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Review

Analysis of Saline-Alkali Land Improvement Based on Big Data Mining

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Abstract

Saline land is widely distributed and large in the world. It has low fertility and is difficult to utilize, which restricts the economic development of many regions in the world, including China. This paper quantitatively summarizes the hotspots and potential trends of saline-alkaline land research and proposes shortcomings to provide reference for future saline-alkaline land improvement. This paper conducted a bibliometric review of the WoS core collection database using CiteSpace software, and the results show that there is an upward trend in research on improving saline-alkaline land. China is a major contributor to this research field, and the journal PLANT SOIL has many articles with high centrality and high impact factor. Saline and alkaline land improvements mainly focus on the direction of bio-improvement, which is low-cost, has little impact on the environment, and is suitable for large-scale popularization. The application of desulfurization gypsum and biochar to improve soil is also a hot research topic at this stage, and the heat of biochar improvement of saline-alkaline land may continue. The management of saline-alkali land presents challenges, including high costs, transient improvement effects, environmental pollution, and issues related to regional adaptability. Future research should prioritize interdisciplinary studies, sustainable and environmentally friendly improvement methods, investigations into regional adaptability, and long-term monitoring.

Keywords: saline alkali land, saline alkali land improvement, visual analysis, CiteSpace

Introduction

Salt stress is a major environmental factor limiting plant distribution, growth, and crop yields [1, 2]. Soil salinization affects approximately 1100 million hectares of cropland worldwide [3, 4]. Canada and the United States have saline-alkali land areas of 7,238,000 hectares and 8,517,000 hectares, respectively [5]. In addition, India has 7 million hectares of saline land [6]. In fact, three hectares of cultivated land are degraded every minute due to increasing soil salinity [7]. Developing strategies for the use of saline land is critical to addressing the shortage of arable land and the challenge of food security [8] for an estimated 9.3 billion people worldwide by 2050.

A total of 99.13 million hectares of saline alkali land are mainly distributed in northern China [9]. In China, saline alkali land is mainly distributed in provinces north of the Yangtze River, which is determined by the geographical and climatic characteristics of the region. The region is divided into eight regions [10]. Semiarid

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and semi-humid saline and alkaline areas in the Huang Huai Hai Plain, coastal saline and alkaline areas, alpine arid saline and alkaline areas in the Xizang Plateau, tropical and subtropical salt marsh areas (mangrove areas). For example, the saline alkali land in Shandong Province is mainly distributed in the Yellow River Delta, because the Yellow River brings sediment into the Bohai Bay, filling it up and forming new land. Saline alkali land can be divided into three categories: coastal saline alkali land, inland saline alkali land, and heavily irrigated soil [11]. According to established guidelines from institutions such as the United States Salinity Laboratory [12] and the Food and Agriculture Organization of the United Nations [13], saline-alkali soils are classified into mildly, moderately, and severely saline-alkali soils. Electrical conductivity (EC) classifies these soils as follows: 2-4 dS/m indicates mildly saline-alkali soil, 4-8 dS/m indicates moderately saline-alkali soil, and above 8 dS/m indicates severely saline-alkali soil. In terms of pH value, soils with a pH below 8.5 are classified as mildly saline-alkali, those with a pH between 8.5 and 9.5 as moderately saline-alkali, and those above 9.5 as severely saline-alkali. When classified by exchangeable sodium percentage (ESP), soils with less than 15% ESP are considered mildly saline-alkali, those with 15%-30% as moderately saline-alkali, and those exceeding 30% as severely saline-alkali. The formation of these saline-alkali lands is influenced by both climatic factors and human activities. Unsustainable irrigation practices over centuries have exacerbated the salinization of farmland. At present, various strategies have been developed to improve and utilize saline alkali land [14], such as planting halophytes as food and forage.

This article explores the research on saline alkali land or improved saline alkali land from October 31, 2003, to October 31, 2023, from the perspective of bibliometrics. In this article, we elucidate the main research status, potential trends, and existing problems in the field of saline alkali land through a bibliometric review. Compared with traditional discourse, the analysis based on bibliometric software has weaker subjectivity and provides better insight into the focus and trends of saline alkali land research. However, CiteSpace analysis also has certain limitations. For example, if similar keywords may appear in the analysis results, they need to be merged and analyzed. In addition, some keywords used for retrieval may have appeared in the literature but do not match the topic of interest. Then these keywords must be deleted before analysis. Undoubtedly, visual analysis provides valuable information for future researchers. To some extent, visual analysis has promoted our understanding of saline alkali land research and helped us identify potential research priorities and trends in the field of saline alkali land.

Review and Analysis Methods

In order to explore the research progress of saline alkali land improvement, a literature analysis was conducted on the WoS core collection database. WoS is an important database resource for obtaining global academic knowledge, with powerful combination retrieval functions [15, 16]. The search is based on a search benchmark using the "AND" and "OR" operators, and the search code in the database is as follows:

TS = (xxx* AND/OR xxx*)

It is known that "TS" represents the topic of the article, "xxx" and "*" are search terms and fuzzy search criteria, respectively. Further details of the author search benchmarks are as follows:

The search process described in this paper is as follows: First, a comprehensive set of keywords covering various aspects of the topic was compiled based on a preliminary review of the literature and consultations with domain experts. Since this article primarily focuses on the review of saline-alkali land improvement, the keywords selected for this search were "Improvement saline-alkali soil", "improvement saline-alkali land", "saline-alkali land", and "saline-alkali soil". Boolean operators were then employed to combine the keywords using the expression ("Improvement saline-alkali soil" OR "improvement saline-alkali land" OR "saline-alkali land" OR "saline-alkali soil") to maximize the inclusion of all relevant literature. Papers published between October 31, 2003, and October 31, 2023, were retrieved from the database. Additionally, to ensure high-quality papers, only English articles and review articles [14] were selected as the document types [17]. A total of 875 papers were screened. To maintain the consistency and reliability of the data over time, the same parameters were used to repeat the search within three months after the initial paper retrieval, aiming to supplement and rectify any omissions in the literature. In the CiteSpace network, each node represents an object with a colored circle (or cross, triangle, square). Some objects are connected by lines. The strength of the partnership is represented by the thickness of the link. Colors are used to correspond to different years. In keyword co-occurrence networks, each node represents a keyword, and the size of the node (or font size) reflects how often the keyword appears in the dataset. The higher the frequency, the larger the node size.

Studies published after October 31, 2023, were excluded due to insufficient citation data, which may affect the representation of very recent breakthroughs. Readers are encouraged to consult updated databases for the latest developments.

Results and Discussion

Visual analysis relies on several bibliometric techniques applied using CiteSpace [18, 19], including quantitative analysis, keyword clustering, and burst analysis, journal co-citation analysis, document co-citation analysis, etc. CiteSpace maps knowledge domains by systematically creating accessible graphs that uncover semantic knowledge hidden in large amounts of information and track the frontiers of technology [20, 21]. CiteSpace software provides a variety of input threshold options, such as time slicing, data selection criteria, and pruning policies. A reasonable input threshold can make the generated network layout clearer and more reasonable. Since no articles on saline soils were retrieved between October 31, 2003, and December 31, 2003, the following analyses begin in 2004.

Analysis of the Number of Articles Issued

As shown in Fig. 1, according to the information in the literature records to identify the publication time of the paper, the number of publications has been slowly increasing until 2018, and the number of publications has increased sharply since 2018. In 2004, there was only one article on saline-alkali land, and in 2022, the number of articles reached 205. According to the trend line, it can be predicted that the number of articles about saline-alkali land will reach 208 in 2024, which is closely related to scholars 'continuous efforts to overcome scientific research problems and people's increasing emphasis on ecological construction. General Secretary Xi Jinping pointed out that the comprehensive transformation and utilization of saline-alkali land should be done well. Comprehensive transformation and utilization of saline-alkali land is an important aspect of cultivated land protection and improvement. There are many saline-alkali lands in China, and the salinization trend of cultivated land in some areas is aggravated. It is of great significance to carry out the comprehensive transformation and utilization of saline-alkali lands.

Author and Organization Analysis

Author co-occurrence analysis can identify the core authors in the field and the cooperation intensity among authors. The size of the node indicates the number of posts, and the larger the node, the more posts; the thickness of the link indicates the density of cooperation between authors; the color of the node indicates the time of posting. And if the node itself is located in the middle of the connection, then the node has a high centrality. In Fig. 2, you can see that N = 539, E = 865, and the network density is 0.006. The largest cooperation teams in the nodes displayed are Liu, Wei, Li, Pengfei, Li, Jing, Liu, Hongguang, Li, Yi, Liang, Jiaping, Liu, Zhen. Most of these scholars come from universities. Their research directions include forestry, agriculture, ecology, and water resources. These authors have published articles in recent years. The top 10 authors are listed in Table 1. The author with the most publications is Tang J., with 11 articles, and his first article was published in 2012. Liu S., was the next most published author with 10 articles, and his first article was also published in 2012. These two scholars are from Jilin University and Northeast Forestry University, respectively, which are among the top 10 institutions in terms of publications. Tang J.'s most recent publication is from 2021, The Development and Utilization of Saline-Alkali Land in Western Jilin Province Promoted the Sequestration of Saline-Alkali Land in Western Jilin. Province Promoted the Sequestration of Organic Carbon Fractions in Soil Aggregates [22] was published in the journal AGRONOMY-BASEL, which is of high quality. Liu S., recently published an article in 2020. Sexual Differences in Physiological and Transcriptional Responses to Salinity Stress of *Salix linearistipularis*

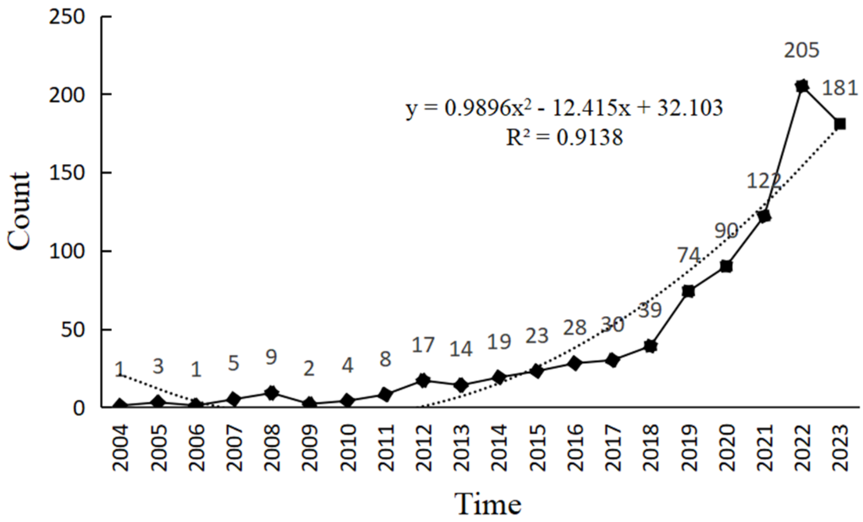

Fig. 1. Curve diagram of issued documents from 2004 to 2023.

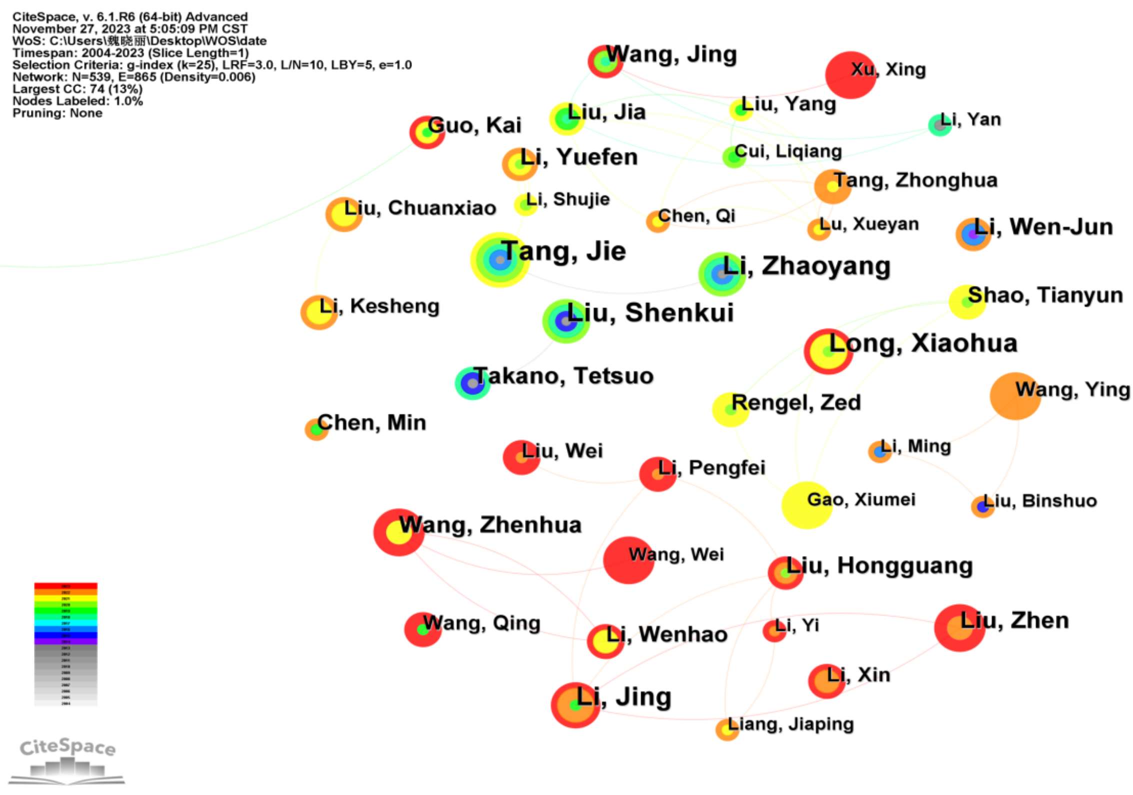

Fig. 2. Author atlas of articles published from 2004 to 2023.

[23] was published in the journal FRONTIERS IN PLANT SCIENCE, which has an impact shadow of 5.6 and is of high reference value.

The author conducts research in a certain disciplinary field by publishing papers or participating in academic activities, and the research content of the institution is, to some extent, presented through academic papers. CiteSpace reflects research hotspots in related fields based on node size and centrality, and utilizes the Institution module in CiteSpace to study the publishing institutions of literature. Fig. 3 shows a shared node N = 350, with a connection E = 401 and a network density of 0.0066. The size of the node reflects the number of the organization's publications, while centrality measures the importance of the node and reflects its degree of importance. Table 1 lists the top ten core research institutions that have published papers. It can be seen that 8 of the top 10 institutions are universities, with 311 papers published, accounting for 60% of the top 10 papers. Therefore, research on saline alkali land mainly focuses on universities and research institutes. The top-ranked is the Chinese Academy of Sciences, with a publication volume of 161 articles and relatively high centrality, reaching 0.69. After extensive reading of these 161 articles, it can be seen that the main research directions of the Chinese Academy of Sciences are "halophytes" and "soil microorganisms", as well as research on "amendments" [24, 25], "soil monitoring" [26, 27], and "irrigation methods" [28, 29], but the number of publications is relatively small. It is worth noting that the cooperation among various institutions is relatively scattered, with only a small part of the cooperation network centered around Chinese Academy of Sciences, Jilin University, Jilin Agricoltural University, and Chinese Academy of Agricultural Sciences, and there is less academic exchange between other institutions.

Generally speaking, there is a problem of little cooperation and exchange between authors and institutions. It can also be found that there is little interdisciplinary cooperation according to the research direction of cooperative scholars. Most of the cooperative scholars are in the same type of research direction. Most of the cooperation among institutions is also in the same region, and there is little cross-regional cooperation and exchange. Therefore, there is much room for cooperation and exchange between scholars and research institutions in the field of saline-alkali land in the future.

Given the current situation characterized by low collaboration intensity and weak cooperation among authors and institutions in this field, it is essential to establish specific mechanisms that foster a more robust research network. The following measures are recommended: 1) Build collaboration platforms and databases. Establishing dedicated collaboration platforms and databases can significantly enhance communication and data sharing among researchers. These platforms should store research findings, datasets, and best practices, making them accessible to the global scientific community.

Table 1. Number of publications by authors and institutions.

Rank	Author				Institution			
	Count	Centrality	Year	Name	Count	Centrality	Year	Institution
1	11	0.01	2012	Tang, Jie	161	0.69	2005	Chinese Acad Sci
2	10	0.02	2012	Liu, Shenkui	62	0.12	2013	Univ Chinese Acad Sci
3	9	0.01	2019	Li, Jing	50	0.1	2008	Jilin Univ
4	9	0	2012	Li, Zhaoyang	46	0.09	2014	Northeast Forestry Univ
5	9	0	2020	Long, Xiaohua	45	0.18	2013	Chinese Acad Agr Sci
6	7	0	2018	Wang, Jing	37	0.11	2012	Shihezi Univ
7	7	0	2014	Li, Wen-Jun	35	0.07	2016	Shandong Agr Univ
8	7	0	2020	Li, Yuefen	27	0.02	2012	Jilin Agr Univ
9	7	0	2021	Wang, Zhenhua	27	0.09	2015	Nanjing Agr Univ
10	7	0.01	2020	Liu, Hongguang	27	0.11	2012	China Agr Univ

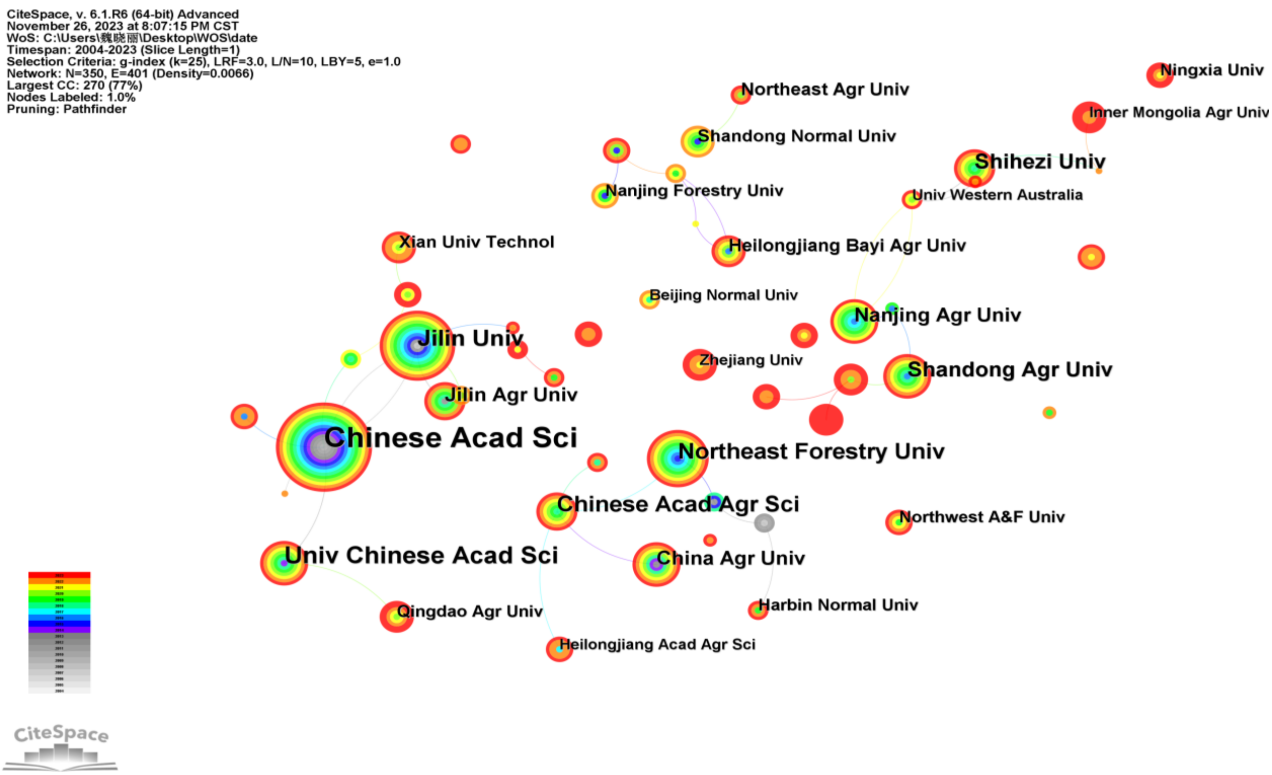

Fig. 3. Atlas of issuing organizations from 2004 to 2023.

2) Organize international seminars and conferences. Regularly organizing international seminars and conferences focused on saline-alkali land management will provide researchers with a platform to showcase their results, exchange ideas, and establish cooperative relationships.

3) Promote joint research projects and funding. Encouraging joint research projects and funding can incentivize researchers from various institutions and countries to collaborate. Funding agencies can play a crucial role by establishing dedicated funds to promote international cooperation.

4) Establish interdisciplinary research centers. Creating interdisciplinary research centers that focus on saline-alkali land management can foster collaboration among experts in soil science, agronomy, ecology, and socio-economics. These centers can serve as innovation hubs, providing a supportive environment for collaborative research.

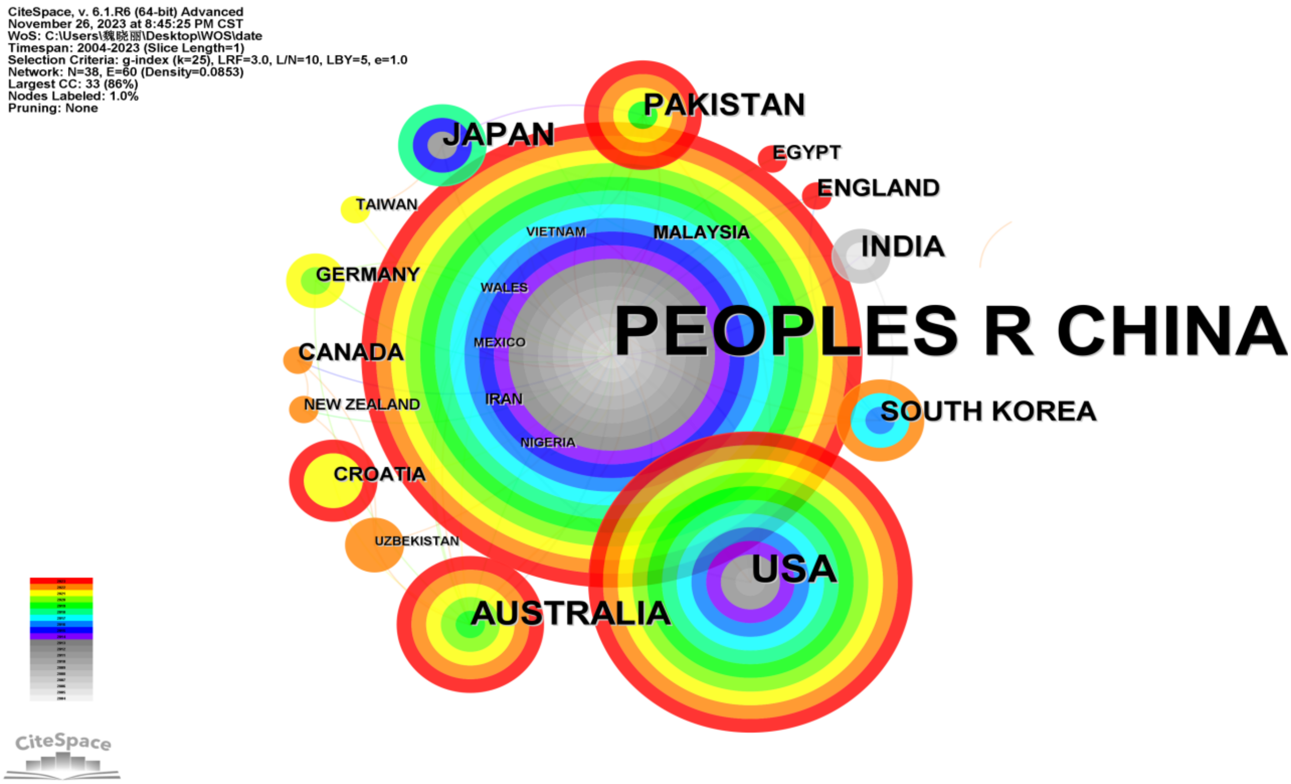

Fig. 4. Issuing countries from 2004 to 2023.

Analysis of the Sending Country

As shown in Fig. 4, in this network, the time slice length is 1. The criteria for data selection are g-index (k = 25), LRF = 3.0, L/N = 10, LBY = 5, e = 1.0. There are a total of 38 nodes and 60 links. Each node represents a country, and the size of the node reflects the number of articles published by that country. The more papers a country publishes, the larger its node size. Centrality represents the importance of specific nodes in a network [30]. Therefore, the more central a country is, the more publications it collaborates with other countries to publish. Table 2 shows that China has the largest number of publications and centrality, followed by the United States. The frequency of publications related to saline alkali land in China is 846, with a centrality of 1.32. The research results on saline alkali land in China are worth learning from around the world.

China's saline-alkali land area constitutes 10% of the global total, representing a substantial land resource that has prompted the nation to focus on developing scientific and technological solutions aimed at improving soil quality and enhancing agricultural productivity. Saline-alkali lands are predominantly located in the Yellow River Delta, the Bohai Rim region, and the northwestern provinces, which provide favorable conditions for targeted research programs and large-scale demonstration projects [31]. The Chinese Academy of Sciences (CAS) and the Ministry of Science and Technology (MOST) have played a pivotal role in advancing research and innovation in saline-alkali land management. For example, initiatives such as the “Bohai Granary Science and Technology Demonstration Project” have facilitated collaboration among multidisciplinary teams to develop and implement cutting-edge technologies, including salt-tolerant crop breeding, brackish water irrigation, and soil enhancement techniques [9]. These efforts have not only increased local agricultural productivity but have also established China as a global leader in this domain. Given the widespread nature of saline-alkali land issues globally, international cooperation and technology transfer are essential for addressing these challenges on a large scale [32]. China's experience in managing saline-alkali lands offers valuable insights for other countries confronting similar issues. The techniques developed in China to improve soil fertility and enhance crop yields in saline-alkali areas can be adapted and applied in regions such as Central Asia, the Middle East, and Africa [33].

To facilitate international cooperation and technology transfer, the following strategies are recommended: 1) Establish knowledge-sharing platforms: Create international forums and online platforms to disseminate research findings, best practices, and case studies on saline-alkali land management. 2) Launch joint research projects: Promote collaborative research between Chinese institutions and international partners to develop tailored solutions for the specific needs of various regions. 3) Strengthen capacity building:

Table 2. Issuing countries.

Rank	Count	Centrality	Year	Countries
1	846	1.32	2005	CHINA
2	34	0.09	2007	USA
3	21	0.05	2012	AUSTRALIA
4	17	0	2007	JAPAN
5	16	0.02	2014	PAKISTAN
6	13	0	2004	INDIA
7	11	0.01	2007	SOUTH KOREA
8	7	0	2015	CANADA
9	7	0	2016	ENGLAND
10	5	0	2019	GERMANY

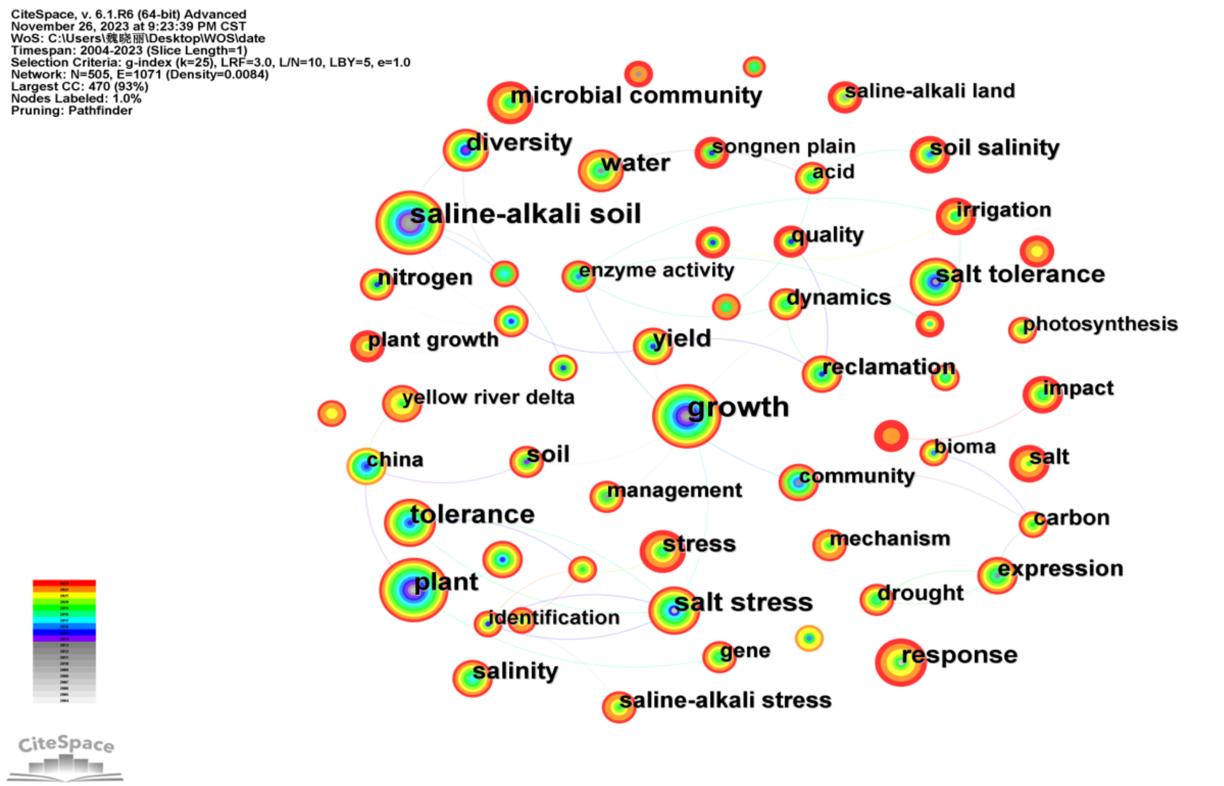

Fig. 5. Keyword co-occurrence graph.

Implement training programs and workshops for researchers and practitioners from other countries, enabling them to leverage Chinese experiences and adapt relevant technologies to local contexts. 4) Provide policy and financial support: Encourage governments and international organizations to offer financial and policy support for saline-alkali land research and development projects, thereby promoting the transfer and implementation of established technologies.

Keywords Clustering and Burst Analysis

Through keyword cluster map and emergent word analysis, the current research trend of saline-alkali land was explored. Cluster analysis is used to detect and analyze research trends that emerge over time and to determine the focus of research trends at a particular time in its knowledge base [20, 21]. Clustering can reveal interrelationships between different research trends. A burst word represents a significant increase in the number of occurrences of the keyword in a short

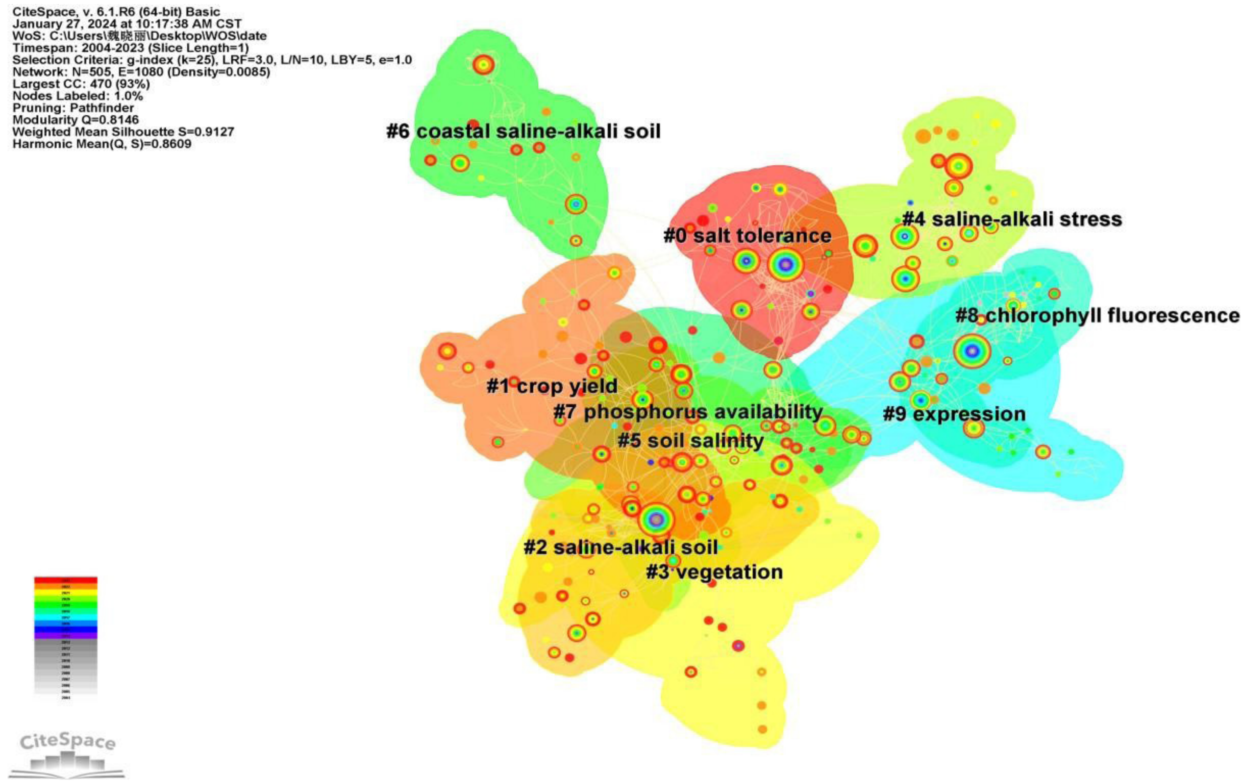

Fig. 6. Keyword clustering.

period of time, indicating that the article received a lot of attention in the corresponding year [20, 21]. First, a keyword co-occurrence ring network is generated. As shown in Fig. 5, the keyword co-occurrence network has 505 nodes and 1071 links. Time slice length is 1. The selection criteria were g index (k = 25), LRF = 3.0, L/N = 10, LBY = 5, e = 1.0. There are 12 keywords with frequency over 50, including growth (frequency = 143), saline-alkali soil (frequency = 109), tolerance (frequency = 90), salt stress (frequency = 84), plant (frequency = 76), etc.

Secondly, using the log likelihood ratio (LLR) algorithm, a total of 16 important clusters were identified based on keywords, and Fig. 6 only shows the top 10 clusters. The LLR algorithm can select the best clustering labels based on uniqueness and coverage [34]. Clustering is sorted by size, i.e., the number of members included in the cluster. Cluster # 0 "salt tolerance" is the largest with 42 members, while cluster # 15 "Phenotype" is the smallest with 17 members. Table 3 lists all clusters and their information, including "cluster size", "contour value", "average year", and "LLR label". The silhouette metric measures the average homogeneity of a cluster [35]. The larger the contour score, the stronger the consistency of cluster members. The silhouette values of the clusters range from 0.832 to 0.987, indicating a high degree of consistency among the members of each cluster. The average publication year of clustering refers to whether it is composed of recent or older papers. If we use 2014 as the dividing line to distinguish between old and new papers, there are 11 clusters composed of recent papers. Based on the cluster diagram, cluster # 0-15 has formed a technical application framework with saline alkali land and improved saline alkali land as the core, supporting research on saline alkali land. These 16 clusters can be roughly divided into two categories: research on methods for improving saline alkali land and research on the physical and chemical properties of saline alkali soil. The main methods for improving saline alkali land include clustering # 0, # 1, # 4, # 7, # 9, etc. Based on the keywords shown in Table 3, we can see that more research on saline alkali land improvement focuses on plant improvement, involving plants such as Qinghai Plateau Jerusalem artichoke, star grass, two-color blood supplementing grass, Arabidopsis, and other salt alkali-tolerant forage plants. The clustering of soil physicochemical properties in saline alkali land mainly includes # 3, # 6, # 8, # 10, etc. The keywords involved in these clustering mainly include saline alkali soil, soil properties, soil physicochemical properties, etc.

Finally, perform burst detection based on the algorithm developed by Kleinberg [36]. Fig. 7 ranks the top 16 keywords with the strongest citation burst by intensity. China (2013-2019) received the strongest attention with a burst strength of 5.75, which is consistent with the results of the publishing country. Next are ecosystem (burst strength = 3.99,2009-2017) and photosynthesis (burst strength = 3.75,2019-2021), and the relationship between the overall environment and saline alkali land has also been explored by many

Table 3. Keyword clustering by size.

Cluster ID	Size	Silhouette	Mean (Year)	Label (LLR)
#0	42	0.959	2011	salt tolerance; alkali stress; trait; helianthus tuberosus; transport
#1	37	0.881	2013	chlorophyll fluorescence; puccinellia tenuiflora; saline-alkali resistance; limonium bicolor
#2	35	0.832	2015	Biochar; soil amendment; coastal saline soil; heavy metal; crop yield
#3	34	0.964	2012	saline-alkali soil; bacterial community; soil properties; biodegradation; microbial community
#4	33	0.956	2014	saline-alkali stress; salt stress; abiotic stress; arabidopsis; metabolome
#5	31	0.937	2015	phosphorus availability; remediation technology; material composition; daan city, msc-elm
#6	31	0.853	2016	soil physicochemical properties; amelioration; clay; water content; fractal dimension
#7	29	0.987	2013	coastal saline-alkali soil; salt; wheat yield; alkaliphile; environmental variable
#8	29	0.947	2014	bacterial diversity; microbial community; pennisetum sinese; oil contamination; community structure
#9	29	0.837	2016	Vegetation; carbon; soil microbial diversity; nov; polyphasic taxonomy
#10	28	0.868	2017	saline-alkali land; soil salinity; deoxyribonucleic acid; emended description; halophilic
#11	28	0.941	2017	nacl stress; saline-alkali soil; transcription factors; available phosphorus; plant biomass
#12	26	0.933	2015	leymus chinensis; gene expression profiles; morphological plasticity; root growth; salt stress
#13	23	0.951	2010	soil CO_2 flux; landscape fragmentation; hydrogeochemistry; sustainable land management; irrigation activities
#14	18	0.921	2018	tall fescue; endophyte; biomass; arbuscular mycorrhizal fungi; arbuscular mycorrhizal fungi (amf) diversity
#15	17	0.928	2020	Phenotype; antioxidant enzymes; agronomic traits; forage nutritive value; antioxidant enzyme

scholars. Some keywords have always been the focus of attention in the field of saline alkali land, such as *Arabidopsis thaliana* (burst strength = 3.04,2008-2019), abiotic stress (burst strength = 2.84,2007-2017), and *Puccinellia tenuiflora* (burst strength=3.43,2007-2016), indicating that biological control has always been a topic of concern in research on saline alkali land improvement. From the timeline of keyword burst, there is no particularly clear pattern, but keywords that erupted before 2014 were all plants, ecosystems, etc. After 2014, mechanism research began to emerge, and the keyword "heavy metal" appeared, indicating that the scientific research level is constantly improving. People not only focus on improving measures for saline alkali land, but also pay attention to the impact of improvement methods on the environment [37]. This is the process of scholars' research and development transformation on saline alkali land.

Journal Co-Citation Analysis

Journal co-citation analysis reflects the correlation among journals. Through this type of analysis, the intellectual roots of published work in a field are obtained. The number of co-citations of various journals is shown in Fig. 8, where the time slice length is 1. The selection criteria are: Top30, LRF = 3.0, L/N = 10, LBY = 5, e = 1.0. To remove excessive links, network pruning is used via the Path-finder strategy, which is recommended by Chen and Morris [38]. There are 671 nodes and 3307 links in this network. Each node represents a journal, and the size of the node represents the number of times the journal has been co-cited. The more times a journal is co-cited, the larger the node size. Among them, SCI TOTAL ENVIRONMENT, PLANT SOIL, GEODERMA, PLOS ONE, and APPL SOIL ECOL were cited most frequently.

Moreover, if a node connects two or more large node clusters, and the node itself is in the middle, it has a high centrality. Table 4 lists the top 5 journals for centrality. Plant Soil magazine had the highest centrality, 0.16. High school psychology represents a great deal of importance to these journals. The journal has an impact factor of 4.9, which belongs to Q1, so the quality of articles in this journal is relatively high. The results of these analyses provide the basis for further research,

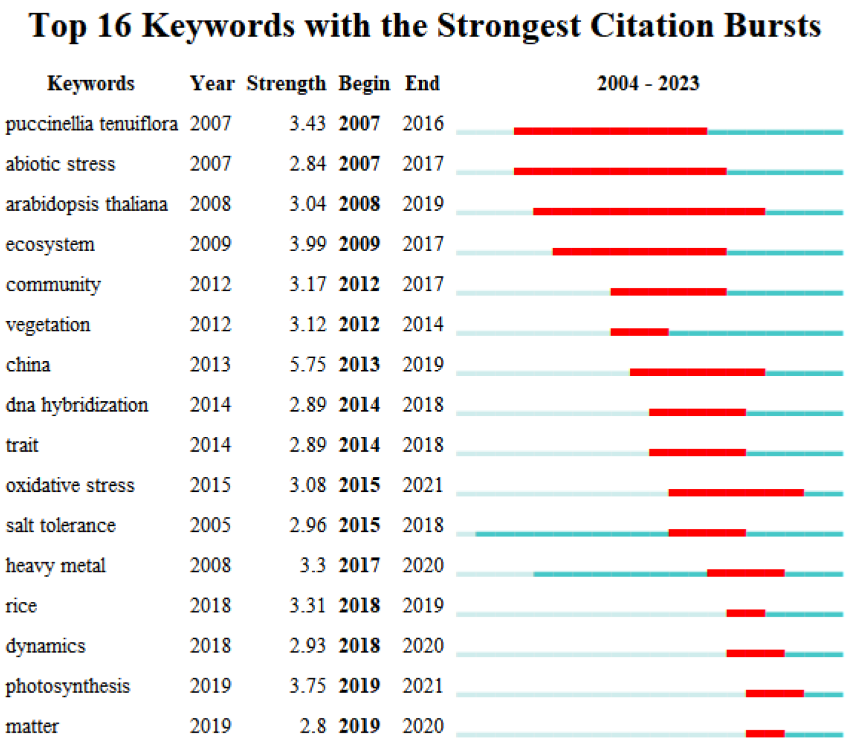

Fig. 7. Top 16 keywords with the strongest references to outbreaks.

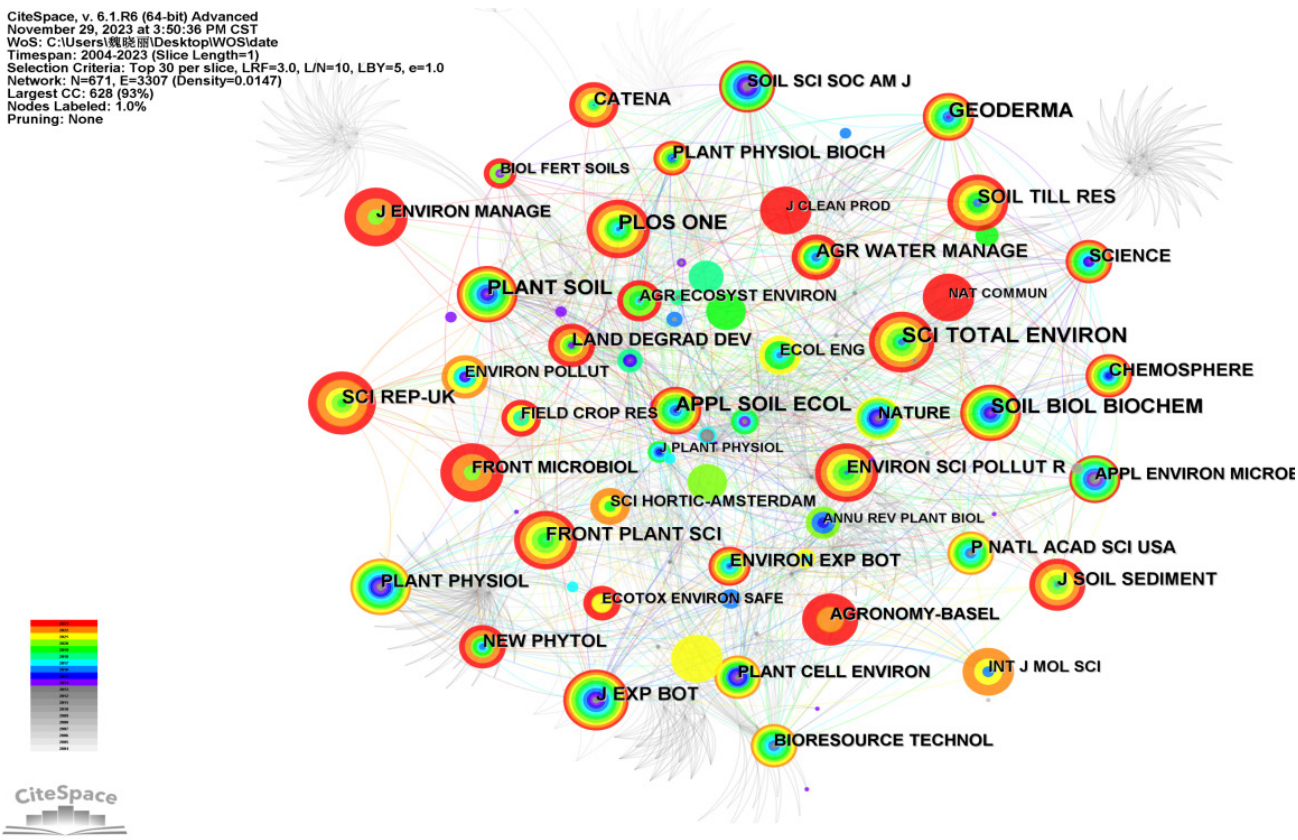

Fig. 8. Journal co-citation network.

Table 4. Top 5 co-cited journals.

Rank	Cited journals sorted by count				Cited journals sorted by centrality			
	Count	Centrality	Year	Journal co-citation	Count	Centrality	Year	Journal co-citation
1	358	0.01	2013	SCI TOTAL ENVIRON	330	0.16	2004	PLANT SOIL
2	330	0.16	2004	PLANT SOIL	191	0.12	2005	AGR WATER MANAGE
3	293	0.02	2011	GEODERMA	119	0.08	2007	BIORESOURCE TECHNOL
4	266	0.01	2015	PLOS ONE	159	0.07	2011	ENVIRON EXP BOT
5	246	0.03	2013	APPL SOIL ECOL	107	0.06	2005	SOIL SCI SOC AM J

and subsequent researchers can further investigate the direction of saline land research by collecting papers from these top journals.

Document Co-Citation Analysis

The literature co-citation analysis shows the number and authority of references cited by publications and their authors [34]. Identify leading researchers in a field of knowledge. Fig. 9 shows a co-citation network for various documents with a time slice length of 1. The selection criteria are: LRF = 3.0, L/N = 10, LBY = 5, e = 1.0. Network pruning is a pathfinder strategy. In this network, there are 701 nodes and 2005 links. Each node represents an article with the first author's name and publication year, and the size of the node represents the number of times the article has been co-cited. The analysis yielded 8 clusters with modularity equal to 0.8172, reflecting that the clustering division is clear. The average silhouette value equals 0.8838, indicating that the cluster division is neat and the members have high consistency. The largest subnetwork of the co-cited network is the most important knowledge link in the domain, containing 106 papers (accounting for 12%), see Fig. 9. In this network graph, a node represents a paper, and the link between papers reflects the co-

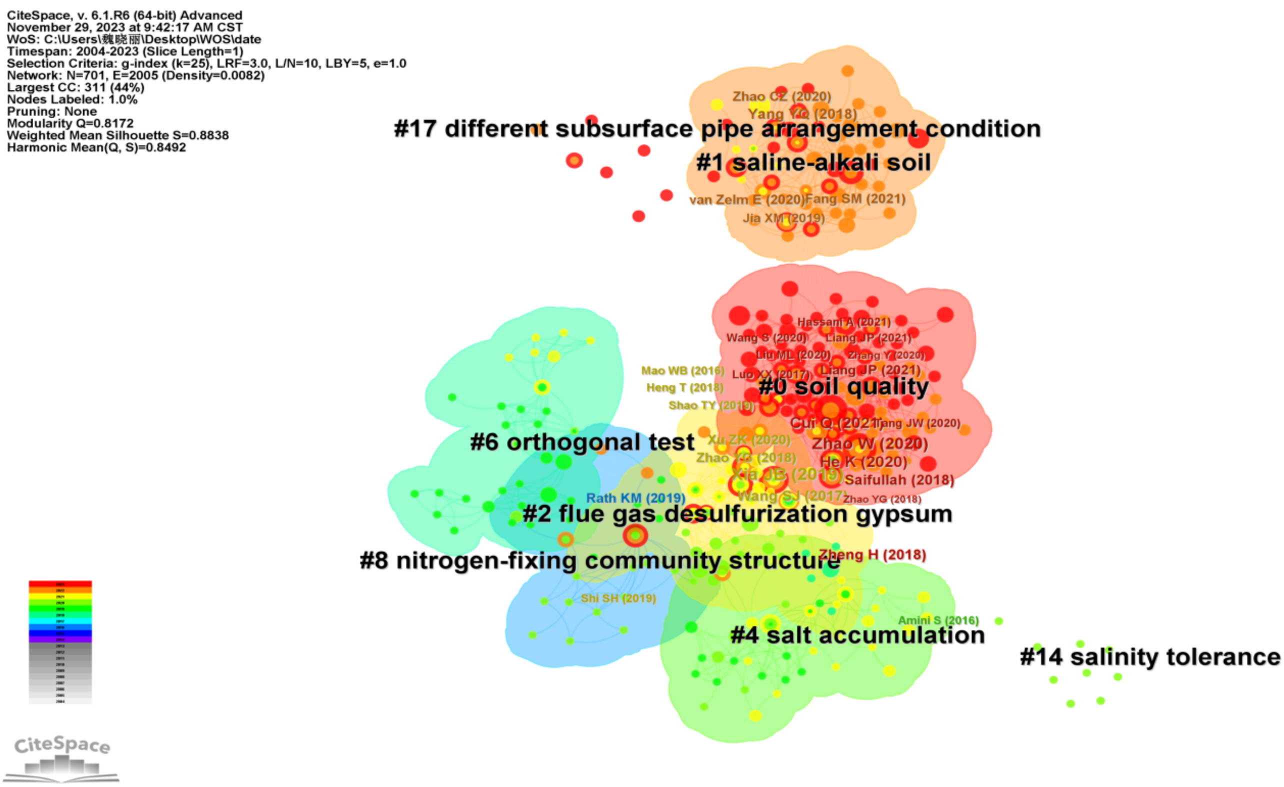

Fig. 9. Document co-citation network clustering.

Table 5. Knowledge base papers on saline-alkali soil research (highly cited papers).

Rank	First Author	Publications	Year	Underlying cluster
1	Xia J.B. [56]	GEODERMA	2019	2
2	Zhao W. [39]	SCI TOTAL ENVIRON	2020	0
3	Cui Q. [57]	SCI TOTAL ENVIRON	2021	0
4	He K. [38]	APPL SOIL ECOL	2020	0
5	Saifullah [58]	SCI TOTAL ENVIRON	2018	0
6	Wang S.J. [34]	RESOUR CONSERV RECY	2017	2
7	Zheng H. [59]	PLANT CELL ENVIRON	2018	0
8	Yang Y.Q. [60]	NEW PHYTOL	2018	1
9	Zhao Y.G. [61]	GEODERMA	2018	2
10	Zhao C.Z. [62]	INNOVATION-AMSTERDAM	2020	1

citation relationship between the 2 papers. The color of the link represents the time when the first co-citation relationship between the 2 papers was established. The closer the time is to the present, the closer the color is to red. The change of rainbow color reflects the evolution of research.

Using the automatic label adding technology of CiteSpace clustering [21], the literature co-citation network clustering is named. The largest cluster here is named #0 soil quality, indicating that there are a large number of studies on "soil quality" that cite literature in this cluster. Cluster numbers are marked in the form of increasing from 0, and the smaller the number, the more documents are contained in the corresponding cluster, reflecting its importance in saline-alkali soil research. In the network, the average time of documents in each cluster is calculated to reflect the time characteristics of documents cited in the corresponding cluster. The published time of the cited articles on saline-alkali soil located at the upper right side of the co-citation network is generally relatively recent, belonging to the latest literature on saline-alkali soil research. The three main clusters included are #0 soil quality (2019), #1 saline-alkali soil (2019), and #17 different subsurface pipe arrangement condition (2019).

In the cluster formed, a batch of research results that have an important influence on saline-alkali land is produced. It can be concluded from the network that a group of documents that play a key role in saline-alkali soil research has been identified in the clustering of saline-alkali soil research in recent years. For example, Zhao W. (2020), Xia JB. (2019), Cui Q. (2021), and He K. (2020) have done important research on saline-alkali land. Zhao W. applied biochar to ameliorate soda saline-alkali land, improve soil function, and increase corn nutrient availability in the Songnen Plain. They concluded that corn straw biochar can be used as an organic amendment to reduce the adverse effects of salinity and alkalinity on soil function, depending on the amount of corn straw biochar added. Forest and grass composite patterns improve the soil quality in the coastal saline-alkali land of the Yellow River Delta, China. Cui Q.'s Biochar and effective microorganisms promote *Sesbania* cannabis growth and soil quality in the coastal saline-alkali soil of the Yellow River Delta, China study shows that: in coastal saline-alkali soil, the combination of appropriate proportion of biochar (3%) and effective microorganisms is an effective strategy to improve soil salinity, improve soil quality and promote plant productivity. He K.'s Biochar amendment ameliorates soil properties and promotes *Miscanthus* growth in a coastal saline-alkali soil. It was found that biochar amendments effectively promote the growth of Portulaca oleracea and mitigate salt stress damage to plants in coastal saline-alkali soil by improving soil physical, chemical, and biological properties. These articles are mainly located in cluster #0.

The knowledge base can be thought of as papers frequently cited by scholars in their research. These papers are like the shoulders of giants, providing basic knowledge support for new research. In the literature co-citation network, the analysis of highly cited papers helps to have a clear understanding of the knowledge base of hot topics. At the same time, clustering the literature composed of a knowledge base is helpful in recognizing the research frontier. Chen Chaomei constructs the mapping relationship between the knowledge base and research frontier in CiteSpace, which provides an effective method for understanding the knowledge base and research frontier in the field concerned. The cited frequency of the top 10 papers in the overall cited ranking exceeded 78 times, and these highly cited papers mainly came from cluster #0 soil quality (5 papers), cluster #2 Flue gas purification gypsum (3 papers), and cluster #1 saline-alkali soil (2 papers). See Table 5 for details.

Prominent literature refers to the node literature with a sudden change in citation volume. Such nodes usually represent the rise or transformation of a certain research field, which has innovative characteristics. The articles

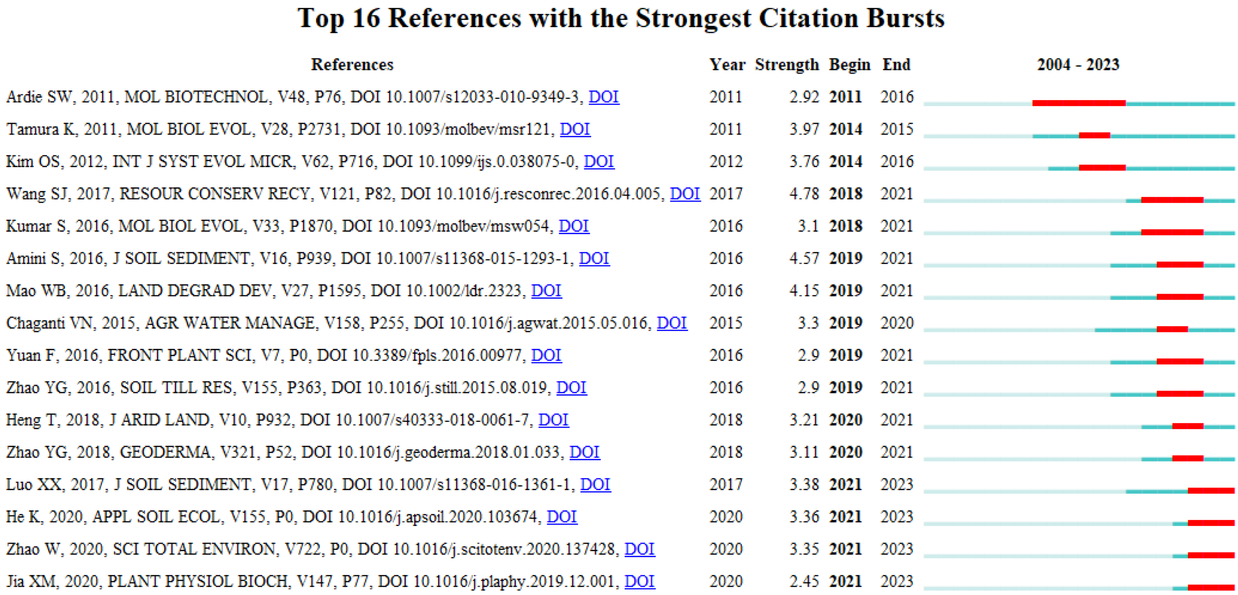

Fig. 10. References with strong citation bursts.

citing prominent literature will reflect emerging topics [39]. 16 articles with the highest emergent intensity in the saline-alkali land domain in the Web of Science database were obtained through three algorithms (see Fig. 10). The sudden increase in citations for a paper indicates that the field has noticed the potential contribution of this paper.

As shown in Fig. 10, the most prominent reference is Wang S.J.'s Research on saline-alkali soil amelioration with FGD Gypsum. Highlight from 2018 to 2021, this is a review article, the article mainly describes that flue gas desulfurization gypsum can be used to improve saline-alkali land, in China has been applied to about 120 km^2 of saline-alkali land; application of desulfurization gypsum in saline-alkali soil can improve the yield of plants in the soil and improve the physical and chemical properties of the soil; the concentration of heavy metals in desulfurized gypsum, soil and plants growing on soil meets the national standard, and the organic carbon content of soil increases greatly after the improvement of saline-alkali land. Finally, it is concluded that the use of desulfurized gypsum to improve saline-alkali soil is a promising technology and deserves to be widely used worldwide [40]. This article is highly referenced to illustrate that the use of desulfurized gypsum to improve saline-alkali land in this direction has been studied by many scholars.

This was followed by Amini S.'s Salt-affected soils, reclamation, carbon dynamics, and biochar: a review, which had a highlight intensity of 4.57 and lasted from 2019 to 2021. The article is also a review of the chemical, physical and biological problems of salt-affected soils and the different improvement methods used to restore these soils; discusses ways to increase carbon stocks on these lands, with emphasis on the use of biochar, a potential new method that not only increases carbon content but also improves soil properties; Little knowledge is presented on the use of biochar in salt-affected soils, and most studies to date have only assessed the use of biochar in salt-unaffected soils [41].

Scholar Mao W.B.'s Yellow River Division as a Soil Amendment for Amelioration of Saline Land in the Yellow River Delta highlights the period from 2019 to 2021, with an intensity of 4.15. This article provides the first evidence that Yellow River sediment can be used as a soil amendment to remediate soil affected by salinity and alkalinity. The conclusion drawn from the four treatments used in the article is that applying Yellow River sediment on saline alkali land is a technically feasible and environmentally sustainable method for the restoration of saline alkali land in the Yellow River Delta [42].

There are 4 articles in Fig. 10 that are relatively recent in the outbreak year, respectively from scholars Luo X.X. [43], He K. [44], Zhao W. [45] and Jia X.M. [46]. Three of the articles were related to the improvement of saline-alkali land by biochar, and the outbreak intensity was 3.35 or above, and the highlight time was from 2021 to 2023. This indicates that biochar as an amendment to saline-alkali soil has become a research hotspot in recent years, and the heat may continue.

The above analysis indicates that biochar and desulfurized gypsum have been extensively researched and applied in the field of soil improvement. However, when assessing their long-term sustainability, it is essential to fully consider their distinctly different characteristics and potential tradeoffs. Firstly, in terms of environmental impact, biochar is renowned for its ability to sequester carbon in soil, thereby helping to mitigate climate change. In contrast, desulfurized gypsum, while lacking a direct carbon sequestration effect, can indirectly promote carbon storage by improving soil structure and reducing soil erosion [47]. Secondly, biochar enhances soil fertility by increasing soil water retention, nutrient availability, and microbial activity [48, 49]. On the other hand, desulfurized gypsum is particularly effective in ameliorating saline-alkali soils by replacing sodium ions and improving soil porosity and hydraulic conductivity [50]. However, the application of biochar necessitates careful consideration of feedstock sources and pyrolysis conditions to avoid potential negative impacts on soil pH and nutrient balance [51]. Additionally, the long-term performance of both materials merits attention: biochar is highly stable in the soil environment, persisting for decades or even centuries, thereby providing long-term benefits for soil quality and carbon storage; whereas flue gas desulfurization gypsum may dissolve over time (especially in acidic soils), its effects on soil structure can persist in the long term [52]. Notably, the addition of biochar promotes microbial diversity and activity, which are crucial for maintaining soil health and nutrient cycling. Flue gas desulfurization gypsum also influences microbial communities, but its effects are more closely related to changes in soil salinity and pH [53].

Improvement of Saline-Alkali Land

After conducting an intuitive visual analysis of the retrieved papers, a critical review analysis was employed to further assess the research progress in the improvement of saline-alkali land. Firstly, the methods for improving saline-alkali land were summarized; then, the existing problems at the current stage were identified. Finally, solutions to these problems and future development trends were proposed.

Methods for Improving Saline-Alkali Land

Physical Improvement

Physical improvement refers to a land reclamation technique that regulates and optimizes the soil structure, physical properties, and the movement patterns of water and salt in saline-alkali soils through various physical means and methods. The aim is to enhance the soil's physicochemical properties, reduce salinity, and improve soil fertility and crop yield. This process includes drainage and salt leaching, soil structure enhancement, and soil compaction management. Gao H. [54] studied the impact of groundwater level depth on the evolution of saline-alkali soils in Huanghua City, located along the Bohai Sea coast in China. His findings indicated that the degree of soil salinization varies with the water level when the groundwater level depth ranges from 1.35 to 3.58 meters. Through appropriate drainage measures, the groundwater level can be effectively managed to mitigate salinization. Xu N. [55] designed and optimized the soil-breaking components of a power harrow suitable for coastal saline-alkali lands. By employing the Discrete Element Method (DEM) and Box-Behnken Design (BBD), he identified an optimal parameter combination that significantly improved the soil-breaking rate, thereby creating favorable conditions for crop cultivation. Lei G.N.[56] proposed a stability control method for agricultural tractor-trailer systems based on dual-trajectory collaborative planning. Through optimized trajectory planning and lateral stability control, this method effectively alleviated soil compaction issues in saline-alkali lands.

The effectiveness of management in physical improvement measures is significant, as these measures are based on straightforward concepts that are easily understood and promoted. However, physical improvement measures primarily focus on the current season, resulting in short-term impacts that are subject to natural conditions, leading to variability in their regulatory effects. Furthermore, substantial investment is required for physical improvement measures, and it is essential to consider the input-output ratio during implementation.

Chemical Modification

Chemical amelioration measures involve the application of various chemical substances, including gypsum, phosphogypsum, superphosphate, humic acid, peat, and vinegar residue, to rehabilitate saline-alkali soils. The fundamental principle underlying this rehabilitation process is to induce chemical reactions with the soil components, resulting in the degradation of the original saline-alkali and other chemical constituents. Foronda D.A. [57] examined the ameliorative effects of combining cattle manure and chicken manure with gypsum on saline-alkali soils, finding that this combined treatment was more effective than gypsum alone. This approach significantly reduced the soil's exchangeable sodium percentage (ESP) and electrical conductivity (ECe), while also improving soil structure. Jiang Z.W. [58] investigated the long-term effects of organic compost application on saline-alkali land and reported a significant increase in the soil's organic carbon content, enzyme activity, and the stability and complexity of the bacterial community. Zhang Y. [59] explored the ameliorative effects of lithium slag on saline-alkali soil and found that appropriate amounts (0.5% and 1.0%) of lithium slag could significantly lower soil pH and promote crop growth. Additionally, Zhang B.X. [60] studied the impact of combining biochar of different particle sizes with bio-organic fertilizer on saline-alkali land, discovering that the combination of 60-mesh biochar and bio-organic fertilizer yielded the most favorable results, significantly enhancing soil fertility and plant growth.

Chemical improvement measures provide the advantages of being both quick and effective, making them suitable for urgent land improvement needs. However, this method involves the use of chemicals that may adversely impact the environment and human health. Therefore, careful control of dosage and application methods is crucial. Current research on chemical improvement measures primarily focuses on their effectiveness. The analysis above indicates a growing awareness of the environmental impacts associated with these methods.

Biological Improvement

Biological improvement involves the use of plants and microorganisms to ameliorate saline-alkali soils. This method relies on the physiological metabolism and ecological impacts of these organisms to regulate various soil factors, including moisture, salinity, organic matter, nutrients, microorganisms, and enzymes. By leveraging these biological processes, soil quality and fertility can be enhanced. Wang X.Q. [61] investigated the ameliorative effects of 5 salt-tolerant plants (including broomcorn millet, wheatgrass, *Leymus chinensis*, *Suaeda salsa*, and *Caragana*) on saline-alkali soils, finding that *Suaeda salsa* had the most significant ameliorative effect on saline-alkali lands, notably increasing the contents of organic matter, total nitrogen, total phosphorus, available phosphorus, and alkali-hydrolyzable nitrogen in the soil. Zhou B.B. [62] examined the combined effects of nitrogen-fixing bacteria and *Chlorella* on wheat growth and saline-alkali soil quality, discovering that the joint application of these two significantly increased wheat biomass, improved saline-alkali soil fertility, and reduced soil pH. Liang S. [63] studied the impact of the combined application of biochar and functional bacteria on saline-alkali land, revealing that this joint application significantly enhanced soil fertility and plant growth, with the most notable promotion effect observed in maize growth.

Biological improvement technology primarily focuses on ameliorating saline-alkali lands through the selection and cultivation of salt-tolerant crops, thereby reducing reliance on chemical fertilizers and pesticides, which contributes to environmental sustainability. This approach is emphasized as a low-cost and scalable method. However, several limitations and risks warrant careful consideration: 1) Although halophytes are naturally adapted to saline environments, their performance varies significantly across different regions and soil conditions, which may limit the predictability and scalability of biological improvement strategies [64]. 2) The introduction of non-native halophytes or salt-tolerant plants for biological improvement may pose invasion risks [65]. Therefore, it is crucial to select plant species judiciously and conduct monitoring to minimize the risk of invasion. 3) Large-scale cultivation of halophytes or other biological amelioration plants may also lead to ecosystem disturbances [66]. Additionally, the removal of salt through phytoremediation may alter soil salinity levels, potentially resulting in unintended consequences for local flora and fauna. 4) While biological amelioration is generally considered cost-effective, its implementation may encounter socio-economic and management challenges. Furthermore, long-term monitoring and management are essential to ensure the sustainability of biological amelioration projects, which may necessitate substantial resource investment [67].

Development Trend

In the future improvement of saline-alkali land, we should focus on the following points.

(1) Future interdisciplinary research should prioritize the integration of various fields, merging insights and technologies from soil science, ecology, microbiology, and materials science. This approach aims to develop more efficient, environmentally friendly, and sustainable methods for the improvement of saline-alkali land. The research conducted by Professor Qiao Jianjun's team at Tianjin University exemplifies a successful integration of soil science and microbiology to develop a biological method for enhancing saline-alkali land [68]. This innovative approach underscores the potential of interdisciplinary collaboration in creating sustainable solutions for soil management. Similarly, several studies have integrated soil science with economic analysis to evaluate the effectiveness of biochar application in saline soils. Research indicates that biochar can improve soil structure, enhance water retention capacity, and reduce salt content, ultimately leading to increased crop yields. Cost-benefit analyses demonstrate that the use of biochar is economically viable in the long term, particularly when combined with reduced nitrogen fertilizer application [69]. This case illustrates that the integration of soil science and economic considerations is essential for developing practical and sustainable soil improvement strategies.

(2) Establishing a long-term monitoring and evaluation system is essential for continuously tracking and assessing the effectiveness of saline-alkali land improvement. This approach ensures the long-term stability and sustainability of the implemented measures. For instance, Chen L. [70] investigated the impact of saline-alkali land improvement on soil carbon storage, highlighting the critical role of long-term monitoring.

(3) Green Sustainable Improvement Technologies aim to develop and apply innovative methods that reduce reliance on chemical amendments, mitigate environmental risks, and enhance the economic and social benefits of saline-alkali land improvement. For instance, Zhang H. [71] proposed a novel approach that combines biochar with functional microorganisms, thereby demonstrating the potential of green sustainable improvement technologies in enhancing soil quality and sustainability. Researchers have utilized CRISPR/Cas-mediated gene editing technology to enhance the salt tolerance of crops such as rice and wheat. These genetically improved varieties have demonstrated significant improvements in yield and stress resistance

under saline-alkali conditions [72, 73]. Additionally, pilot projects in regions like the Yellow River Delta have successfully applied molecular breeding techniques to develop salt-tolerant crops that can thrive in saline soils, contributing to sustainable agricultural practices [74].

(4) Regional Adaptability Research: Conduct research on regional adaptability by examining the types and causes of saline-alkali lands in various areas, and develop improvement techniques tailored to local conditions. For instance, Li Y.F. [75] investigated the enhancement of saline-alkali lands in the Northeast Plain and proposed region-specific improvement strategies.

(5) The application of intelligent agricultural technologies, including drones, remote sensing, and big data analytics, can optimize measures for improving saline-alkali land, thereby enhancing the efficiency of the improvement process. For example, the stability control method for agricultural tractor-trailer systems proposed by Lei G.N. [56] exemplifies the potential of intelligent technology in the enhancement of saline-alkali lands. A recent study has fully demonstrated the potential of remote sensing technology in providing timely and accurate information for saline land management. By integrating multi-source satellite image data such as Landsat and Sentinel, and combining machine learning algorithms, the study developed a high-precision remote sensing identification method for saline-alkali land. With this method, the research achieved fine mapping of soil salinity at a resolution of 10 meters, significantly improving the accuracy of salinity assessments [76].

Conclusions

In recent years, advancements in scientific research have led to a significant increase in the number of articles focused on saline-alkali land. Authors such as Tang J. and Liu S. have contributed the most publications, with the Chinese Academy of Sciences emerging as the leading institution in this field, primarily concentrating on halophytes and soil microorganisms. However, research output remains predominantly driven by universities. Nevertheless, a notable issue of low centrality persists among authors and institutions, indicating a deficiency in collaboration and communication. To address this shortcoming, future efforts should focus on establishing collaborative platforms and databases, organizing international seminars and conferences, promoting joint research projects and funding, and founding interdisciplinary research centers. The current research emphasis on saline-alkali land is on biological improvement, attributed to its minimal ecological impact, cost-effectiveness, and feasibility for large-scale implementation. The journal Plant SOIL is recognized as a crucial resource for future research due to its high co-citation rates, centrality, and overall influence. Co-citation analysis identifies soil quality as a key cluster, underscoring the importance of soil characteristics in the management of saline-alkali land. Technological advancements have facilitated the use of satellite remote sensing for monitoring and forecasting salinization, in conjunction with molecular genetic techniques aimed at developing salt-tolerant crops. Chemical methods, such as the application of desulfurized gypsum or biochar, are gradually gaining attention; however, they necessitate a careful balance between investment costs and environmental impact. Biochar, as a prominent research topic, continues to hold significant potential for sustained investigation.

The formation of saline-alkali land is influenced by multiple factors, and its improvement necessitates tailored approaches and interdisciplinary collaboration. Severe saline-alkali lands are typically treated with physical amelioration, while mild to moderate cases are more amenable to biological-chemical methods. Biological amelioration is particularly effective in areas with high evaporation rates; however, it requires the comprehensive application of various measures. Nevertheless, managing saline-alkali land presents numerous challenges, including high costs, short-lived amelioration effects, environmental pollution, and issues of regional adaptability. Looking ahead, research should prioritize interdisciplinary studies, green and sustainable amelioration practices, regional adaptability research, and enhanced monitoring through technologies like remote sensing, to proactively address these challenges and ease management difficulties.

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Conflict of Interest

The authors declare no conflict of interest.

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