although the research publication numbers of Spain (n = 98, 2%) and Italy (n = 109, 2.2%) were relatively small, their influence cannot be underestimated. Furthermore, international research collaborations indicate that in the field of studying salt-tolerant plants and rhizosphere soil microorganisms in the process of saline-alkali wetland restoration, the cooperation between China and the United States, Canada, and Australia is the most frequent (frequency = 523), followed by the cooperation between the United States and Italy, Brazil, Portugal, and Russia (frequency = 161), Russia and Iran, the United Kingdom, etc. (frequency = 127), and the United States and Iran, Tunisia, etc. (frequency = 103) (Figure 3A). Although China has a significant lead in the number of publications in this field, its research results mainly focus on SCP (single country authors), accounting for as high as 81.3%, while the research of the United States, Italy, etc. is more involved in international cooperation, and the ratio of MCP (multi -national authors collaboration) is higher than that of China. This indicates that the relevant research results in this field in China need to be further internationalized (Figure 3B).

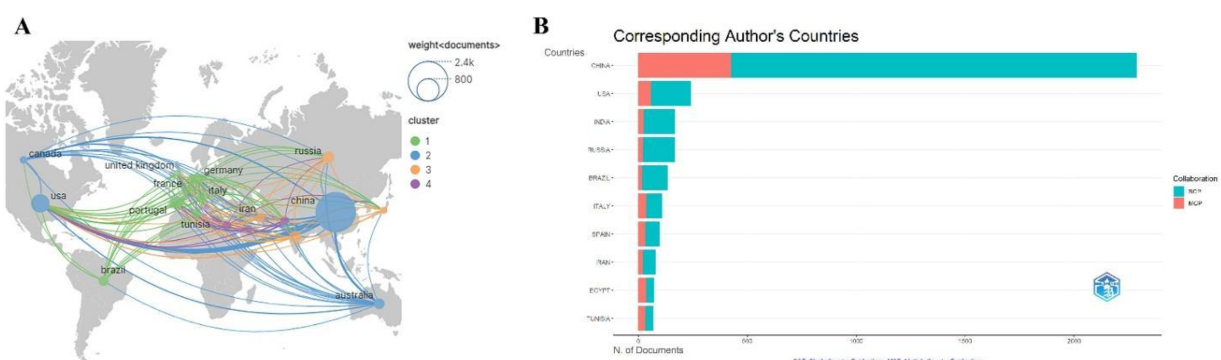

Figure 3 Analysis of Collaboration in Countries and Regions

3.3 Analysis of Institutions and Authors

According to the analysis of the Bibliometrix R software package, it was found that a total of 2,563 institutions conducted research on the restoration of saline-alkali wetlands using halophyte-root-associated microorganisms. Among the top 20 research institutions in terms of the number of published papers, 75% were from China (Figure 4A). Among them, the research results of the Chinese Academy of Sciences were the most (n=563), followed by the University of Chinese Academy of Sciences (n=222) and the Chinese Academy of Agricultural Sciences (n=128). The results of the cooperation among research institutions showed that in terms of the number of papers, the Consejo Superior de Investigaciones Cientificas (n=59) had a relatively small number of publications but its influence was far ahead in this field (centrality = 0.23). In addition, the research results of the Chinese Academy of Sciences were also very worthy of attention (n=563, centrality = 0.14). For the analysis of the authors of the research on halophyte-root-associated microorganisms for restoring saline-alkali wetlands, the results showed that the author with the most published papers was Li Y (n=64) and Wang J (n=60), while the author with the highest total citation frequency was Ding JL (n=58, TC=723). In addition, the Bibliometrix R software package also analyzed the changes in the number of published papers and the total citation frequency of the top ten authors over time, where the size of the circles represents the number of published papers and the color represents the total citation frequency each year (Figure 4B).

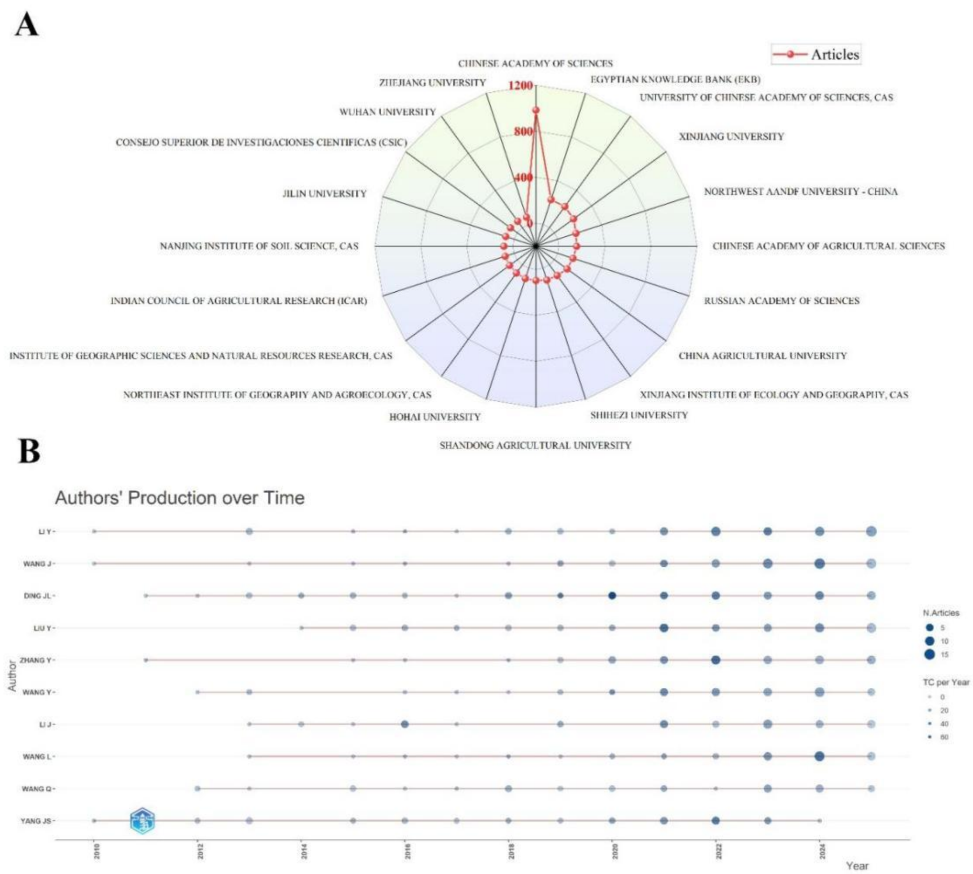

Figure 4 Analysis of Institutions and Authors

3.4 Analysis of Co-Cited Journals and Reference Bursts

According to the analysis of the Bibliometrix R software package, this study covered 4,986 articles published in 942 journals. Among the top 3 journals, the number of published articles exceeded 150 each, including "AGRICULTURAL WATER MANAGEMENT" (n = 161, IF = 5.9), "AGRONOMY-BASEL" (n = 160, IF = 3.3), and "SCIENCE OF THE TOTAL ENVIRONMENT" (n = 150, IF = 8.2). The total citation counts of the journals were analyzed, including those with at least 20 citations. The top 3 journals with the highest total link strength were "SCIENCE OF THE TOTAL ENVIRONMENT" (total link strength = 345,705), "FRONTIERS IN PLANT SCIENCE" (total link strength = 331,790), and "AGRICULTURAL WATER MANAGEMENT" (total link strength = 289,699) (Figure 5A). Additionally, the citation frequencies of the top 10 publications were analyzed, and it was found that the paper titled "Mechanism of Salinity Tolerance in Plants: Physiological, Biochemical, and Molecular Characterization" received 1,443 citations. The second and third were "Salt Tolerance Mechanisms of Plants" (n = 1,413) and "A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States" (n = 1,178) (Figure 5B). Unfortunately, no papers were identified as highly cited papers, indicating a lack of guiding research results on the restoration of saline-alkali wetlands related to salt-tolerant plants and rhizosphere soil microorganisms.

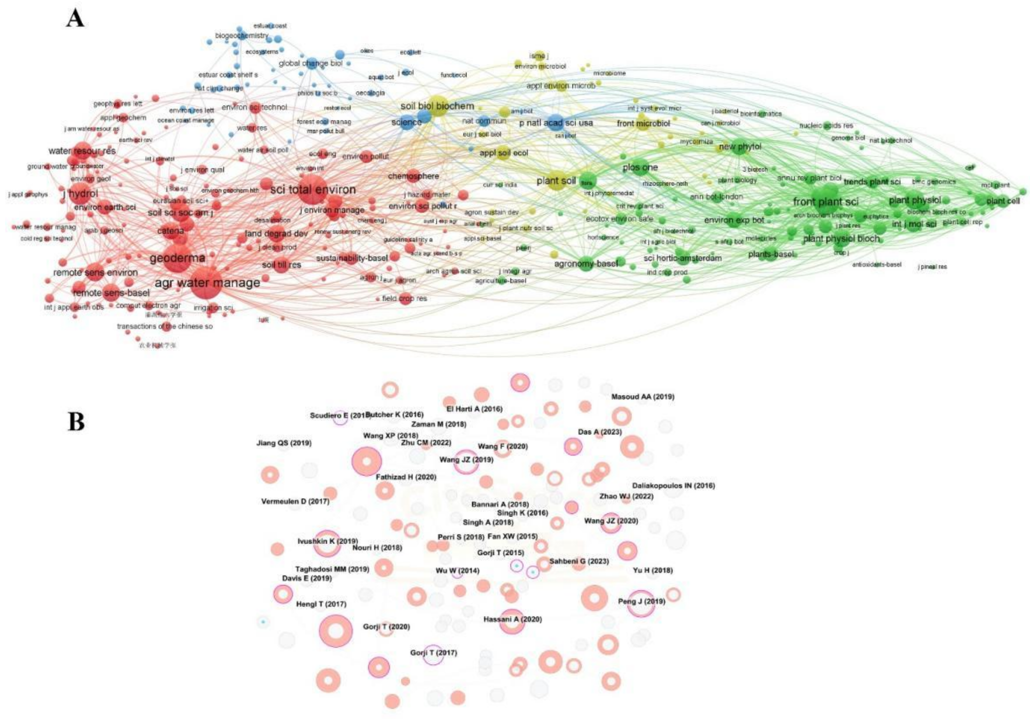

Figure 5 Analysis of Co-Cited Journals and Reference Bursts

3.5 Analysis of Keywords and Hotspots

Key words represent the core content of a paper, not only enabling the rapid retrieval of appropriate literature, but also reflecting the activity level of related research. Conducting co-occurrence analysis on the keywords of the article is crucial for grasping the research hotspots and the evolution of research trends in the study of salt-tolerant plants and rhizosphere soil microorganisms in the process of saline-alkali wetland restoration. In the co-occurrence analysis of keywords in VOSviewer, excluding the search terms, the keywords with higher co-occurrence frequency are "salt stress/tolerance", "water", "irrigation", "drought", "plants", "remote sensing", "microbial community", which indicate that the research hotspots in this field mainly focus on the important role of water in the formation process of saline-alkali land, the impact of the salt stress environment of saline-alkali land on plants, and the composition of microbial diversity in saline-alkali environments. In the research of saline-alkali land restoration, microorganisms play an indispensable role. Microorganisms can regulate the dynamic of soil salt content through their own metabolic activities, alleviate the stress of salt on plant growth. At the same time, microorganisms can optimize the soil moisture condition, improve the water utilization efficiency of plants, and enhance the ability of plants to resist drought. Remote sensing technology can monitor the changes in soil and plant conditions during the restoration process. Moreover, changes in the microbial community can also affect the physical and chemical properties of the soil, providing a basis for the formulation of reasonable irrigation strategies and fully contributing to the ecological restoration and sustainable development of saline-alkali land (Figure 6A).

Keyword clustering analysis helps researchers identify the correlations among frequently occurring keywords in a certain field, revealing the hotspots and themes of that research field. The keyword clustering analysis results of VOSviewer indicate that all keywords can be classified into 6 categories. These include "Salinity", "Water", "Growth", "Management", "Dynamic", and "Mineral-nutrition", etc. This suggests that the related research on microbial restoration of saline-alkali wetlands not only focuses on halophytes and the role of water in the formation process of saline-alkali land, but also explores the role of human intervention in the dynamic balance of the soil microenvironment of saline-alkali land. In the research on microbial restoration of saline-alkali land, the core is to improve the dynamic of soil salinity through microbial regulation, alleviate the inhibition of high salinity on plant growth. Microorganisms can reduce soil salinity through metabolism, optimize the water transport and retention capacity of the soil, and regulate the mineral nutrient cycle, increasing the content of available nutrients in the soil, providing suitable conditions for plant growth. Based on this, the comprehensive management strategy formed can coordinate the elements of microorganisms, soil, and plants, promoting the dynamic of soil salinity and nutrients in saline-alkali land to develop in a favorable direction, ultimately achieving the improvement of the ecological function and productivity of saline-alkali land, and providing key support for the sustainable utilization of saline-alkali land (Figure 6B).

Keyword emergence analysis is helpful for analyzing the evolution of research hotspots in a certain research field. Through keyword emergence analysis, we can identify the keywords that frequently appear within a specific time period. These keywords reflect the current research hotspots and trends in this field. The keyword emergence analysis results of CiteSpace indicate that, in addition to the search terms, the keywords with high emergence intensity include "indicators", "electrical conductivity", "shallow groundwater", "ecosystem services", "nitrate", etc. That is, the research in this field focuses on the study of saline-alkali land remediation, and microorganisms play a key role. Microbial activities can change the water quality of shallow groundwater, and the influencing indicators such as conductivity and nitrate content can reflect the desalination of the soil and the transformation of nutrients. Microorganisms can also regulate the physical and chemical properties of the soil, reduce soil conductivity, improve soil structure. At the same time, the remediation process involving microorganisms helps to enhance the ecosystem service function, increase soil fertility, promote vegetation growth, and promote the benign succession of the saline-alkali ecosystem (Figure 6C).

The keyword timeline analysis is helpful for understanding the evolution and changing trends of keywords in related research fields. Based on the time distribution of keyword clustering in CiteSpace, this paper divides the research topics into three time periods. The first period (2010-2015): In the research on microbial restoration of saline-alkali land during this period, its core value lies in addressing two key issues: salt stress and seawater intrusion. Microorganisms can reduce soil salt content through metabolism, improve soil structure, alleviate the inhibition of salt stress on vegetation, and reduce the aggravation of soil salinization caused by seawater intrusion. Remote sensing technology can quickly and widely monitor the dynamic changes of soil salt content, vegetation coverage, etc. during the restoration process, providing efficient technical support for evaluating the microbial restoration effect. The three elements work together, not only exerting the core role of microorganisms in restoration, but also achieving precise monitoring of the effect through remote sensing, providing a scientifically feasible solution to the problem of salinization caused by seawater intrusion. The second period (2015-2020): In the research on microbial restoration of saline-alkali land during this period, the microbial community is the core acting entity, and its structure and functional changes directly affect the restoration efficiency - through metabolism, it can reduce soil salt content, improve soil structure, and alleviate the degradation caused by salinization. In addition, drip irrigation, as an efficient water-saving irrigation method, can precisely control the distribution of soil moisture and salt content, providing an appropriate living environment for the microbial community and promoting their proliferation and function. Based on fundamentally improving the degraded soil condition through microorganisms, drip irrigation optimizes the restoration micro-environment, forming a "microbial-drip irrigation" linkage salt-alkali land restoration model, providing an important technical path for curbing soil degradation and enhancing the productivity of saline-alkali land; The third period (2020-2025): Representative keywords include the in-depth molecular regulation technology of this period's research, through transcriptome analysis, the molecular mechanism of functional microorganisms regulating salt-alkali soil restoration was explored, focusing on the promoting effect of microbial community dynamic changes on the growth of crop seedlings. Microorganisms can alleviate the inhibition of salt stress on seedling growth by regulating soil physical and chemical properties and optimizing the micro-environment. Transcriptome analysis can reveal the dynamic gene expression of seedlings responding to salt-alkali stress at the molecular level, clarify the activation mechanism of stress-related genes, and analyze the molecular pathways by which microorganisms promote the adaptation of seedlings to the salt-alkali environment. That is, under salt-alkali stress, microorganisms activate salt-resistant related gene expression, regulate plant hormone signaling pathways, and enhance the antioxidant capacity and ion homeostasis maintenance ability of plants. This not only clarifies the macroscopic effect of microbial restoration of saline-alkali land, but also reveals its microscopic molecular mechanism through transcriptome technology, providing a scientific basis for targeted regulation of microbial-plant interaction and improving the survival rate of crop seedlings in saline-alkali land (Figure 6D).

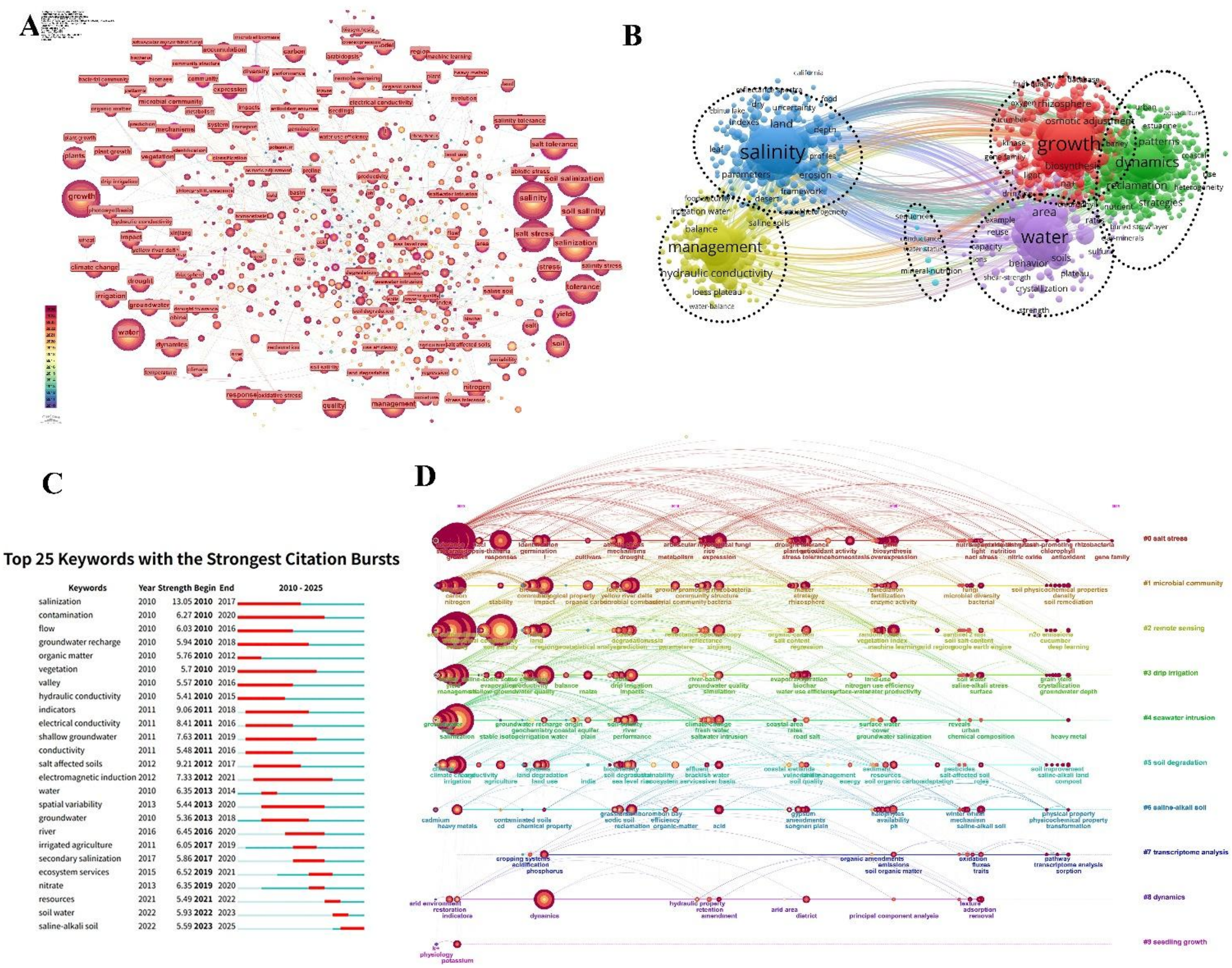

Figure 6 Visualization of Co-Occurrence Keywords Analysis based on Microorganisms in Soil Salinization Remediation

4 DISCUSSION

The phenomenon where soluble salts accumulate in the soil due to natural or human-induced unreasonable irrigation and other human activities is called soil salinization. The salt input caused by human activities (such as unreasonable irrigation, unreasonable development and utilization of water resources, excessive use of fertilizers, seawater intrusion, etc.) is the main source of secondary salinization salts[11]. The excessive accumulation of salts in the soil not only increases the salt stress on plants, inhibits their absorption of water and nutrients, and reduces their photosynthetic capacity, thereby leading to a decrease in soil organic carbon input and crop yield; but also, may inhibit microbial activity and metabolism, thereby affecting the process of material and energy exchange between the soil-vegetation-atmosphere continuum[12]. Although saline-alkali soil is not suitable for the survival of animals and plants, it is home to a large number of salt-tolerant and even salt-loving microbial groups. The life activities of these microorganisms, while changing the physical and chemical properties of saline-alkali soil, are also affected by its extreme physical and chemical properties, thus possibly forming cell structures, genetic characteristics and physiological functions adapted to high saline-alkali environments, different from those of ordinary microorganisms[13]. Therefore, this paper conducted a visual analysis of international research papers on microbial remediation of saline-alkali land from 2010 to 2025 using CiteSpace, VOSviewer and Bibliometrix R. The results show that Chinese researchers have a high level of attention and a high number of publications in this research field, and have a high influence in this research field. Among them, the research institution with the highest number of publications is the Chinese Academy of Sciences.

The research focus on the restoration of saline-alkali wetlands is concentrated on using functional microorganisms to drive the core process of ecological restoration, that is, the structure and dynamic succession rules of microbial communities, aiming to clarify the key beneficial microorganisms (such as salt-tolerant root nodules, phosphate-solubilizing bacteria, etc.)

and their growth patterns in different restoration stages[14]. In addition, the core of this field of research lies in analyzing the interaction mechanism between microorganisms and plants (especially pioneer plants or salt-tolerant crops), and using transcriptomics and other multi-omics technologies to reveal how microorganisms regulate plant gene expression (such as activating ion transport proteins, synthesizing osmotic regulation substances-related genes) to enhance the host's salt tolerance and promote seedling establishment and healthy growth[11,15,16]. At the same time, paying attention to the mechanism of soil microenvironment improvement mediated by microorganisms is also a current research hotspot in this field. This includes the dynamic effects of metabolites (such as organic acids, extracellular polysaccharides) on soil aggregation structure, pH value, sodium ion adsorption and leaching [17].

The potential research hotspots tend to be more refined and comprehensive. One is the construction and application of synthetic microbial communities (SynComs), that is, designing artificial probiotic communities based on community functions to obtain more stable and efficient remediation effects than single microbial agents [18]. The second is the integration analysis of multi-omics (metagenomics, transcriptomics, metabolomics) data to systematically reveal the interaction network and regulatory hubs between "microorganisms-plant-soil environment"[19]. The third is the linkage effect of microbial-assisted plant remediation and carbon sequestration, exploring the dynamic changes of soil organic carbon pools and the driving role of microorganisms in the ecological restoration process of saline-alkali wetlands, which has both ecological benefits and carbon neutrality value [20].

5 CONCLUSION

Our research has for the first time provided a scientific and comprehensive overview of the trends in microbial remediation of saline-alkali land over the past 25 years. The study found that the related research results have gradually attracted the attention of the international community. Functional microorganisms play a crucial role in restoring saline-alkali wetlands by regulating the expression of plant salt-tolerance genes and improving the soil microenvironment. Future research will focus on designing synthetic microbial communities, analyzing multi-omics interaction networks, and jointly enhancing the efficacy of ecological restoration and carbon sequestration, providing innovative solutions for the sustainable management of saline-alkali wetlands.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

FUNDING

The authors thank all participants who agreed to take part in this study. This work was supported by the Project of Weinan Science and Technology Bureau (2023ZDYFJH-276); Weinan Public Scientific Literacy Enhancement Program Project (WNKS24-1-13); Weinan Normal University Talent Project (201122170; 201425108); National College Students' Innovation Training Program (8308).

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