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Role of silicon and silicon fertilizers in the world: a review of papers from the Scopus database published in English for the period of 2012–2022

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Abstract

Silicon (Si) is a chemical element that is not yet considered essential for plants. However, over the past few decades, an increasing number of scientific studies have focused on the role of Si in soil-plant interactions. At the same time, many countries are leading the development and use of silicon-based fertilizers. Si can be taken up by plants predominantly in a mobile form (H_4SiO_4) in the soil through both passive and active uptake mechanisms. Therefore, Scopus data from 2012 to 2022 were used to understand the implementation and current status of research on the beneficial effects of silicon fertilizers on soil and plants and the role of soil forms of silicon in improving soil quality. A bibliometric study of articles published in the database on the role of Si in soil and silicon fertilizers was carried out. Various tools, such as Microsoft Office Excel 2021, VOS Viewer and Mapchart.net were used in this study. The final literature includes 440 articles, 82% of which are scientific. Over the past decade, the number of published articles has increased significantly. For example, in the years 2021–2022, a total of 91 articles were published, which is six times higher than the number of articles published in 2012–2013 (15 articles). This significant increase in publications highlights the growing interest in the role Si and Si fertilizer research. It was found around 32.04% of China, 13.2% of the USA and 9.8% of Brazil the reviewed publications focused on the role of Si and Si fertilizers studies. Among the authors who published the most articles on this topic during the selected period are Wang X. (with 12 articles), Liang Yu., Rizwan M. and Ali S. (each with 8 articles).

1. Introduction

Complex biogeochemical and physical processes involving minerals, soil organic nutrients, living organisms, gas and water create the diverse and dynamic system that is soil. Silicon, despite being abundant in nature, has not been viewed as an important element. Si is a metalloid element and is the most abundant element in the earth's crust after oxygen (Luyckx et al., 2017). In recent years, research has been conducted on the importance of Si for soil and plants (Kovács et al., 2022). Due to the indeterminate nature and stability of the Si element, much attention is paid to Si fertilizers in agricultural practice (Pavlovic et al., 2021). The O_2 makes up 47% of mineral soil's overall elemental composition, while Si makes up 28% (Lepolu et al., 2016). Si in soil consists mainly of the solid phase, namely quartz and crystalline forms (plagioclase, orthoclase and feldspar), secondary clay minerals (kaolinite, vermiculite and smectite) and amorphous forms (Imtiaz et al., 2016). Plants can absorb some of this enormous quantity of Si from soluble forms [Si $(OH)_4$] over time (Johan et al., 2021; Canny et al., 1990; Lumsdon et al., 1995; Mitani et al., 2005). Numerous researchers have investigated how plants absorb Si from the soil (Kaur et al., 2019; Mabagala et al., 2020; Mitani et al., 2005). Monosilicic acid (H_4SiO_4) is the form of Si that plants absorb (Greger et al., 2018) and moves through the xylem in the same way (Huang et al., 2020; Imtiaz at al., 2016; Mitani et al., 2005). Si uptake is considered passive (Vivancos et al., 2016). In the root exo and endodermis, a number of Si transporters have been discovered

in recent years (Greger et al., 2018). The absorption and transport of Si in plants depends on the plant species, the type of root system and the chemical composition of the soil (Mandlik et al., 2020). Minerals are actively taken up by plant cells in ionic forms, for example nitrate (NO_3^-), phosphate (HPO_4^-), potassium ions (K^+) and etc. Silicon plays a very important role in the absorption of such ions by plant tissues (Pavlovic et al., 2021). According to the article, among the macronutrients, nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) are affected differently and not separately (Veazie et al., 2022). In addition, Si also plays an important role in plant uptake of certain trace elements such as boron (B) and manganese (Mn) (Pavlovic et al., 2021). Other benefits of Si include an increase in the rate of photosynthesis, a decrease in the rate of transpiration and resistance to UV radiation (Thakral et al., 2021). Plants face different types of biotic and abiotic challenges during their vegetative improvement stages, such as saltiness, dry season, microbe diseases, flooding and heavy metal harming (Mir et al., 2022; Thakral et al., 2021). The presence of Si in soils is insufficient (Thakral et al., 2021). Thus, high amounts of Si in the soil do not indicate that there is enough soluble Si for plant uptake (Coskun et al., 2021).

In recent years, knowing the important role of Si in various soils, new large-scale research has been carried out on the production and application of various Si fertilizers (de Tombeur et al., 2021; Fan et al., 2019; Stephano et al., 2021; Guntzer et al., 2012; Haynes and Zhou, 2018; Ji et al., 2017; Song et al., 2021; Tripathi et al., 2021; Valle et al., 2016). Results from many years of Si research are compiled to provide insight into the state of knowledge regarding Si fertilizer recommendations for crop production (Boorboori et al., 2021). The concentration of H_4SiO_4 in soil solution is affected by soil pH and the amount of clay, minerals, organic matter and Fe/Al oxide/hydroxide, which depends on the geological age of the soil (Katz et al., 2021). The role of Si fertilizers in relieving biotic and abiotic stress has been well studied (Rangwala et al., 2018). Several studies have been carried out to improve the properties of Si fertilizers, not only in the response of plants to various stressful influences but also in improving the structure of the soil (Devanna et al., 2021). The use of Si-fertilizers contributes to the regulation of soil fertility, that is, to improve its enzymatic status, meet the needs of crops in the absorption of nutrients from the soil, improve soil moisture, and increase the ratio of nutrients received by crops (Zargar et al., 2019). The use of Si-fertilizers even on saline soils increases the adaptability of plants to adverse environmental conditions and increases the growth rate and productivity, protecting them from various harmful pathogens (Das et al., 2021; Gottardi et al., 2012; Verma et al., 2021). For instance, in rice (*Oryza sativa*), Si fertilizer increases seed wall thickness, vascular bundle size and stem strength while increasing peroxidase activity, which in turn promotes stress tolerance (Hussain et al., 2021). In addition, it prevents the penetration of pathogenic fungi into the plant cell and inhibits hyphae in the soil (Camargo et al., 2013; Gottardi et al., 2012; Liang et al., 2021). Similarly, the application of Si as fertilizer tends to alter proline levels in water-stressed upland rice cultivars at vegetative and genetic stages; this effect may indicate stress resistance (Mauad et al., 2016). In addition, Si fertilizers have been shown to increase the water flow rate in xylem vessels and increase water use efficiency by reducing transpiration losses in maize (*Zea mays*) plants under drought conditions (Nisar et al., 2022; Tayade et al., 2022). Si-fertilizers have a dual effect on the relationship between soil and plants (Huang et al., 2020). Firstly, it increases the protective reactions of plants against biotic and abiotic stresses (Ahmed et al., 2022).) Secondly, Si fertilizers have a positive effect on the biological, chemical, and physical properties of the soil. In addition, Si fertilizers also play an important role in the presence of minerals (essential nutrients for the plant organism) in the soil (Mandlik et al., 2020). The use of Si fertilizers has a positive effect on plant growth, mineral balance and survival rate (Malik et al., 2021). Silicates such as potassium silicate (K_2SiO_3) and magnesium silicate ($MgSiO_3xH_2O$) have a beneficial effect on the growth and yield of wheat (Sarto et al., 2019). Plants treated with Si fertilizers have additional root properties, such as full root length, root surface area and parallel root length, which can protect plants from supplementation inadequacy conditions as well as dry season conditions (Parveen et al., 2019). Despite large differences in Si uptake by rice, tomato, cotton, onion, and chili peppers, all crops showed higher yields (Crooks and Prentice, 2017). The Si in plants is lacking in most agricultural soil (Tubana et al., 2016). Thus, Si is commonly used as a fertilizer to assess the effects on plants (Liang et al., 2021). Si fertilizers have recently been reported to increase genes associated with the carbon/nitrogen cycle and metal neutralization in soils (Das et al., 2021). Many other silicon-containing fertilizers are being studied with interest by scientists and researchers. For example, based on 5-year experiments, the influence of phosphogypsum (including silica 5–10%) on the physicochemical properties of eroded soils in the Ural region of Russia was studied (Komissarov et al., 2022). Agrisilica (containing 26% Si) is one of the 100% natural fertilizers. Agrisilica contains a uniquely high number of PAS (plant-available silicon). This Agrisilica fertilizer was studied for the growth, yield and nutrient uptake of rice during 2012 and 2013 in the new alluvial zone of West Bengal, India (Pati et al., 2018). The effect of Aminosid Si (which includes 17% Si) on improving biological properties, including enzyme activity, and the dynamics of the number of microorganisms in saline soils of the Bukhara region of Uzbekistan was studied (Mamasolieva and Holmurodov, 2023). Knowing the important role of Si in the relationship between soil and plants, as well as the role of Si fertilizers in mitigating the effects of abiotic and biotic stress, which are used today in many countries, researchers in subsequent years are studying (Zellner et al., 2021). Therefore, this study developed and analyzed various studies on the role of Si in soil and Si fertilizers over the past decades. The purpose of this study is to find out how many developed countries have already taken the step to study and use silicon fertilizers.

Bibliometric research is a quantitative tool for analyzing the topic of scientific processes from macro and micro points of view (Donthu et al., 2021). While macroanalysis usually analyzes the entire topic, including articles, categories, countries, authors and institutions, microanalysis focuses on identifying citations and keywords (Wang et al., 2019). The analysis combines

statistical and mathematical methods to display the state of research areas over time (Mejia et al., 2021). Due to the advantages of combining different disciplines such as soil science, agriculture, ecology, etc., this method can be applied in more than 20 areas (Hu et al., 2019). This approach is widely used in various fields and disciplines, such as bibliometric analysis of sustainable agriculture (Sarkar et al., 2022) for advanced study of precision farming (Coulibaly et al., 2022) bibliometric analysis of soil science as a scientific area (Mokhnacheva and Tsvetkova, 2020) and bibliometric analysis of soil nutrient research between 1992 and 2020 (Pan et al., 2021). The purpose of this study is to identify recent and historical bibliometric data on the use of the role of silicon in the soil-plant system and Si fertilizers (which have been studied as positive in mitigating the impact of abiotic and biotic factors) and analyze them. With the help of bibliometric statistics, authors, countries, publishers, and sponsors have been identified who have carried out significant research work on the topic. This study serves as a guide and reference in the study of soil Si and Si fertilizers.

2. Materials and methods

All articles analyzed in this study were taken from the Scopus database, where Scopus is one of the most comprehensive peer-reviewed journal databases in the world and can provide good scientific and academic information (Klapka and Slaby, 2018). Special search keywords such as “silicon soil” and “silicon fertilizers” were used to analyze all logs. The study period was chosen from 2012 to 2022 (September 16). In the search results, 440 articles in English were selected. The database was searched, and the list of journals, number of articles, list of top authors, map of top countries, type of publication, list of top publishers, number of journal citations and main funding sponsors were divided into categories such as list and interest. We have used 440 articles published in English and created a table and diagram intended to show 10 important aspects. The subject area was based on three scientific fields: Soil Science, Environmental Science and Agricultural Science. We used silicon and silicon fertilizers as a keywords. Microsoft Excel, VOS viewer and A Map chart are used to create graphics Fig. 1). Various tools such as Office Excel 2021, VOS viewer (van Eck and Waltman, 2010), and map (https://www.mapchart.net/world.html), were used to analyze the dataset and generate 440 articles. A useful tools were also applied to showcase the most active authors (co-authorship) and the most frequently used keywords (match) in the form of a VOS viewer. The map chart is used to generate the top countries. This sample uses the period of the last 10 years 2012–2022, given that the topic of Si fertilizers is something new. Sample articles were uploaded in *.ris format.

3. Results

3.1. Number of papers on the role of Si and Si fertilizers

The number of scientific papers published on a particular issue indicates its importance to the region. In total, 440 articles on the role of Si and Si fertilizers were published worldwide in the last decade (2012–2022). Figure 2 shows that more than a hundred scientific abstracts were published in the first five years, and the number of articles on Si fertilizers increased significantly in the next five years. The highest rate of published articles on Si fertilizers was in 2019, 2020, and 2021; this line of research has accelerated. The last two years of the decade, namely, 2020 and 2021, were the most productive years for the use of Si fertilizers in the world. During these two years, almost 38.8% of the total number of publications were published. In recent years, the prospect of all fundamental and practical work on the development and application of the most important Si in soil and silicon fertilizers has suddenly increased. The interest of scientists and researchers in this area is developing; the effective impact of fertilizers on agriculture and the country’s economic system is relatively appreciated (Fig. 2).

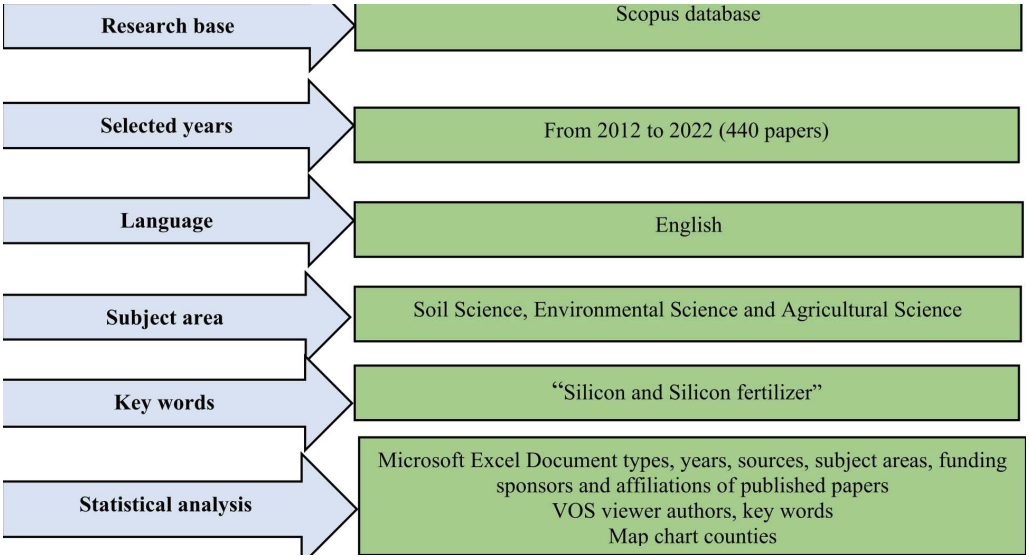


Fig. 1. Methodology flowchart for the research

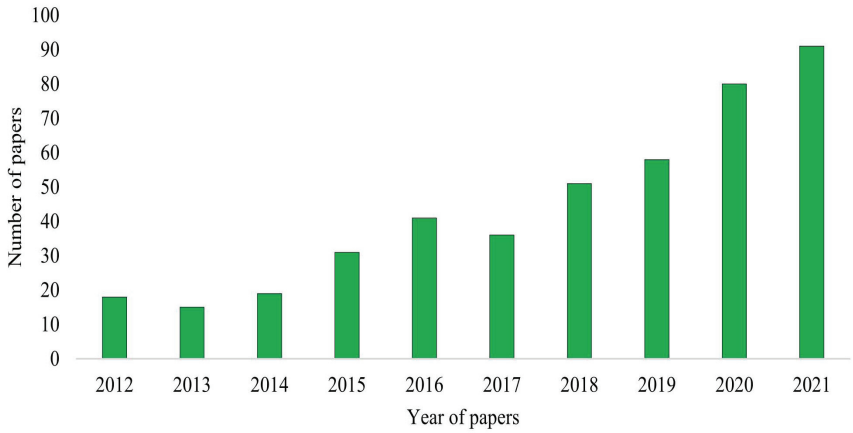


Fig. 2. Number of publication roles of Si and Si fertilizers

3.2. Top journals published on the role of Si and Si fertilizers

The choice of scientific journals is an important factor in informing the public about scientific research. The Scopus database is based on 440 scientific articles on the issue of Si fertilizers published in 60 different journals around the world between 2012 and 2022. Regarding the quantity of published articles on Si fertilizers, the journals Environmental Science in General, Environmental Sciences, and Pollution Research and Chemosphere used the guidelines in Table 1. The top 10 journals listed in Table 1 accounted for approximately half of the total number of

Table 1
List of top journals published on the role of Si and Si fertilizers (2012–2022)

Scopus Source title	Number	Scopus Source title	**Number**
Science Of the Total Environment	23	Acta Horticulturae	3
Environmental Science and Pollution Research	18	Bioresource Technology	3
Chemosphere	17	Bulgarian Journal of Agricultural Science	3
Communications In Soil Science and Plant Analysis	14	E3s Web Of Conferences	3
Top Conference Series Earth and Environmental Science	13	Journal Of Agronomy and Crop Science	3
Journal Of Plant Nutrition	13	Journal Of Integrative Agriculture	3
Ecotoxicology And Environmental Safety	11	Journal Of Sustainable Metallurgy	3
Geoderma	10	Plos One	3
Journal Of Environmental Management	10	Scientia Horticulturae	3
Soil Science and Plant Nutrition	9	Soil And Tillage Research	3
Journal Of Cleaner Production	8	Waste Management	3
Environmental Science And Technology	7	3 Biotech	2
Pedosphere	7	Agrociencia	2
Environmental Pollution	6	Agronomy	2
Frontiers In Plant Science	6	Applied Ecology and Environmental Research	2
Journal Of Hazardous Materials	6	Biology And Fertility of Soils	2
Plant Archives	6	Biomolecules	2
Plants	6	Bulletin Of Entomological Research	2
Journal Of Soil Science and Plant Nutrition	5	Bulletin Of Environmental Contamination and Toxicology	2
Crop Protection	4	Environmental Engineering Science	2
Ecology Environment And Conservation	4	Environmental Science Nano	2
Japan Agricultural Research Quarterly	4	Environmental Technology United Kingdom	2
Journal Of Environmental Quality	4	Field Crops Research	2
Journal Of Plant Nutrition and Soil Science	4	International Journal of Environmental Research and Public Health	2
Plant And Soil	4	International Journal Of Phytoremediation	2
Plant Physiology And Biochemistry	4	Journal Of Agricultural and Food Chemistry	2
Research Journal of Pharmaceutical Biological and Chemical Sciences	4	Journal Of Zhejiang University Science B	2
Water Air and Soil Pollution	4	Neotropical Entomology	2

articles published. The next 10 journals were also the most popular for Si fertilizer publications. Some journals, such as Plants and Soil and the Journal of Plant Nutrition and Soil Science, contain information about Si fertilizers and their use in soil and plants around the world. Most of the information on fertilizers is published in Soil Science and Plant Nutrition and the Journal of Plant Nutrition. At the same time, the above journals have published articles on silicon fertilizers 9 and 13, respectively.

3.3. Type of documents on the role of Si and Si fertilizers

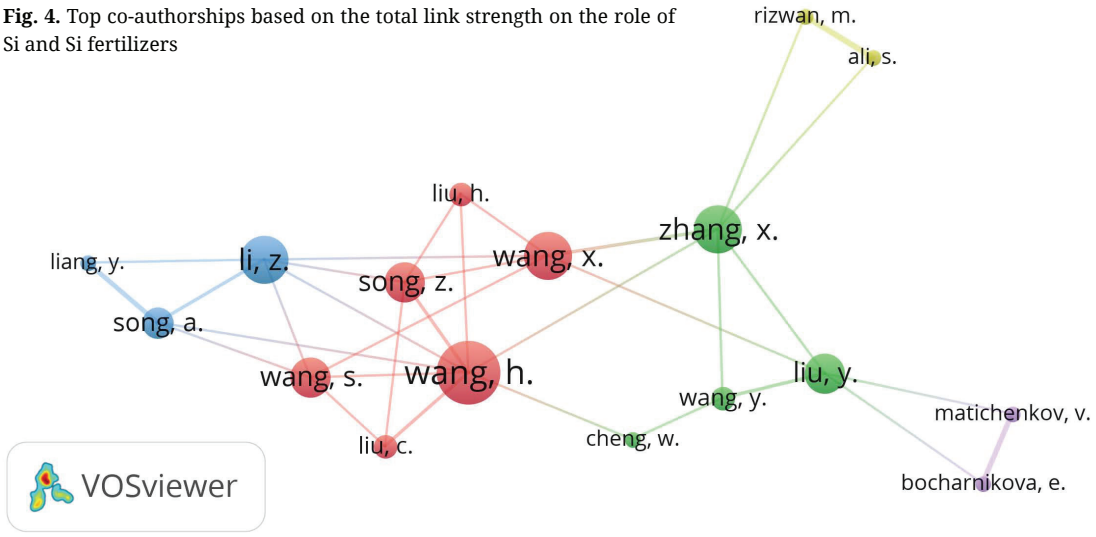
Document types can also express the relevance of the area being studied. There are seven different types of publications in which researchers can provide information on the above topic based on their scientific results. Figure 3 provides information on the number of styles of documents published in recent decades. There are 396 articles. The highest count is for articles around 324. The next level was for review, conference paper, and book chapters 26, 23, and 14, respectively. Book, erratum, and retractions each showed three results. Many scientists and young researchers prefer to publish science news in the form of articles. The study of the role of Si in soil– plant relations, as well as the scientific explanation of the fact that Si fertilizers mitigate the effects of abiotic and biotic stresses, increase crop yields, and give great positive results for agriculture and the economy will develop in the next decades.

Fig. 3. Type of documents on the role of Si and Si fertilizers

3.4. The network of contributors published on the role of Si and Si fertilizers

A network of co-authors in a research area. Based on the data, the total co-authorship network count was calculated using the VOS viewer software. On the map, each circle shows the name of the author, and the size of the circle characterizes the number of scientific publications on the topic of research in the role of Si. An author combination network is defined as a network in which the nodes are authors and the links between them represent co-authorship. The size of the links indicates the number of articles written by a scholar. As illustrated in Fig. 4, 5 clusters were present. The single clusters included a few authors, indicating that participation was limited to a few authors for the topics covered in this bibliometric investigation. After the study using a VOS viewer, there were 5 clusters in different colors, which showed the relationship between one topic and another. The VOS viewer can display bibliometric mapping in three different visualizations: network visualization, overlay visualization, and density visualization. We chose network visualization (Fig. 4). Author names are marked with colored circles. The size of the circle was positively correlated with the appearance of the author's name in the titles and abstracts. Therefore, the size of the letters and circles is affected by the frequency of occurrences. The more often the authors name appears, the greater the size of the letters and circles. Cluster 1 (pink) contains five authors, namely Wang, H., Wang, X., Liu, C., Lu, H., and Sun, Z., working collectively on the topic of the role of silicon and silicon fertilizers. In cluster 2 (green), there are 4 co-authorships working together: Cheng, W., Liu, Y., Wang, Y., and Zang, X. They are also interrelated within the above theme. Cluster 3 (blue) shows that Li Z., Liang Y., and Song. A. were also interested in and worked on the role of Si and Si fertilizers. Rizvan M., Ali S, Bocharnikova E., and Matichenkov V. occupied Clusters 4 and 5, respectively, and collaborated on this study.

Fig. 4. Top co-authorships based on the total link strength on the role of Si and Si fertilizers



3.5. Top countries on the role of Si and Si fertilizers

The number of countries researching a particular issue reflects the level of internationalization in the region. In total, 81 countries worked as a team on the role of Si and Si fertilizers in the world from 2012 to 2022. The article selected the 12 top countries that participated in the publication of at least two or three or more publications (Fig. 5). The top countries, China, the US, India, and Brazil, head the list by the number of publications 141, 58, 44, and 43), respectively. Australia, Japan, Iran, and Russia were next on the list with 26, 18, 17, and 17, respectively. Four countries, such as Pakistan, Indonesia, South Korea, and Spain, have approximately 15 published research papers. In the past decade, many scientific innovations in the development of Si fertilizers and their practical application have been conducted in China, which ranks first in the world. This country has the highest rate of publication of articles on this topic; more than 141 papers have been published. The United States, as a competitor, has recorded high positions in scientific papers on Si fertilizers.

3.6. Name of top institutions on the role of Si and Si fertilizers

Institutions play an important role in the publication of scientific papers published by researchers. Because it makes a big difference in the ranking of this institution and the country. It can be recognized that (Fig. 5) above shows the highest point in China, and (Fig. 6) also shows that the 5 largest institutions in China, namely the Chinese Academy of Sciences, the Ministry of Education of China, Zhejiang University, the Ministry of Agriculture of the People's Republic of China, the Academy of China Agricultural Sciences, which also recorded good results, working on the role of Si and Si fertilizers. Indeed, the Chinese Academy of Sciences is one of the first with the highest score: 24 scientific articles published by this institution. The following three institutes, namely, the Ministry of Education China, Zhejiang University, Ministry of Agriculture of the People's Republic of China, noted equality in the number of 15 scientific papers. The following institutes: The College of Environmental and Resource Sciences showed the same result as the Chinese Academy of Agricultural Sciences, which published 11 scientific papers. The names of other institutions and the number of published publications are shown in Fig. 6.

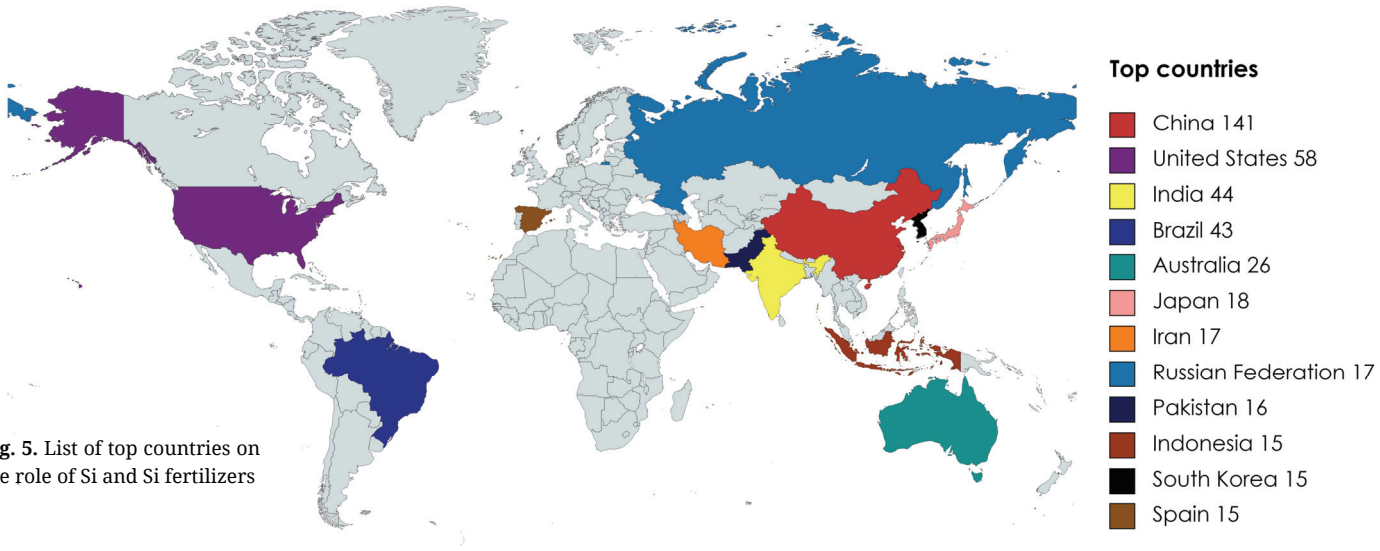


Fig. 5. List of top countries on the role of Si and Si fertilizers

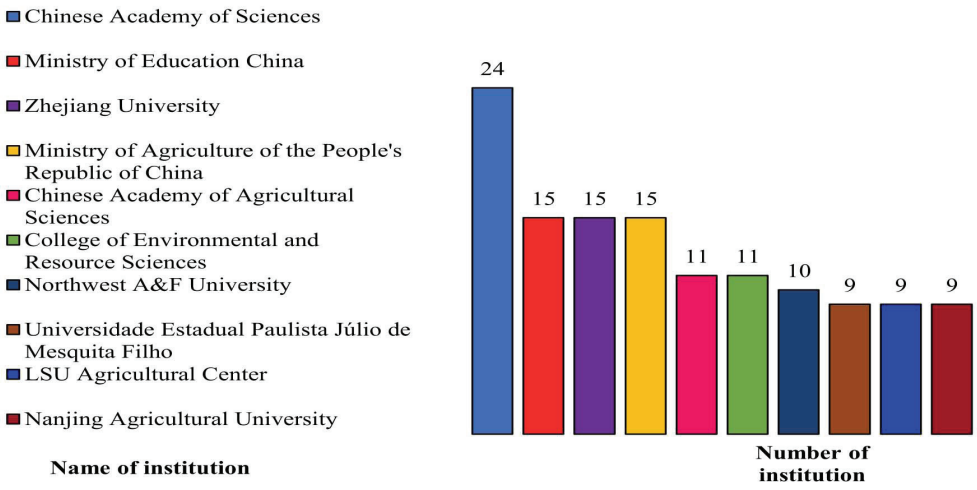


Fig. 6. Top institutions on the role of Si and Si fertilizers

3.7. Top sponsors on the role of Si and Si fertilizer

The frequency of linked nations is related to the support of significant funding schemes and projects. One hundred and fifty-eight different sponsors worked collectively to publish 440 articles on the role of Si and Si fertilizers in the world during the period 2012–2022. On the basis of our assessment of publications from the top 10 funders on the role of Si in the soil plant system, we were able to identify the most influential and productive institutions in this area. Figure 7 shows the top 10 funding sponsors. The National Natural Science Foundation of China has the highest number of results, publishing approximately 74 papers. The next two sponsors, the National Council for Scientific and Technological Development and China's National Key Research and Development Program, achieved the same results as 21. The highest number was held by the Coordination of the Improvement of Higher Education Personnel and the Ministry of Science and Technology of the People's Republic of China on 13 and 12, respectively. The remaining six sponsoring organizations funded six and seven research papers on this topic. The demand for silicon fertilizer production is growing rapidly today because of its role in eliminating various stress factors. Today, many countries have agrocenters that produce Si fertilizers. HAITOR is an innovative silicon fertilizer company headquartered in Qingdao, China. However, the key players involved in the global silicon fertilizer market are Plant Tuff Inc., Maxsil, Redox Pty Ltd., BASF SE, The Mosaic Company, Agripower, Denka Co. Ltd., Aries Agro Ltd., Compass Minerals International, Inc., and Yara International ASA.

3.8. Network map of keywords based on the total link strength on the role of Si and Si fertilizers

Working with keywords allows the use of many scientific dissertations and research papers. The VOS viewer was used for sorting the most frequently used keywords in the articles. In total, 4454 keywords and 41 threshold keywords were selected, and the minimum number was set to 30. So, there are three clusters: total strength of links: 33; occurrences: 38; and items: biomass. The cluster of three types includes different items. Cluster number one has 18 items, cluster number two has 16 items, and cluster number three has 7 items, so 41 keywords were selected. In these three types of clusters, the keywords were proportionally related to each other. According to the keyword map shown in Figure 8, it can be confirmed that scientific publications on the role of Si and Si fertilizers have been mainly divided into three

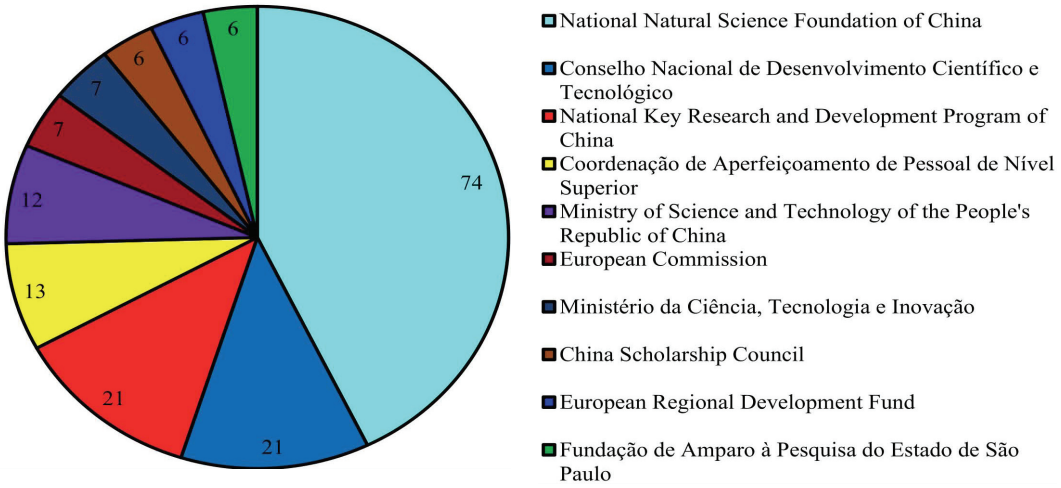


Fig. 7. Top sponsors on the role of Si and Si fertilizer

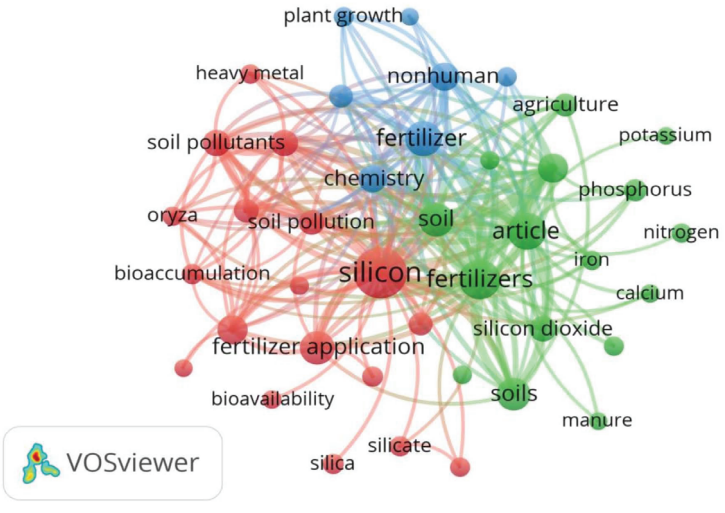


Fig. 8. Keywords based on the total link strength on the role of Si and Si fertilizers

separate areas, represented by a group of characteristic colors. The first of these (pink clusters) contains studies involving the role of Si in the soil. The second group (green clusters) shows studies related to the interaction of Si fertilizers with inorganic soil elements such as phosphorus, nitrogen, iron, calcium, etc. in the soil. Studies on the impact of soil Si and Si fertilizers on plant growth and agriculture are presented in the third group (blue clusters).

3.9 List of subject area names on the role of Si and Si fertilizers

The subject area plays an important role in finding important documents. Regarding the role of Si and Si fertilizers, 29 subject areas have been identified. Figure 9 shows 10 subject areas that cover most of the articles published worldwide. Most scientific papers belong to two subject areas: Agricultural and Biological Sciences and Environmental Science. Both of them recorded the largest number of 240 and 235 published articles on the role of Si and Si fertilizers in recent decades. The next subject areas, namely, Biochemistry, Genetics, Molecular Biology, Chemistry, Engineering, and Earth and Planetary Sciences, were the highest in the published research papers 63, 32, 29, 25, respectively. Scientific papers related to this field have been published in several medical disciplines, such as medicine, energy, pharmacology, toxicology and pharmaceuticals, immunology, and microbiology, and scientific news has been published on 23, 18, 15, and 13, respectively.

3.10. List of top-cited publications on the role of Si and Si fertilizers

A huge number of citations indicate quality and novelty. We examined the most cited articles on the role of Si and Si fertilizers (Fig. 10). First, we sorted the original Excel extension file names from the 192 documents alphabetically. The systematic

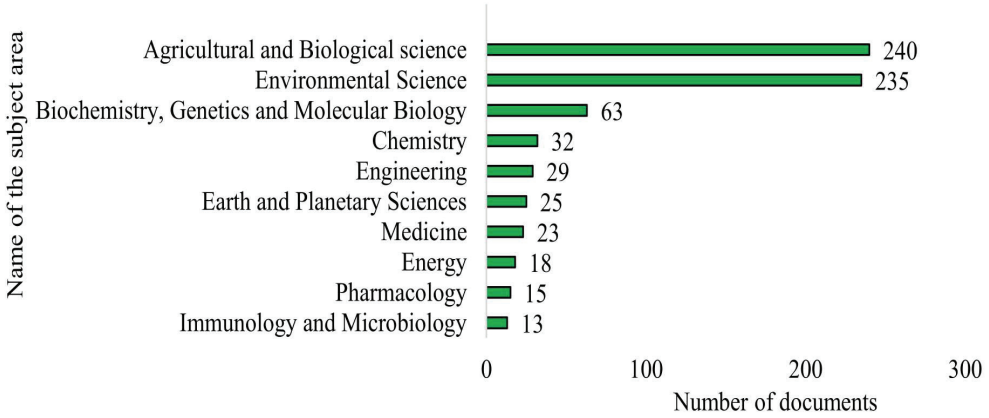


Fig. 9. Top subject area on the role of Si and Si fertilizers

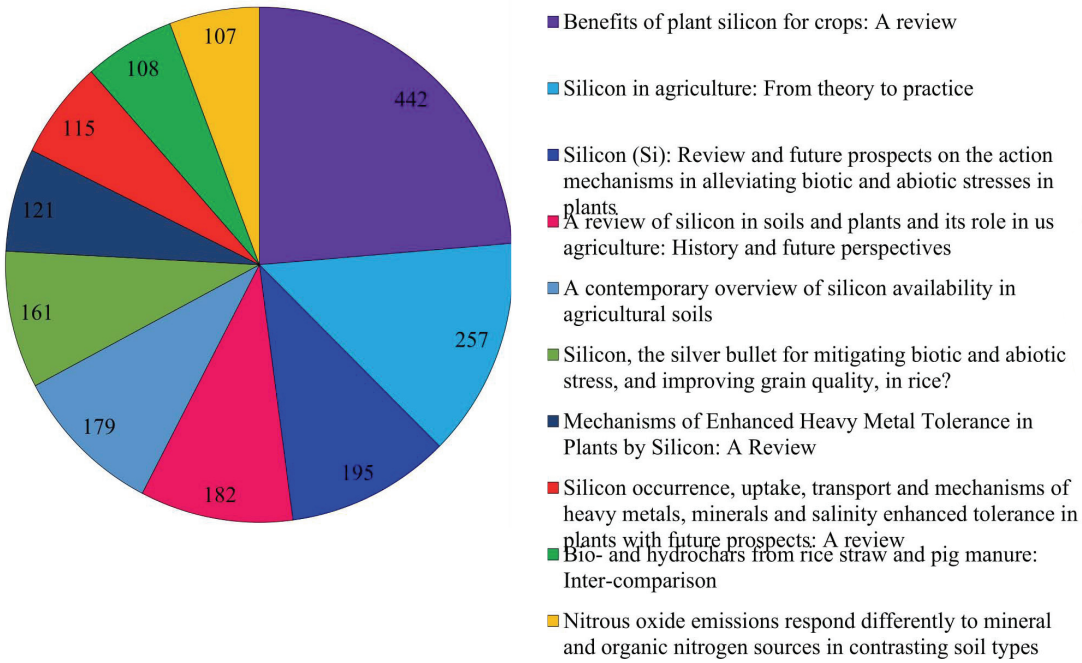


Fig. 10. Top cited publications on the role of Si and Si fertilizers

total citations of the articles are then summarized. Interestingly, the result is an updated list of potential article titles. Originally, 19 articles and one book chapter were selected. Almost 21% (8743 citations) of the total number of citations came from articles published in these 10 articles. Approximately 5% of the total citations come from the review article "Benefits of plant silicon for crops: a review," which ranks first with 442 citations. The next most cited publication was the book chapter "Silicon in Agriculture: From Theory to Practice" written by Liang (2015). This book consists of 13 chapters, and the corresponding keywords (abiotic stress, biotic stress, silicon, silicon uptake and accumulation, silicon nutrient management) in each chapter are also explained by its high citation rate. Silicon (Si): Review and prospects on the action mechanisms in alleviating biotic and abiotic stresses in plants was written by Etesami (2018), and "A Review of Silicon in Soils and Plants and its Role in US Agriculture: History and Future Perspective" was written by Tubana et al. (2016). Their citations total 257, 195, and 182, respectively. Figure 10 shows only the number of the greatest quantity cited publications. Therefore, to expand this section, Table 2 has been created with additional information about the journal in which the cited publications were published, the country, year, and corresponding authors, as well as the type of document. Table 2 lists the highly cited articles, authors, years, and document types. In total, 8743 citations from 440 publications and 190 journals on the specified topic were provided for the specified period. Benefits of plant silicon for crops: a review of an article comprising 5% of the total number of citations. According to this, 15% of the total number of citations, considering the nine subsequent scientific papers in the table. According to this table, the corresponding documents with high citations were published in France, China, Iran, and the United States. The journal with the most citations is published as a review. Topics related to this article were published between 2015 and 2018. Chinese scholars have published important papers in this field.

4. Conclusions

This research offers a comprehensive bibliometric statistical review related to the literature on the role of Si and Si fertilizers worldwide between 2012 and 2022. During the analysis of the collected data sources, important aspects including eminent authors, contributions from various institutions, geographical locations, major funders and publishers were thoroughly discussed and explored. The findings indicate a significant increase in the number of publications over the past decade. These fertilizers have been widely implemented in farming practices across the

Table 2
List of top cited publications on role of Si and Si fertilizers

No	Title of the abstract	Name of Journal	First author	Country	**Year**	**Total citation**	**Document type**
1.	Benefits of plant silicon for crops: A review	Agronomy for Sustainable Development	Guntzer F.	France	2012	442	Review
2.	Silicon in agriculture: From theory to practice	Silicon in agriculture:	Liang Y.	China	2015	257	Book
3.	Silicon (Si): Review and future prospects on the action mechanisms in alleviating biotic and abiotic stresses in plants	Ecotoxicology and Environmental Safety	Etesami H.	Iran	2017	195	Review
4.	A review of silicon in soils and plants and its role in us agriculture	Soil Science	Tubana B.S.	USA	2016	182	Review
5.	A contemporary overview of silicon availability in agricultural soils	Journal of Plant Nutrition and Soil Science	Haynes R.J.	Australia	2014	179	Review
6.	Silicon, the silver bullet for mitigating biotic and abiotic stress.	Environmental and experimental botany	Meharg C.	UK	2015	161	Review
7.	Mechanisms of Enhanced Heavy Metal Tolerance in Plants by Silicon: A Review	Pedosphere	Wu J.-W.	China	2013	121	Review
8.	Silicon occurrence, uptake, transport and mechanisms of heavy metals, minerals and salinity enhanced tolerance in plants with future prospects:	Journal of Environmental Management	Imtiaz M.	China	2016	115	Review
9.	Response of water deficit-stressed Vigna unguiculata performances to silicon, proline or methionine foliar application	Scientia Horticulturae	Merwad A.	Egypt	2018	103	Article
10.	Silicon in soils and plants	Silicon and Plant Diseases	Tubaña B.S.	USA	2016	97	Review

USA, China, India, Brazil, and Australia. China has been a leader in researching and developing these fertilizers, collaborating with institutions worldwide. In the US, special Si fertilizers are produced and extensively utilized in soil management. The majority of research articles on this topic have been published in English, with China, the USA, India, Iran, and Brazil leading the way. The role of silicon and its preparations in the biological and chemical processes of soil, as well as the scientific foundation for these processes, hold great promise for agricultural projects. Exploring methods to convert solid and amorphous silicon into a mobile form in soil can lead to beneficial outcomes in various stress conditions. The research reviewed on the role of silicon in soil-plant interactions and the potential use of silicon fertilizers offers valuable insights for future analytical articles.

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