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Research progress and trends of the effects of saline alkali soil stress on plant growth: a bibliometric analysis

Xincheng Ji, Haoming Chen*

School of Environmental and Biological Engineering, Nanjing University of Science and Technology, Nanjing, China

* Correspondence author; E-mail: chenhaoming89@hotmail.com.

Abstract: Soil salinization is a hot issue that threatens plant growth and hinders agricultural development. This study used VOSviewer and Citespace software to conduct a bibliometric analysis of 1362 articles on the effects of saline-alkali soil on plant growth from the Web of Science Core Database for 1 January 2000, to 30 November 2022. The analysis revealed that research on the impact of saline-alkali soil on plant growth has been ongoing since 2000, with a notable surge in publications until 2016. It is projected that the number of publications will reach 309 by 2025, nearly three times the count in 2016. The interdisciplinary nature of this research is evident, encompassing fields such as animal science, plant biology, ecology, and zoology, and has progressively diversified over time. Through cooperative network analysis, China, the country with the most publications, has dramatically contributed to close cooperation with the United States, India, and other countries. The literature co-citation analysis shows the evolution of research in this field, from exploring the salt tolerance mechanism of plants to improving plant salt tolerance through soil improvement and plant transformation. The four clusters of keywords represent the 4 primary research directions in this field: the mechanism of plant salt tolerance in saline-alkali soil, the effect of salt stress on crop yield, the synergistic effect of microorganisms and plants, and the response of plants to organic amendments such as biochar under salt stress. This study provides a reference for scholars who study the effects of saline-alkali soil on plant growth in the development history, development trend, and popular research direction.

1. Introduction

Recently, soil salinization has become a global problem, threatening crops' growth and yield and hindering modern agriculture's sustainable development [1]. The increment of ion concentration, pH value, and the conductivity ratio to exchangeable sodium in saline-alkali soil solution decreased carbon and nitrogen mineralization. Meanwhile, the enzyme activity in the soil is inhibited, which affects the movement of soil microorganisms and the transformation of organic matter, resulting in a decrease in soil nutrient utilization, organic

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matter content, and soil fertility. Soil salinization has threatened sustainable agricultural development and land use efficiency [2-4].

Soil salinization leads to poor soil fertility, low nutrient utilization, and low air permeability, which is not conducive to plant growth [5,6]. High salinity and pH in saline-alkali soils can lead to severe degradation of soil structure, high soil mineral content, nutrient deficiency, and disturbance of microbial activity [7-9], which seriously limits the absorption of water by plants and disturbs the normal physiological function of plant cells [10,11]. Meanwhile, excessive salinity in saline-alkali soils will increase the bioavailability of heavy metals in the ground and their toxicity to plants [12].

Exploring and statistically analyzing the vast amount of scientific data in published articles can identify nuances in the evolution of progress in a given field and shed light on emerging areas in the area [13]. In recent years, bibliometric analysis has been widely used to study research trends and prospects in soil and plant fields. For example, arsenic-contaminated soil *in situ* remediation and ex-situ treatment practice research [14], research characteristics, and hotspots of the relationship between soil microorganisms and vegetation [15]. To elucidate the research progress and trend of the effects of saline-alkali soil stress on plant growth, this study adopts the method of bibliometric analysis. It uses VOSviewer and Citespace two visualization software to systematically show the research progress and theme evolution of the effects of saline-alkali soil stress on plant growth from a global perspective.

2. Materials and methods

2.1. Data sources

In this study, the Web of Science Core Citation Database was used as the data source to collect the literature with "saline-alkali soil" and "plant" as the topics. Applying the "Advanced Search" function of Web of Science, the query string was TS= ("saline-alkali soil*" OR "saline soil*" OR "saline-alkaline soil*" OR "saline-sodic soil*") AND TS= ("stress" OR "coerce") AND TS= ("plant*"). The time span was set to finish until 30 November 2022. Subsequently, a total of 1388 articles were retrieved. Finally, 1362 articles were available for analysis after removing deduplication and manual screening.

2.2. Bibliometric analysis

In this bibliometrics study, VOSviewer (version 1.6.18.0) and Citespace software (version 6.1.R3) were used to analyze and visualize the research progress [16,17]. Research trends in the effects of saline-alkali soil stress on plant growth can be seen from journal publication volume, author co-occurrence networks, and keywords clustering analysis (VOSviewer). Country and institutional co-occurrence networks, co-citation clustering, and keyword timeline analysis can draw the research hotspots in this field (Citespace) [18]. In addition, OriginPro version 9.0 was used for charting.

3. Results and discussion

3.1. General trend analysis

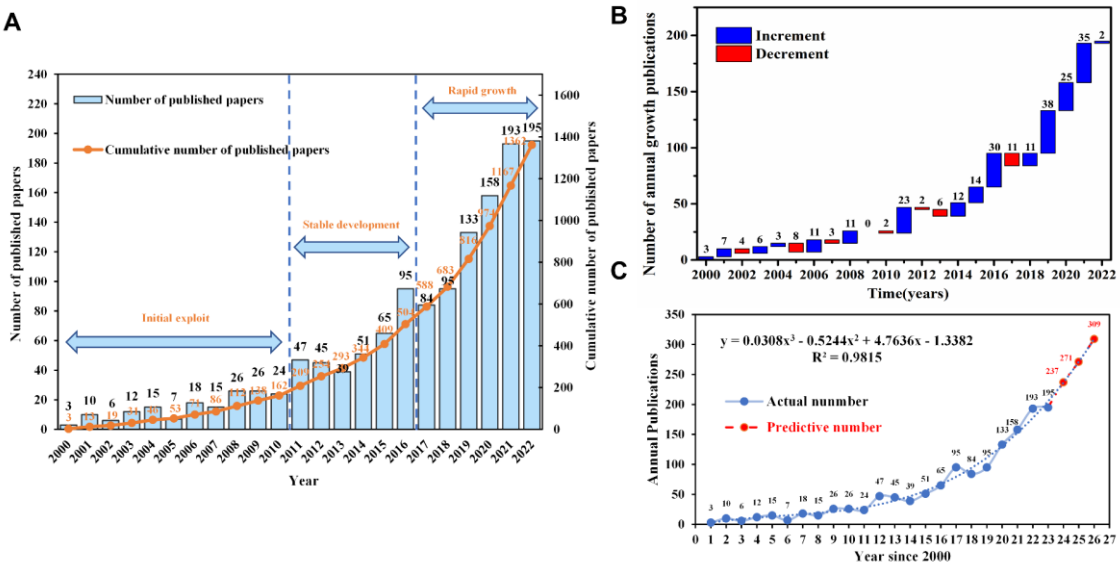


Figure 1. (A) General growth trend of publications of the effect of saline-alkali soil stress on plant growth. Annual and cumulative publications from 2000 to November of 2022 regarding the impact of saline-alkali soil stress on plant growth. **(B)** Annual increment or decrement of publications of the effect of saline-alkali soil stress on plant growth. **(C)** Polynomial model on growth tendency of yearly publications and the predictive number of annual publications from 2022 to 2025.

Figure 1A shows the trends in the annual publication, cumulative publication, and publication growth over the 22 years from 2000 to November 30, 2022. The number of publications on the effects of saline-alkali soil stress on plant growth showed a steady growth trend. According to the journal over the years, the development process of saline-alkali soil stress affecting plant growth can be divided into three stages: initial development, stable development, and rapid growth. (i) Initial development (2000-2010). At this stage, there were few studies on the effects of saline-alkali soil stress on plant growth, accounting for only 11.89% of the total number of publications in 22 years, and there were no more than 50 publications in any year. However, the number of publications continued to increase each year. (ii) Stable development (2011-2016). At this stage, the research development in this field is more pronounced. With further expansion of research topics and content, the growth rate has increased significantly compared with the previous stage. This field has developed steadily at an average annual growth rate of 34.77%. (iii) Rapid growth (2017-November 2022). Since 2016, the number of publications on saline-alkali soil stress affecting plant growth has shown a rapid growth trend. The most significant increase in the number of annual publications can be seen in Figure 1B for 2019 and 2021. Compared with the number of annual publications in 2018 and 2020, it increased by 40.00% and 22.15%,

respectively. This indicates that the research on the effect of saline-alkali soil stress on plant growth has taken a seat in China and abroad in recent years, and the attention and research direction of academia are still increasing.

Figure 1C shows the predicted results of the number of publications in the coming years. The polynomial curve fitting of the annual publication growth from 2000 to 2022 in the study on the effect of saline-alkali soil stress on plant growth showed a good correlation between the publication year and the number of publications (R^2=0.9815). The polynomial curve (trinomial curve) generated by fitting is shown in Figure 1C. According to the results of curve fitting, it can be predicted that the number of annual publications in 2023 may reach about 237, and about 271 documents will be published in 2024. The number of yearly publications is expected to reach 309 in 2025.

3.2. Inter-journal citation analysis

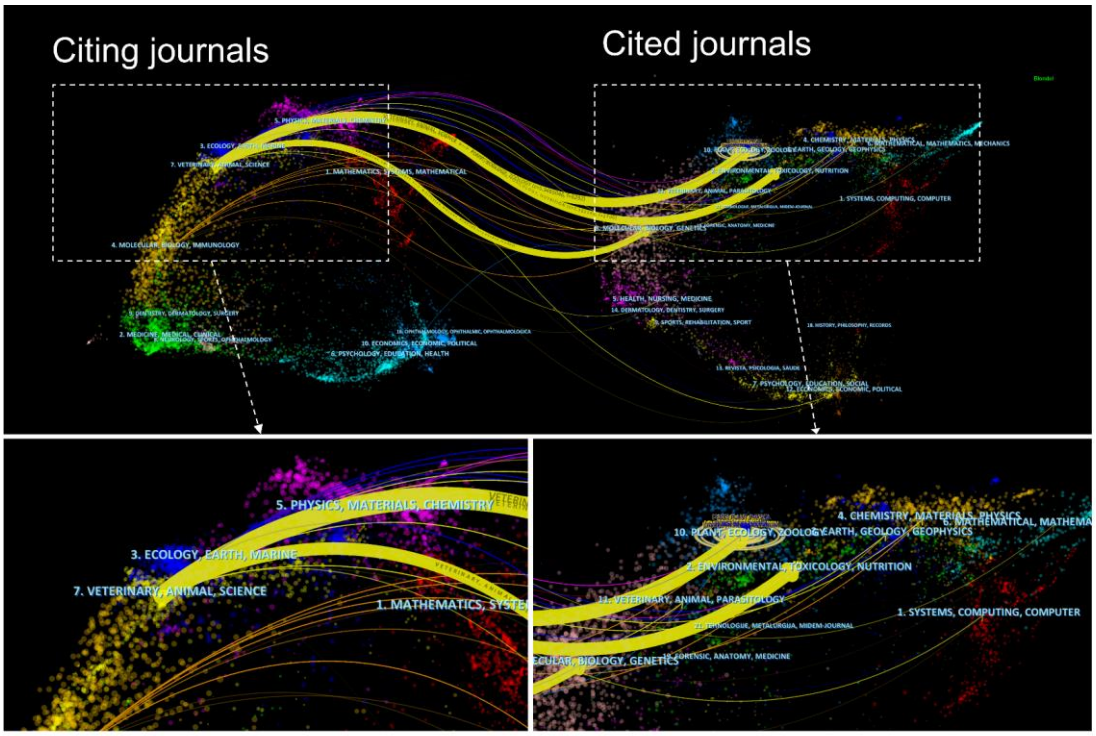


Figure 2. Dual-map overlay graph of journals and disciplines regarding the effect of saline-alkali soil stress on plant growth.

Figure 2 shows the citation trajectory and knowledge flow of journals in this research field. The curved color line between the left and right represents the citation link (The thicker the line, the closer the connection.) [19]. The citing journals are mainly distributed in 3# Ecology, Earth, Marine, 5# Physics, Materials, Chemistry and 7# Animal, Veterinary, Science. The cited journals are mainly distributed in 2# Environment, Toxicology, Nutrition, 8# Molecular, Biology, Genetics and 10# Plant, Ecology, Zoology, *etc*. There are three obvious yellow links in the picture. Among them, 7# and 10# are connected to represent the research on the effects of saline-alkali soil stress on plant growth. Early research developed from

veterinary, animal, science and other disciplines and has been extended to plants, ecology, zoology and other related fields. The research on the effects of saline-alkali soil stress on plant growth is further developed into the areas of molecular, biology and genetics. Plant molecular breeding and transgenic research are the hot spots of current research. Whether these new plant improvement techniques can resist the salt stress of saline-alkali soil is the focus of the subsequent study [20]. The research of 7# and 2# connected represents that the effect of saline-alkali soil stress on plant growth may involve environmental science, toxicology, nutrition, and other disciplines, which constituted the theoretical basis of the impact of saline-alkali soil stress on plant growth [21].

3.3. Collaborative network analysis

3.3.1 Collaborative network analysis for countries

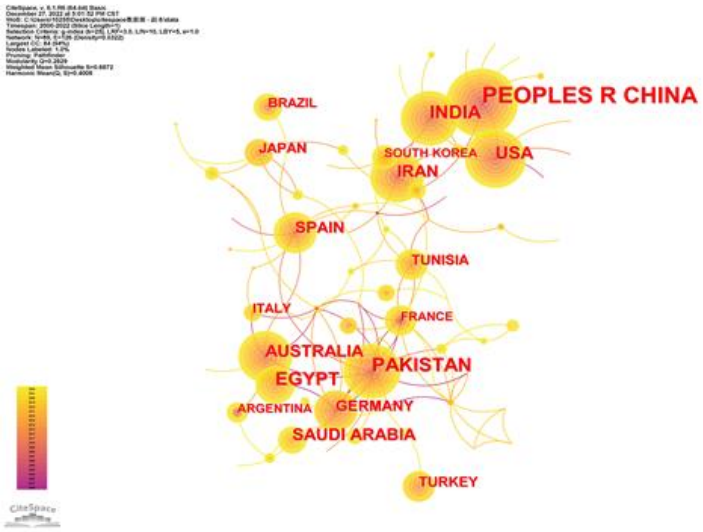


Figure 3. Mapping of countries publishing on the effect of saline-alkali soil stress on plant growth.

The national visualization and collaborative network in the study of saline-alkali soil stress affecting plant growth is shown in Figure 3 using CiteSpace software. From 2000 to November 30, 2022, 88 countries were published in the relevant field. Figure 3 shows the top 18 countries regarding the number of publications. China occupied the first place in the number of articles published in this field, accounting for 24.05% of the total publications. Pakistan and India had a similar number, accounting for 7.72% and 7.22%, respectively. In addition, Egypt, the USA, Australia, Iran, Saudi Arabia, Spain, and Germany had more than 50 publications. It reflects that saline-alkali soil stress affecting plant growth has received much attention from various countries, and most of them have conducted some research in this field. China has the most significant number of link lines and has made the most outstanding contribution. In addition, the development of saline-alkali soil stress affecting plant growth research is multinational and diverse.

3.3.2 Collaborative network analysis for institutions

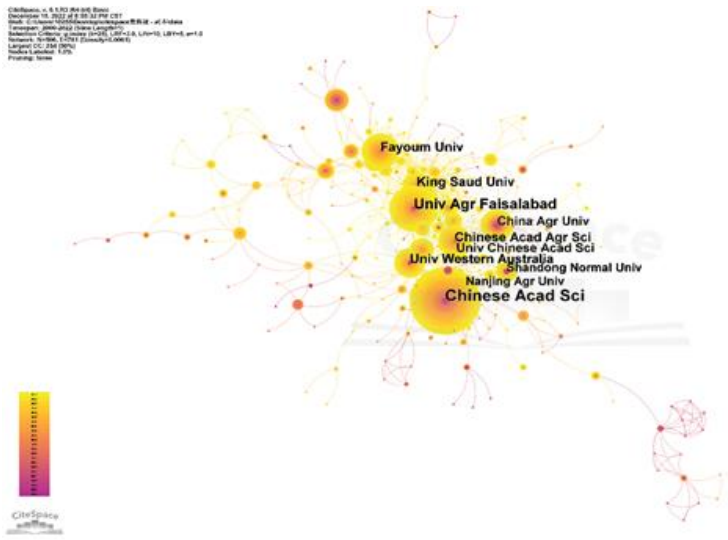


Figure 4. Institution network of published papers on the effect of saline-alkali soil stress on plant growth.

Based on the Web of Science Core Collection Database, 504 institutions cooperated to participate in the field of saline-alkali soil stress affecting plant growth. Close collaboration exists between institutions, such as studying the effects of biochar, acid-modified biochar, and wood vinegar on saline-alkali remediation and strawberry growth [22]. The study was carried out by 6 institutions: Qingdao University of Science and Technology, School of Environmental and Safety Engineering, Institute of Coastal Environmental Pollution Control, School of Environmental Science and Engineering, Ocean University of China, Key Laboratory of Marine Environment and Ecology, Ministry of Education, National Key Laboratory of Environmental Protection, Shanghai Agriculture and Forestry Vocational Institute, and Narowal University. This indicates that several institutions across the country have tried to develop emerging saline-alkali soil remediation materials and have close cooperation with each other. The collaboration network of different institutions is shown in Figure 4. Among them, the most significant node is the Chinese Academy of Sciences, with the most important number of links. The Chinese Academy of Sciences (China) research team began research in this field in 2002 and has published 94 articles. They cooperate closely with Nanjing Agricultural University, Western Australia University, and other institutions. Institutional collaboration across regions and nationalities is conducive to learning between teams and diversifying the field of saline-alkali soil stress affecting plant growth. Meanwhile, new institutions continue to focus on research in this area. In 2022, institutions such as Nanjing Forestry University (China), Russian Academy of Sciences (Russia), Taif University (Saudi Arabia) are leading in the number of publications and have temporarily become vital institutions.

3.3.3 Collaborative network analysis for authors

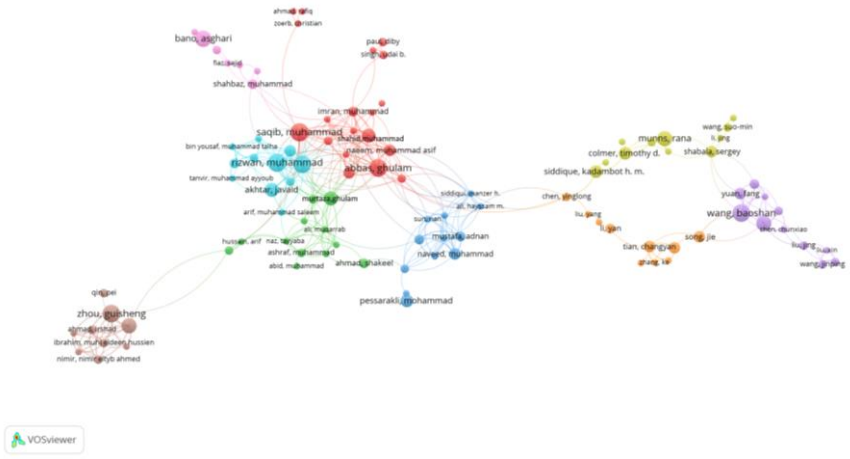


Figure 5. The authors co-authorship network in the effect of saline-alkali soil stress on plant growth.

Table 1. Top 10 most productive authors in the remediation of antibiotic contamination in water using biochar.

Rank	Authors	Documents	Citations	Citation frequency per document	Total link strength
1	Rady, Mostafa M.	18	705	39.17	24
2	Abdelly, Chedly	17	433	25.47	30
3	Rizwan, Muhammad	12	732	61.00	40
4	Egamberdieva, Dilfuza	12	732	61.00	19
5	Abd El-mageed, Taia A.	12	320	26.67	35
6	Saqib, Muhammad	12	227	18.92	32
7	Ali, Shafaqat	11	733	66.64	37
8	Abbas, Ghulam	11	222	20.18	44
9	Baoshan, Wang	11	161	14.64	20
10	Guisheng, Zhou	11	72	6.55	32

A total of 6088 authors published articles on saline-alkali soil stress affecting plant growth between 2000 and November 30, 2022, with 284 having no less than 3 publications. Since 182 authors are not connected to other author collaboration networks, only the collaborative network of 102 authors is shown. The interconnected collaboration network of 102 authors is shown in Figure 5. The clusters of different colors represent the groups with close cooperation between the authors, which are divided into 9 groups. The four groups in the

center are collaborating with authors from at least three surrounding groups. The group represented by the corner brown is more inclined to the cooperation of the authors within the group.

The production and cooperation information of the top 10 most productive authors is shown in Table 1. Among the authors, Rady, Mostafa M, and Abdelly, Chedly are the top two authors, with 18 and 17 articles published, respectively. But the total link strength is only 6 and 12, which means their collaboration with other authors is minimal. It is worth noting that the seventh-ranked author Ali, Shafaqat published only 11 articles in this field but received a very high number of citations (733 times), and the total link strength was as high as 37. Although the number of publications of the author is not the largest, it has a particular influence on the saline-alkali soil stress affecting plant growth.

3.4. Co-citation analysis

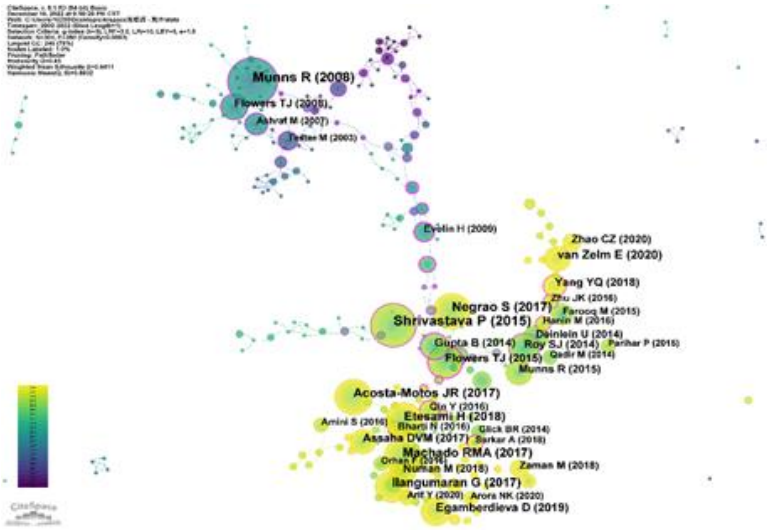


Figure 6. Co-citation analysis in the field of the effect of saline-alkali soil stress on plant growth.

Figure 6 shows the co-citation analysis of the literature in the field of the effect of saline-alkali soil stress on plant growth. The co-citation analysis network contains 304 nodes and 380 links, with a density of 0.0083. The largest sub-network has 240 nodes, accounting for 78.95% of the total, indicating that the research network formed by nodes is relatively concentrated and closely related. A purple node appears on the spectrum's edge, meaning its centrality is no less than 0.1[23]. As can be seen from Figure 6, the three most co-cited articles are Shrivastava and Kumar (2015), Munns and Tester (2008), and Negrao *et al* (2017). Shrivastava and Kumar published an article on the progress of research on plant response to soil salinity and amelioration strategies in the 2015 issue of the Saudi Journal of Biological Sciences. The article shows that soil salinity is the principal abiotic stress. Plants growing in saline-alkali soil conditions experience a high level of osmotic stress, ion toxicity, and nutrient disruption, which are responsible for the poor physical needs of the soil and result in reduced plant productivity. Plants respond to salt stress by affecting morphological,

physiological, and biochemical processes. This shows that in research on saline-alkali soil stress affecting plant growth, the mechanism by which plants develop tolerance to saline-alkali soils is a hot research topic. From the perspective of the centrality of the literature, the study by Gupta *et al* (2014) exhibits the strongest centrality at 0.76, followed by Evelin *et al* (2009) at 0.63. Other highly cited documents demonstrate a high centrality, indicating more frequent citations and closer cooperation between the literature on saline-alkali soil stress affecting plant growth research.

3.5. Keyword analysis

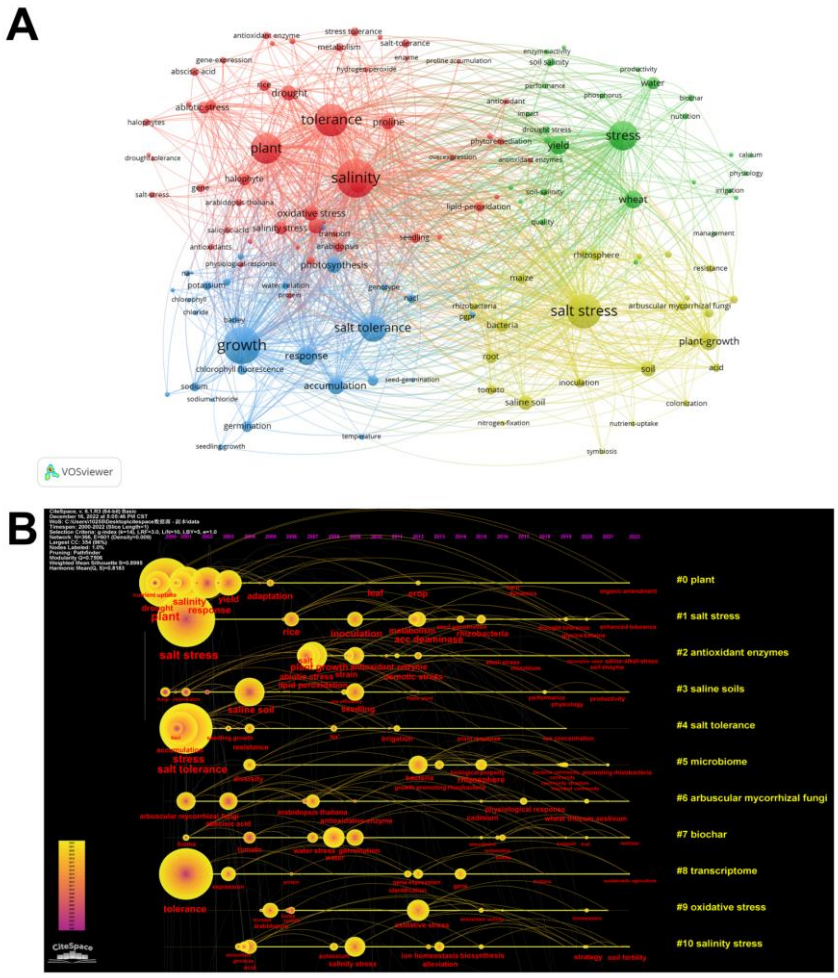


Figure 7. (A) Keywords analysis in the effect of saline-alkali soil stress on plant growth. All keywords co-occurrence network and clustering visualization. **(B)** The timeline map on the impact of saline-alkali soil stress on plant growth.

A total of 5408 keywords are derived from the bibliometric data, and the minimum number of occurrences of keywords is set to 20. A total of 133 nodes are generated for the keyword visualization network. The curve represents the connection between the nodes; the more robust the relationship, the more pronounced the curve [24]. The keywords are grouped into four clusters according to their color, Cluster I (red), Cluster II (green), Cluster III (blue), and Cluster IV (yellow).

Cluster I (red) has the highest number of nodes (51), and the main keywords include “salinity” (426 times), “tolerance” (339 times), “plant” (304 times), “oxidative stress” (115 times). The research may focus on plants’ many responses in saline-alkali soils by influencing morphological, physiological, and biochemical processes. The inhibition of enzyme activity in saline-alkali soil affects the movement of soil microorganisms and the transformation of organic matter. This decreases soil nutrient utilization, organic matter content, and soil fertility. Plants need to reduce the damage caused by adverse environments to their growth and development by synthesizing osmotic adjustment substances, improving the antioxidant capacity of enzymes, selective absorption of ions, nutrient balance, changing metabolic types, and adjusting biomass distribution. Cluster II (green) has a total of 28 keywords, of which the more frequent ones include "stress" (292 times), "yield" (151 times), "wheat" (142 times), "water" (88 times), "soil salinity" (52 times). The study illustrates that crop yields are affected under salt stress. High salt conditions limit plant water uptake, leading to oxidative stress, disrupting the redox balance in plants and damaging plant cells, reducing germination rates and delaying plant development, thereby reducing plant yields. The more frequent keywords in Cluster III (blue) include "growth" (406 times), "salt tolerance" (255 times), "response" (154 times), "accumulation" (134 times), "photosynthesis" (119 times). This relates to the mechanism by which plants develop tolerance to saline-alkali soils. Photosynthesis is a crucial metabolic process of plant material and energy sources. Under saline-alkali stress, plant cell structure changes significantly, photosynthesis is blocked, photosynthetic rate decreases and plant growth is seriously affected. The keywords that frequently appear in Cluster IV include "salt stress" (364 times), "plant-growth" (141 times), "saline soil" (109 times), "root enclosure rhizosphere" (68 times), and "photosynthesis" (119 times), reflecting the effects of salt stress on plant rhizomes, biomass, and photosynthesis. The metabolic regulation of plant roots plays an essential role in the mitigation mechanism of plants to saline-alkali stress. It is the first barrier for plants to cope with saline-alkali stress. Accumulating solutes for osmotic adjustment is the main way to alleviate saline-alkali stress.

In addition, the keyword clustering mapping from a timeline perspective plotted by the Citespace software is shown in Figure 7B, with 366 nodes and 1755 links. A total of 11 topic clusters appear in the atlas. #1 (salt stress), #3 (saline soil) and #4 (salt tolerance) mainly include inoculation, seed germination, and seedling growth. From the #1 cluster, it can be seen that related research on salt stress has begun since 2001. Meanwhile, with time, it has gradually deepened into research on drought tolerance. #0 (plant) is closely related to #5 (microbiome) and #6 (arbuscular mycorrhizal fungi). Rhizosphere bacterial community is closely associated with the salt tolerance of plants. Microorganisms in soil have synergistic effects with plants, which can effectively improve the living environment of plants under salt stress.

Moreover, #2 (antioxidant enzymes) is closely linked to clusters #8 (transcriptome) and #9 (oxidative stress). In addition, with the demand for food security, more attention has been paid to saline-alkali soil restoration. Remediation agents are used to mitigating salt ion toxicity to improve nutrient uptake by plants and to improve osmoregulation to alleviate water deficiency in plants. Alternatively, plant resistance can be increased by activating the

plant's protection system through remediation agents (*e.g.*, functional microorganisms). Therefore, saline-alkali soil improvement and remediation will be hot research topics in the future.

4. Conclusion

The main conclusions of this study are as follows:

(1) The issue of saline-alkali soil stress on plants has been receiving attention, and this area is becoming an international issue as cooperation between countries continues to increase. China has the highest research intensity and strong ties with other countries.

(2) With the development of research, the research focus in this area has gradually evolved from studying the salt tolerance mechanism of salt-tolerant plants to studying the synergistic mechanism of microorganisms and plants in saline lands. Meanwhile, recent research has focused on developing organic amendments such as biochar for saline land restoration.

(3) Future hotspots will revolve around using biological means or organic amendments to regulate bacterial communities in saline-alkali soils.

Conflicts of interests

The authors declare no conflicts of interests.

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