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# Research on the Current Situation and Hotspot of Root Exudates Based on Bibliometrics

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## Abstract

**In order to analyze the research status and hotspots of root exudates, this paper takes the Web of Science core database as the data source, and uses VOSviewer and RStudio to carry out bibliometric visualization analysis on the articles on root exudates included in it. From the analysis of the number of publications, literature sources, research institutions, authors, regional cooperation networks, highly cited literature, and keyword cluster, the results show that the number of publications in this field has maintained an overall growth trend and is currently a hot research field. Most of the literature comes from core journals in the field, mainly involving plants and ecology and other fields. The cooperation between important authors is close, and the rest of the authors are mainly independent research. China ranks first in the number and centrality of publications, followed by the United States and Australia. Domestic and foreign institutions have close cooperation and reasonable distribution. Through the analysis of keyword co-occurrence map, rhizosphere, growth, soil, plant, diversity, identification, resistance, Arabidopsis and so on are the keywords with high frequency. The effect of root exudates on plant growth and its interaction mechanism with rhizosphere microorganisms are the core issues that researchers focus on. Most of the highly cited literatures in this field have been published earlier and the number of citations is higher, which lays a good foundation for subsequent scholars' research. The relationships among plant rhizosphere microorganisms, rhizosphere environment, root exudates and plant growth are a research hotspots in this field. In the future, researchers should also strengthen the update and in-depth study of relevant measurement technologies to achieve multidisciplinary integration.**

## Keywords

**Root exudate; Bibliometrics; Research hotspot; Microorganism.**

## 1. INTRODUCTION

As a bridge between plants and soil and the external environment, roots play an important role in plant growth. Root exudates are the general term for various compounds released by plant roots to the external environment during the entire growth stage, having an important driving effect on the material circulation in the rhizosphere soil ecological environment. They are the key factors for plants to maintain the vitality of the rhizosphere micro-ecosystem, and are also an important part of the material circulation in the rhizosphere [1]. Root exudates are affected by various biotic and abiotic factors, while the root exudates play a role in plant growth and development, physiological and biochemical characteristics, and regulate plants under heavy metal toxicity, allelopathy and other stresses [2]. At present, studies have shown that root exudates are one of the important factors for soil-borne disease prevention and control and soil

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phytoremediation [3, 4]. Exploring the relationship among root exudates, plants, soil and microorganisms, and starting the further study on the types, influencing factors and interactions of plant root exudates are conducive to better application in production.

In recent years, the study of plant root exudates has become a research hotspot in the fields of soil ecology, plant nutrition and metabolism, and the study of the interaction mechanism between plant root exudates and rhizosphere microorganisms has also become one of the hot issues [5]. There are some important research progresses on the interaction between root exudates and rhizosphere microorganisms, which definite the effects of root exudates on the species and distribution of rhizosphere microorganisms, the effects of environmental stress on root exudates and rhizosphere microorganisms, and the effects of rhizosphere microorganisms on plant growth have been further clarified [6]. The interaction between plants and soil microorganisms is mediated by root exudates [7]. At the same time, root exudates can also gather beneficial microorganisms to help plants alleviate stress [8]. As the substance that affects plant nutrient absorption and regulates microbial communities, the nutrient deficiency of plants can be judged according to the substances contained in root exudates [9]. In addition, root exudates can also participate in the process of soil carbon and the nitrogen cycle [10], thus affecting the change of whole element [11].

However, the secretion mechanism of root exudates is insufficient yet. The quantity and content of root exudates of different plant species are different [12], and the formation mechanism needs to be clarified, resulting in slow progress in overcoming continuous cropping obstacle [13]. At present, the research of root exudates mainly focuses on agricultural ecosystems and lacks its influence mechanism in wetland ecosystems [14]. The existing root exudates collection methods and testing technology are difficult to obtain accurate data [15,16]. Some practices have achieved certain results, but it is necessary to improve, and strive to achieve non-destructive identification and analysis of root exudates components [17]. The research of seasonal dynamic changes of root exudates input characteristics should be further studied [18]. There are studies on the input and output of soil organic carbon mediated by root exudates, but there is a lack of research on the effects of chemical composition changes of root exudates and the stoichiometric characteristics on soil carbon process [19]. It is necessary to strengthen the functional localization of target genes and microorganisms in response to biotic and abiotic stresses by using root exudates, and to achieve the purpose of effectively improving plant health by means of genetic engineering.

At present, it is an important nodal point in national territory renovation and construct ecological civilization [20]. Root exudates play an irreplaceable role in environmental ecological restoration. Taking the rhizosphere as the focus, exploring the relationship between multi-nutrient interaction and underground environment have good prospect [21]. By the connect the root exudates with the interaction among soil physical and chemical properties, enzyme activity, microbial community diversity and metabolism [22], it is expected to finally achieve the development of agriculture and forestry, protect the ecological environment.

Based on the literature in the field of root exudates in the core literature database on the Web of Science (WOS) platform, this paper makes the information visualization analysis to summarizes the research status and main frontier dynamics, and provides some theoretical reference in this field.

## 2. METHODS

### 2.1. Analysis methods

As an important method to quickly understand the development and frontier hotspots of related academic fields, bibliometric analysis has been applied in many fields. Combined with the application of information visualization technology in recent years, it can intuitively show

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readers the research hotspots and development trends. In this paper, the bibliometric package in RStudio software was used to analysis the annual average quantity of articles, journals, and distribution of countries published in the English literature on root exudates in the core database of Web of Science, and VOSviewer software was used to visualize the literature for keyword co-occurrence and institutional author cooperation. The development and trend of the research on root exudates are summarized, so that the subsequent research can further explore the function, mechanism and influencing factors of root exudates.

### 2.2. Data sources

The data is derived from the core collection database of the Web of Science (WOS) platform. The search formula is ((AB = ("root exudate" OR "root exudation" OR "root secretion" OR "root exudates" OR "plant root exudate" OR "plant root exudates")), check the Open Access option, the language is English, and the search time is not limited. According to the title, abstract and keyword of articles, there were 1878 articles were screened from 1996 to 2023.

## 3. RESULTS

### 3.1. Trends in quantity of published articles

The changes in the annual quantity of published papers are conducive to understanding the development trend of root exudates, showing the changes in this field during the year, and providing important significance for analyzing its development dynamics and predicting future trends. According to the Figure 1, it can be seen that the quantity of published papers showed an upward trend. It can be roughly divided into two stages: 1996-2014 and 2015-2023. The former is the primary stage of root exudates research, and the quantity of publications is low. However, in the second stage, the quantity of publications had increased significantly, and it has grown rapidly at this stage. In 2022, the number of publications reached 256. This shows that although the field started late, it has attracted wide attention in recent years. Since 2016, the quantity of published papers has increased greatly, and the overall quantity of published papers has increased steadily, which proves that researchers have a strong interest in this direction. This field has development potential and broad research prospects.

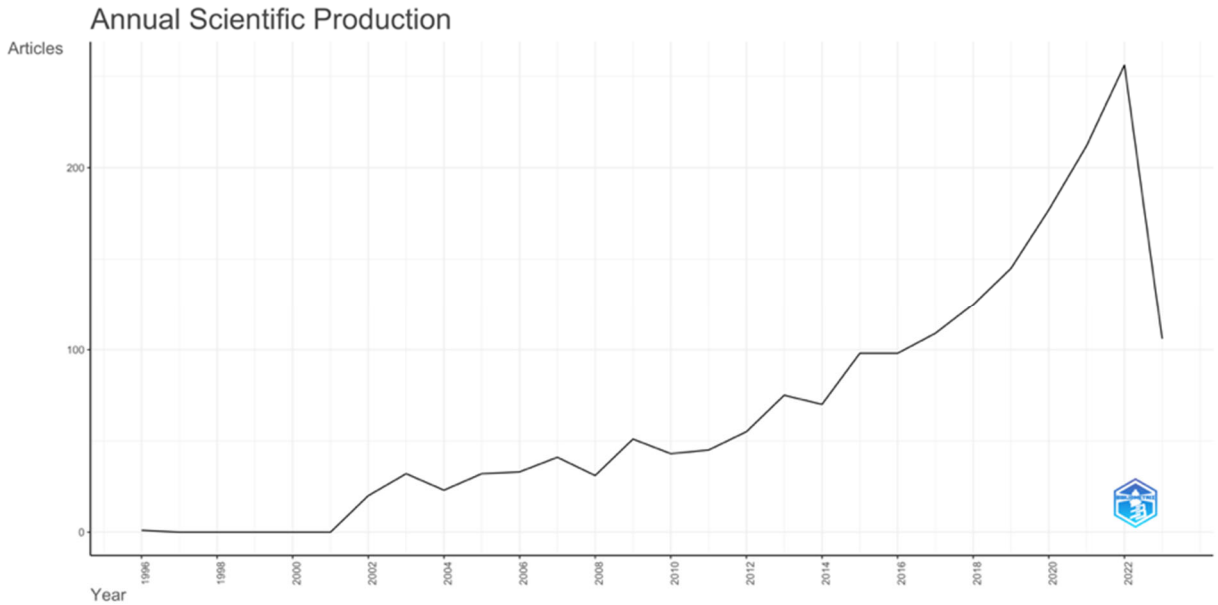


**Figure 1.** The change line chart on annual quantity of published papers

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## 3.2. Analysis of literature source

Statistical analysis on the journals of literature sources was carried out, and the distribution characteristics of journals published in papers related to root exudates were effectively summarized. The 1878 English literatures were retrieved in this paper from 413 journals. Frontiers in Plant Science, Frontiers in Microbiology, PLoS One, New Phytologist and Plant and Soil had the largest quantity of publications, which were 127, 85, 73, 63 and 49, respectively. The impact factors of these five journals in 2021 were 6.627, 6.064, 3.752, 10.323 and 4.993, respectively. The quantity of papers published in the top five journals accounted for about 18.58 % of the total papers, and the topics of these journals mainly involved ecology, soil and other fields.

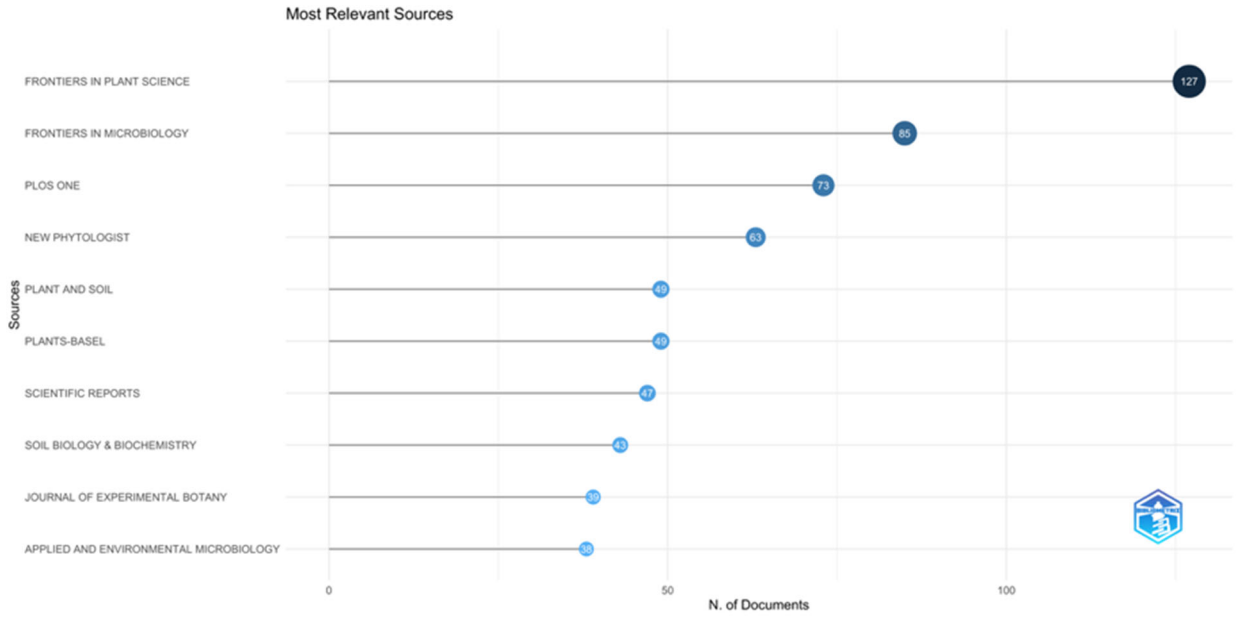


**Figure 2.** Data chart of journals

## 3.3. Analysis of research institutions

The main research institutions retrieved in this paper are the University of Western Australia, Nanjing Agricultural University, Colorado State University, Fujian Agriculture and Forestry University, University of Hohenheim, China Agricultural University, Cornell University, Zhejiang University and so on. The University of Western Australia has the largest quantity of papers, reaching 64, followed by Nanjing Agricultural University, with 62 papers and Colorado State University, with 58 papers. Although the quantity of papers published by foreign colleges and universities accounts for a large proportion, it can be judged that the quantity of papers published by domestic colleges and universities shows a good growth trend.

The core institutions in the research institutions collaboration spectrum are the Chinese Academy of Sciences, The Spanish National Research Council (CSIC), The University of Tokyo, China Agricultural University and Colorado State University in the Figure 4. The Chinese Academy of Sciences occupies the core position and has close cooperation with scientific research institutions at home and abroad. At the same time, the communication among the core institutions is also close and diverse, which is conducive to the development and progress of research in the field of root exudates.

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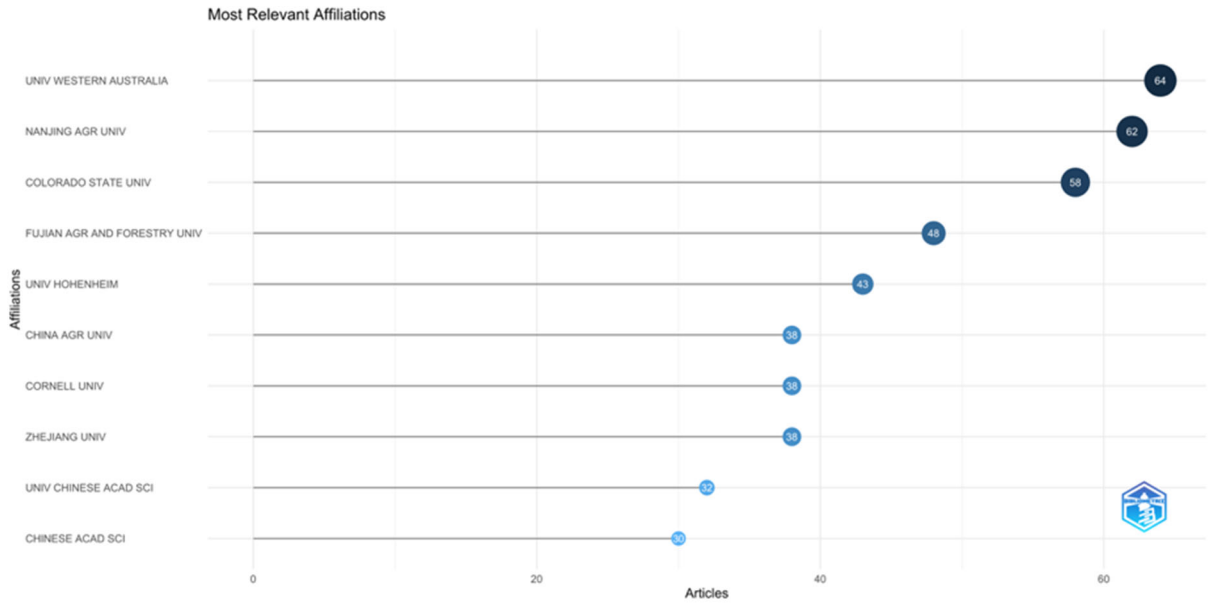


**Figure 3.** The chart on quantity of publishing institutions

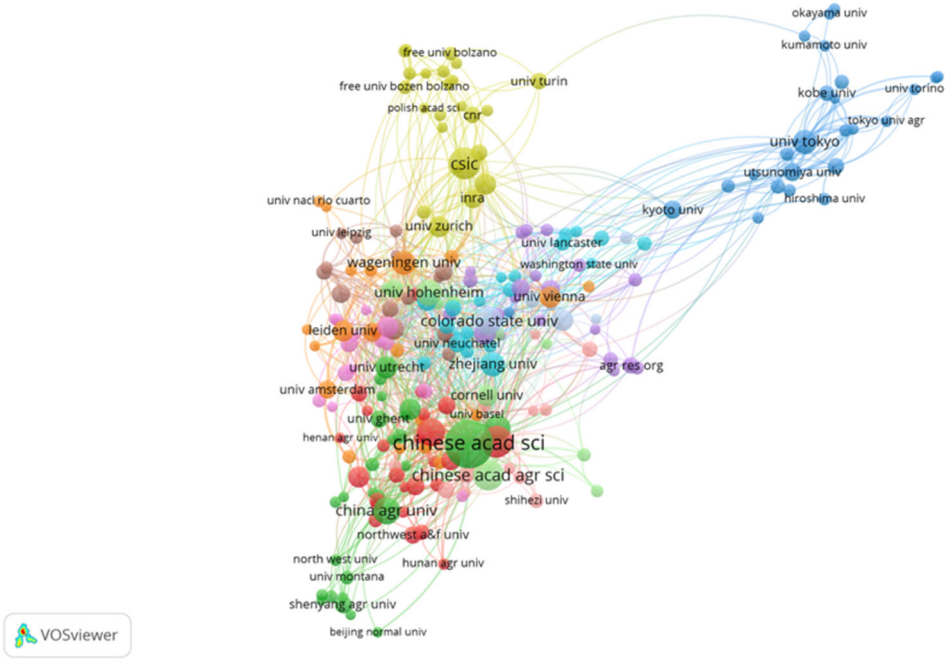


**Figure 4.** The Research Institutions Collaboration Spectrum

## 3.4. Analysis of research country

The distribution of countries in the literature was analyzed. China, the United States, Germany, Japan and France published 1203, 891, 460, 345 and 283 articles respectively, ranking the top five. The quantity of China's publications in this field rank first, indicating that China has made relatively good progress. Figure 4 shows the distribution of publications in root exudates in various countries clearly, and also intuitively shows the contribution to this field. China, the United States, Australia, Germany and the United Kingdom are all key nodes. At present, there are strong international cooperation relationships in this field and China plays a key role as a bridge in the cooperation network.

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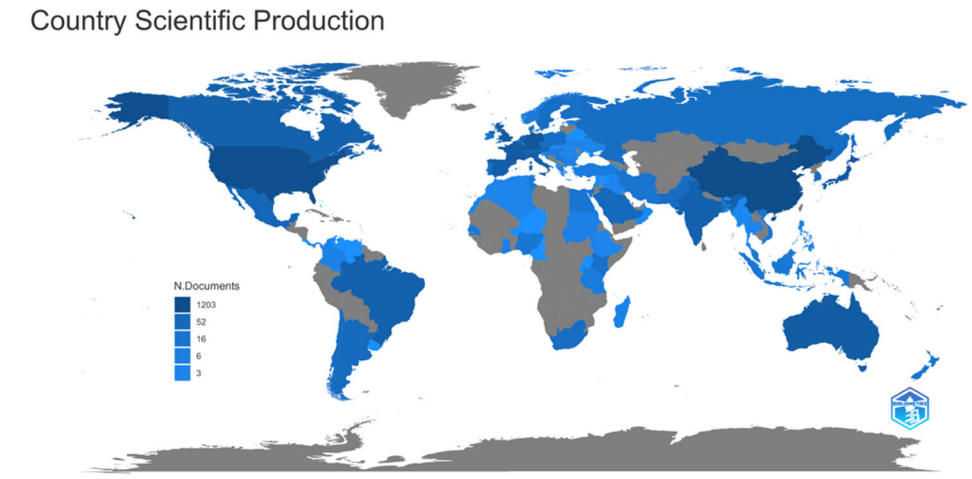


**Figure 5.** Distribution map of publishing countries

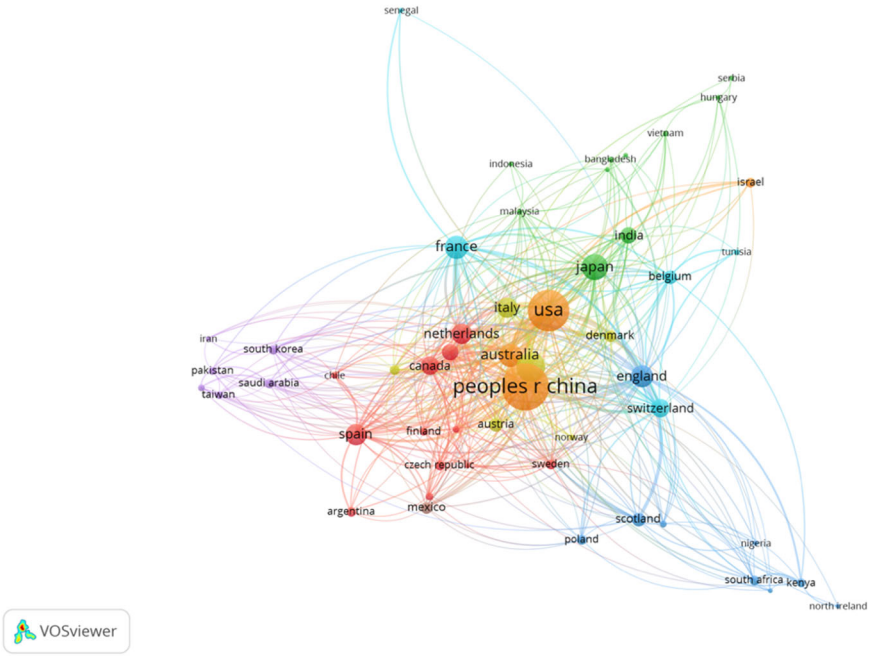


**Figure 6.** National cooperation network spectrum

**Table 1.** National Publication Scale

| region | Freq |
|---|---|
| CHINA | 1203 |
| USA | 891 |
| GERMANY | 460 |
| JAPAN | 345 |
| FRANCE | 283 |
| UK | 239 |
| AUSTRALIA | 236 |
| ITALY | 181 |
| SPAIN | 178 |
| NETHERLANDS | 158 |

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## 3.5. Analysis of research authors

The most relevant author analysis and author cooperation network analysis were performed on the retrieved literature. The top 10 authors with the highest quantity of publications are Yoneyama K, Vivanco J M, Lambers H, Shen Q R, Cesco S, Mimmo T, Wang J Y, Xie X N, Li J and Sugimoto Y in Figure 7. The core authors are Vivanco Jorge M, Shen Qirong, Lambers Hans, Cesco Stefano, in figure 8. And there are also relevant cooperative research among their teams. The close cooperation of important team authors is conducive to the further development of research, while most of the remaining authors are mainly independent research. Vivanco J M mainly studies the function of root exudates and the interaction with plants and microorganisms [23, 24, 25]. Cesco Stefano mainly studied the effects of different treatments on the exudation of root exudates and the limitation of substances on it [26, 27, 28].

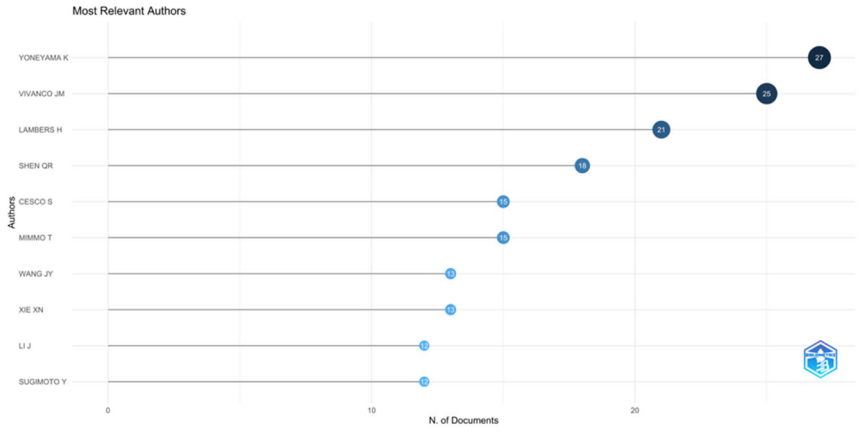


**Figure 7.** Most relevant author chart

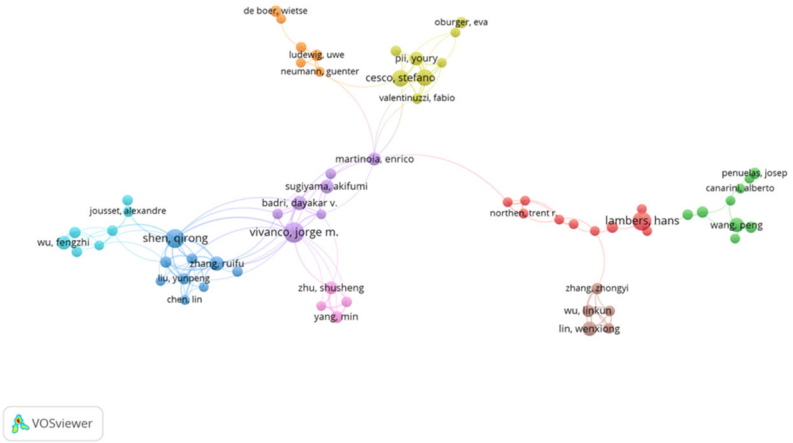


**Figure 8.** The author cooperation network spectrum

## 3.6. Analysis of keyword co-occurrence

The literature keywords can index the content characteristics of the paper, which greatly facilitates the collection of information and the retrieval of readers. The logical combination in keywords can characterize the theme content of the paper and accurately summarize the core content of the paper [29]. The circular area in the figure represents the frequency of the

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keywords, and the line between the circles represents the correlation between the two in Figure 9.

The high-frequency keywords were rhizosphere (405 times), growth (303 times), soil (249 times), plants (171 times), diversity (166 times), identification (121 times), resistance (115 times), Arabidopsis (114 times), nitrogen (113 times), expression (98 times), roots (97 times) in Figure 9. Therefore, the research of root exudates mainly focused on rhizosphere soil, plant growth, plant resistance and nitrogen cycle.

Eight keyword clusters were formed in Figure 9. In the red cluster, the keyword with the largest weight was 'nitrogen'. In the green cluster, the keyword with the largest weight was 'identification'. In the purple cluster, the keyword with the largest weight was 'rhizosphere'. In the yellow cluster, the keyword with the largest weight was '*arabidopsis*'. In the brown cluster, the keyword with the largest weight was 'resistance'. In the dark blue cluster, the keyword with the largest weight was 'growth'. In the light blue cluster, the keyword with the largest weight was 'organic-acids'. In the pink cluster, the keyword with the largest weight was 'maize'. The research of root exudates mainly focuses on rhizosphere environment, plant growth, plant resistance and nitrogen cycle.

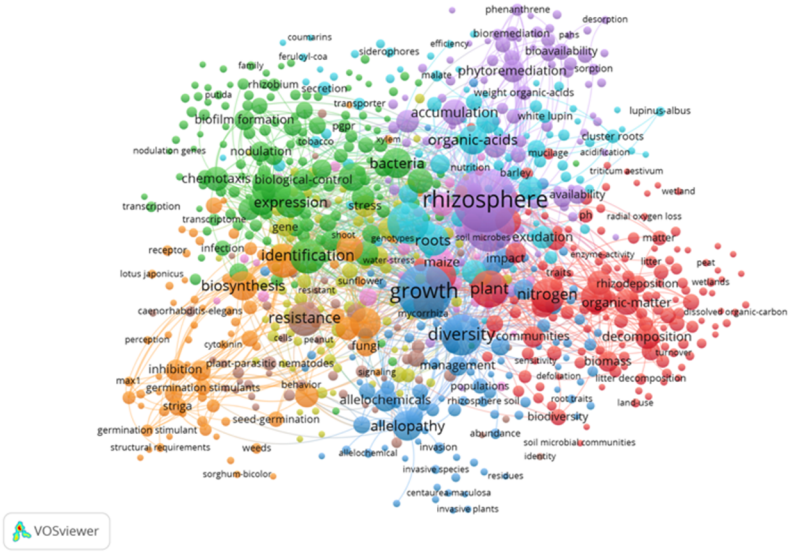


**Figure 9.** Keywords co-occurrence map

## 3.7. Analysis of Literature co-citation cluster

The citation frequency of a literature usually means the influence, which can directly reflect the author 's scientific research level and academic influence. The highly cited literature is the core paper on the basic theory or research methods in this field, which represents the research hotspot and development direction in this field.

The top 10 cited literature in the retrieved literatures were listed in Table 2. The first one published in 2009 and cited up to 1402 times is about the effects of plant species and soil types on rhizosphere-related microbial communities. Root exudates and microorganisms work together to shape the rhizosphere microbial community [30]. The second article about the regulatory function of root exudates on roots and soil microorganisms [31] was published in 2009, and the number of citations was 1120. The third article on the effects of sugar and jasmonic acid concentrations in root exudates on the rhizosphere bacterial community of maize [32] was published in 2022 and cited for 1070 times. Root exudates make plants have higher selective advantages, faster evolutionary speed, and significant performance after invasion [33], and the literature was published in 2004, cited for 1055 times. The fifth article is about the

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activities that root exudates are involved in as substances between soil-borne pathogens and beneficial microorganisms in the rhizosphere [34]. It was published in 2009 and cited for 917 times. The sixth article was published in 2004, cited 881 times, which showed root exudates are involved in rhizosphere nutrient uptake and carbon cycle [35]. The seventh article published in 2018, was cited for 789 times, which explore the root exudates of plants with the same chemical composition and provide a theoretical basis for the study of rhizosphere microbial communities [36]. Through high-throughput characterization, it is the eighth article found that rhizosphere microorganisms were indeed related to the growth and health of plants [37], and was published in 2018, cited for 789 times. The ninth paper analyzed the changes of rhizosphere bacterial community structure at different stages of Arabidopsis growth and development, but there was no significant difference in bacterial community structure. It was speculated that the root exudates of plants were different at different developmental stages to regulate the composition of rhizosphere microbial community [25], which was published in 2014 and cited for 734 times. The tenth article showed that plant habitats and root exudates together affect the soil bacterial community structure, and have an important impact on plant growth [38], published in 2008, cited for 729 times.

Through the first 10 highly cited literatures, it can be seen that the effect of root exudates on plant growth and the interaction mechanism between root exudates and rhizosphere microorganisms are the core issues. Most of the highly cited literatures in this field have been published early and are frequently used as references, which proves that they have laid a good foundation for subsequent scholars' research.

**Table 2.** Highly cited literature table

| Paper | DOI | Total Citations | TC per Year | Normalized TC |
|---|---|---|---|---|
| BERG G, 2009, FEMS MICROBIOL ECOL | 10.1111/j.1574-6941.2009.00654.x | 1402 | 93.47 | 9.92 |
| BADRI DV, 2009, PLANT CELL ENVIRON | 10.1111/j.1365-3040.2009.01926.x | 1120 | 74.67 | 7.92 |
| LOPES LD, 2022, APPL ENVIRON MICROB | 10.1128/aem.00971-22 | 1070 | 535 | 129.39 |
| CALLAWAY RM, 2004, FRONT ECOL ENVIRON | 10.1890/1540-9295(2004)002[0436:NWISAT]2.0.CO;2 | 1055 | 52.75 | 5.87 |
| RAAIJMAKERS JM, 2009, PLANT SOIL | 10.1007/s11104-008-9568-6 | 917 | 61.13 | 6.49 |
| JONES DL, 2004, NEW PHYTOL | 10.1111/j.1469-8137.2004.01130.x | 881 | 44.05 | 4.9 |
| ZHALNINA K, 2018, NAT MICROBIOL | 10.1038/s41564-018-0129-3 | 789 | 131.5 | 14.44 |
| SASSE J, 2018, TRENDS PLANT SCI | 10.1016/j.tplants.2017.09.003 | 789 | 131.5 | 14.44 |
| CHAPARRO JM, 2014, ISME J | 10.1038/ismej.2013.196 | 734 | 73.4 | 10 |
| HAICHAR FE, 2008, ISME J | 10.1038/ismej.2008.80 | 729 | 45.56 | 7.06 |

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## 4. DISCUSSION

At present, the research on root exudates is mainly focused on agricultural science, such as agricultural planting patterns, different crop research, different environmental stresses, heavy metal pollution, microorganisms [39, 40]. The relationship between root exudates and soil element, and the interaction between root exudates and microorganisms were emphasized in foreign countries. The gap between domestic and foreign hot issues is obvious. Scholars should be fully prepared and make further in-depth research on the existing basis.

At present, there are still some problems in the field of root exudates. The existing technology can only determine the common components in root exudates, and there is no effective way to judge and detect the root exudates with low concentration [2]. It is urgent to develop a new technology to analyze and identify a variety of root chemical signal substances [41]. The allelopathy of root exudates has made some progress, but still need further study [42]. And the effects of specific stress on the composition of root exudates need more experimental data as a reference [43]. The relationship between plants and rhizosphere microorganisms affected by root exudates needs to be clarified, and due to different components, the specific selection mechanism of different plant root exudates also needs to be clarified [44]. Although it has been confirmed that arbuscular mycorrhizal fungi can affect root exudates, there are limited reports on the specific effects of arbuscular mycorrhizal fungi [45]. Gene selection and gene recombination can be applied to the relationship between cultivated species and root exudates, but lack of a large number of experimental data support. And the physical and chemical properties of soil affected by plant root exudates can be studied and analyzed by combining the knowledge of molecular biology and other fields [46, 47]. Most of the research are aimed at the influence of single factor stress on plant root exudates, and there is a lack of discussion on the influence of multiple factors [48].

## 5. CONCLUSION

The quantity of literatures on root exudates maintained an overall growth trend, and the growth rate has accelerated significantly since 2016. Frontiers in Plant Science was the journal with the largest quantity of publications. The research institutions in the leading position are University of Western Australia, Nanjing Agricultural University and Colorado State University, indicating the strong scientific research ability. The core institutions of the cooperative institutions are the Chinese Academy of Sciences, the Spanish National Research Council (CSIC) and the University of Tokyo. The cooperation between relevant research institutions at home and abroad is relatively close. At the same time, local agricultural research institutes in China are also jointly studied with universities. China ranks first in the quantity and centrality of publications, followed by the United States and Australia.

Rhizosphere, growth, soil, plant, diversity, recognition, resistance and Arabidopsis thaliana are keywords with high frequency. In agriculture and forestry, plant rhizosphere microorganisms, rhizosphere environment, plant growth and the relationship among them are the research hot issues. The focus of this field is mainly on rhizosphere soil, plant growth, plant resistance, nitrogen cycle and so on, showing a positive development trend. The literature published in recent years has certain innovation, and further deepen on the basis of predecessors.

China is in a leading position in all aspects of root exudates published in the literature, which reflects that Chinese universities and researchers attach great importance to the root exudates. The cooperation with world-class universities in many other developed countries needs to be improved, which can actively broaden academic cooperation. With the improvement of theory, the research directions may change from the mechanism between rhizosphere microorganisms and root exudates to the relationship among root exudates, plant growth and rhizosphere

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microorganisms. Through extensive research on Arabidopsis and maize, specific secreted substances may be widely applied to the treatment of plant diseases caused by soil-borne microorganisms [49]. With the increasing harm of invasive organisms, it should be explored whether invasive plants can be controlled by root exudates or to prevent and control existing diseases [50, 51]. Researchers should pay attention to the progress of related interdisciplinary disciplines such as biochemistry, molecular biology, the updating of technology and theory on extraction and inspection technology to promote the progress of root exudates.

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