

GLOBAL TRENDS AND PROSPECTS IN THE STUDY OF ANTIMONY BIOGEOCHEMICAL PROCESSES: A BIBLIOMETRIC ANALYSIS

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Abstract. The progress, trends and hotspots of global antimony research knowledge have not been systematically analyzed using bibliometric methods over the past few decades. This study performed bibliometric analyses to evaluate the evolution of the biogeochemical processes of antimony in terms of the article, author, source, country, and topic dimensions from 1985 to 2025, based on 1089 articles from the Web of Science, with VOSviewer and Citespace. It was concluded firstly, that article publications and citations have grown rapidly since 2000, respectively, peaking in 2022. Secondly, the majority of researchers are primarily affiliated with China, the United States, and Germany, and they lead research teams with distinct directions and priorities. Meanwhile, co-occurrence and burst keyword analyses revealed the research progress, hotspot changes, and trends. Four primary themes were identified by co-occurrence keyword analysis: water pollution mechanism, adsorption/oxidation technology, speciation analysis and bioavailability, and environmental factor regulation. Burst keywords analysis showed that the focus of research has gradually shifted from early morphological detection to multimedia interaction and micro-scale interface mechanism. The research and development of remediation materials, the interaction between microorganisms and antimony, and the remediation of mining pollution have become emerging hot spots. Finally, suggestions for further research were put forward.

Keywords: *antimony, migration and transformation, biogeochemistry, VOSviewer, CiteSpace*

Introduction

Antimony (Sb) is one of the metals widely distributed in terrestrial ecosystems (Okkenhaug et al., 2011). According to the report of the United States Geological Survey (2024), the global Sb reserves in 2024 exceed 2 million tons, while China's Sb reserves are 640,000 tons, accounting for over 30% and ranking first in the world. At the same time, China is also the world's largest producer of Sb, accounting for approximately 48% of the global Sb mining output. From 2019 to 2022, 63% of the Sb and its oxides imported by the United States originated from China. Sb is widely used in electronics, chemicals, construction, automobiles, and other industries (Liu et al., 2019; Filella et al., 2020; Hu et al., 2021), and the continuous increase in the demand for Sb in these industries has indirectly driven exploitation of Sb ore resources. However, Sb is regarded as a non-essential toxic element for the human body and a suspected carcinogen, and it has been classified as a priority control pollutant by the United States Environmental Protection Agency (USEPA) and the European Union (EU) (Herath et al., 2017). Sb in different environmental media can enter the human body through breathing, the food chain, and even

skin contact, causing damage to the human nervous system, immune system, and genome. Furthermore, due to the influence of natural activities and human factors, the pollution of Sb in the mining area environment is inevitable (He et al., 2019; Li et al., 2018). Therefore, studying the biogeochemical behavior of Sb migration and transformation in the environment is of great significance for understanding its fate and risk.

Previous studies have shown that the biogeochemical processes of Sb involve various complex processes such as dissolution and precipitation, adsorption and desorption, oxidation and reduction, and microbial transformation (He et al., 2019). A series of mechanisms related to the sources, distribution, forms, migration and transformation, as well as removal of Sb have been investigated by researchers (Li et al., 2018; Wen et al., 2023a). Currently, the mechanism of Sb release from host mineral phases and its migration and transformation processes in different environmental media still lack in-depth understanding. Although there are many review-type literature that have elaborated on the biogeochemistry of Sb and the processes of mobility, fate and transport included, and have proposed the current limitations and the gap between current and future studies based on existing technologies (Herath et al., 2017; Bolan et al., 2022; Fu et al., 2023). However, these conclusions or viewpoints are all the results of the conventional review and summary of historical documents, and do not involve any concepts from bibliometrics. Consequently, it is urgent to conduct a systematic analysis based on bibliometrics to understand the research trends, knowledge evolution paths, and regional differences of Sb in the global environment, in order to provide new insights for the study of the Sb biogeochemical processes.

Bibliometrics, a branch of information science, employs mathematical and statistical methods to describe, evaluate, and predict the current status and future trends of science and technology, utilizing the quantitative characteristics of literature (Xie et al., 2022). According to statistics, currently only two articles have adopted this method to study the trends of environmental risks and water quality criteria related to Sb pollution, and there is a lack of information on the research frontier of Sb biogeochemical processes. In this study, the VOSviewer and CiteSpace software are used to analysis the papers related to biogeochemical processes of Sb in the Web of Science (WoS) core collection from 1985 to 2025 to form visualization network maps, including years, countries, authors, institution, journals, references, and keywords. Through the national and institutional cooperation network, co-cited references, co-cited journals, the co-occurrence of high-frequency keywords, the detection of burst words, and other methods, the global research power distribution, the evolution of themes, and research hotspots are systematically analyzed, aiming to achieve the following research objectives: (1) identify the most influential journals, countries, institutions and authors in this research field, and analyze their research priorities; (2) clarify the changes and differences in research content among different teams and institutions; (3) interpret the basic knowledge and research frontiers related to this research field; (4) determine the research focus and future research trends in different periods. The results of this study aim to provide new insights for future exploration of the biogeochemical processes of Sb in water, soil, and sediments.

Methodology

Data source and search criteria

In this study, we selected Web of Science Core Collection as the data source. The setting conditions were as follows: Citation index = "Science Citation Index Expanded";

TI (Title) = (Antimony OR Sb OR “Antimony compounds” OR Antimon* OR Stibium OR Sb(III) OR Sb(V) OR Antimonate OR Antimonite) AND TS (Topic Search) = ((Release OR Mobilization OR Leaching OR Migration OR Desorption OR Solubility OR Dissolution OR Transport OR Liberation OR Leach* OR Mobiliz* OR biogeochemistry) AND (Soil OR Sediment OR Water OR Groundwater OR “Surface Water” OR “Riverine Environment” OR “Lake Water”). The data and materials included author lists, abstracts, references, citation counts, institutions, journal impact factors, countries and other information. Afterwards, we conducted a preliminary screening of the data collected from 1985 to May 2025, resulting in 1138 articles. Excluding irrelevant research fields such as architecture, nutrition, and mechanics, we obtained 1089 articles. After removing duplicates from the 1089 papers retrieved using CiteSpace, the effective number of papers was 1089, which served as the original data source for this study. This study does not contain any studies with human participants or animals performed by any of the authors. Therefore, ethical approval and informed consent were not required for this research.

Analysis method

The 1089 papers downloaded from the WoS database were subjected to the following analysis: (1) Microsoft Excel 2021 and Origin 2025 software were used for statistical analysis and plotting the graph of the number of papers per year, subject distribution, and number of cited. (2) SCImago Graphica (Bate 1.0.49) was used to conduct geographic visualization of the number of papers and cooperative relationships in the main participating countries (Huang et al., 2023). (3) CiteSpace (version 6.3.R3) and VOSviewer (version 1.6.20) software were used to analyze authors, institution, journals, references, and keywords in publications, forming visualization network maps to obtain the research status, hotspots, and future development trends in this field (Li et al., 2017).

These visualization network maps by VOSviewer include three parts: Nodes, lines, and colors: 1) nodes represent authors, countries, literature, or keywords, and their size indicates the number of articles published, the frequency of occurrence or the strength of associations; 2) the line between two node indicates a correlation between them (such as citation, collaboration, or co-occurrence), with thicker line indicating stronger correlation; 3) nodes with the same color represent the same attributes, such as belonging to the same research institution or team, belonging to the same research direction, or belonging to the same time period. the connecting lines represent the citation relationships among the authors; The node size represents the total citation count of the author. The larger the node, the more citations the author has in the field and the stronger the academic influence. The colors represent different clusters (Nees Jan and Waltman, 2017).

Results and discussion

Number of papers and subject distribution

The number of papers published each year can reflect the trend of research direction in a certain field (Chen et al., 2022). As shown in *Figure 1*, the number of papers on the study of Sb biogeochemical processes gradually increased from 1985 to 2025 and went through three different periods.

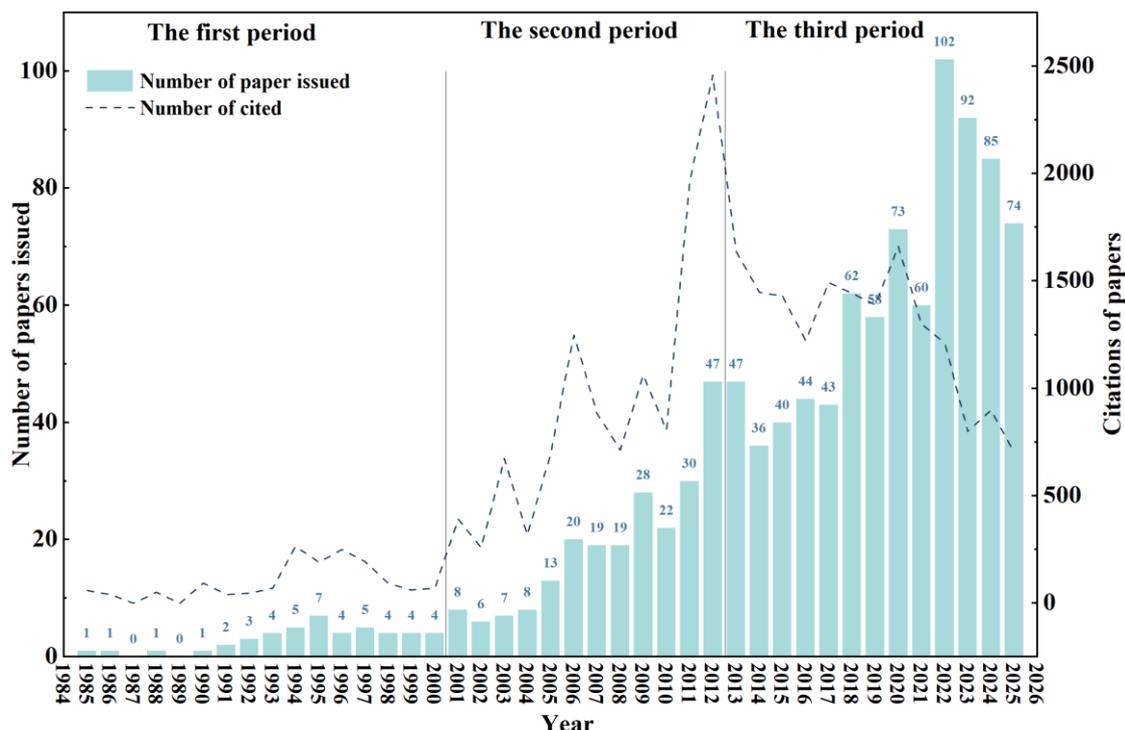


Figure 1. Annual number of papers and citations from 1985 to 2025

The first period (1985~2000): The concentration or content of Sb in different environmental media and its distribution characteristics were preliminarily studied. However, due to technical limitations, the number of relevant papers was at a relatively low level, ranging from 0 to 7 papers per year, with an average of 3.3 papers per year. The second period (2001~2012): The rapid increase in the number of papers was attributed to the gradual exploration of the environmental and human health impacts of Sb. The focus was on three aspects: 1) The optimization and improvement of Sb analysis methods resulted in the emergence of highly sensitive and selective detection techniques for Sb speciation analysis, such as high-performance liquid chromatography inductively coupled plasma mass spectrometry (Krachler and Emons, 2001); 2) The migration and transformation process of Sb in environmental media was identified with technological innovation (Cutter et al., 2001); 3) Highly adsorptive materials for treating high concentrations/contents of Sb were systematically studied, for example, over 95% of Sb(III) in experimental solutions could be removed by hydroxyapatite (HAP) adsorption within 30 min (Leyva et al., 2001). The third period (2012~2025): The number of papers continued to grow and remained at a high level, mainly due to the more prominent environmental problems of heavy metal Sb. During this period, the research entered a more in-depth and detailed stage. In terms of environmental geochemistry and pollution mechanisms, attention began to be paid to the influence of redox conditions on the migration and transformation mechanism of Sb (Hockmann et al., 2014a, b). In terms of pollution control, technologies such as adsorption material development (Alvarez-Ayuso et al., 2013; Lu et al., 2015), electrochemical removal technology (Li et al., 2018; Luo et al., 2025) and bioremediation were widely studied (Van et al., 2015; Rong et al., 2022). In terms of environmental risk assessment, the transmission of Sb in the food chain, human exposure risk and pollution traceability have become research focuses. Previous

studies found that the accumulation of Sb in rice in the tin mine area of China was blocked by iron (Fe) film, but Sb(V) could enter the plant through the root system, then enter the human body through the food chain (Ren et al., 2014). Meanwhile, the influence of microorganisms on the migration and transformation of Sb and the application of emerging materials have become new research trends during this period. In addition, compared with foreign countries, China's research on the biogeochemical processes of antimony started relatively late. From 1985 to 2001, there were almost no related papers published. The rapid increase after 2002 was attributed to the high attention paid to the environmental problems caused by antimony, which comes from the distribution analysis of academic papers. Of course, the increase in the number of articles is also slightly influenced by the rapid development of information technology. For example, the rise of the open access (OA) model has given birth to a large number of new journals. The establishment of these journals themselves contributes to the absolute growth in the number of papers, but this part of the growth reflects the broadening of publishing channels, and it does not necessarily equate to a substantial growth in scientific research activities at the same rate.

In terms of citations of papers, the citations of papers before 2000 were very low. It increased rapidly from 2000 to 2012, and the growth trend was the same as that of the number of papers published. After 2012, the number of paper citations decreased gradually each year, but maintained a high level. In general, the number of research papers on biogeochemical processes of Sb has shown a clear growth trend over the past few decades, especially after 2010, when the research enthusiasm has continued to increase, reflecting the academic community's continuing attention and attention to the issue of biogeochemical processes of Sb.

Through the statistical function analysis of the WoS system, as shown in *Figure 2*, the top 10 disciplines in terms of the number of papers in this field are environmental science, engineering environment, analytical chemistry, geochemistry, water resources, engineering chemistry, multidisciplinary materials science, multidisciplinary chemistry, physical chemistry, and mineralogy. This shows that the research on biogeochemical processes of Sb is a comprehensive issue involving multidisciplinary intersections.

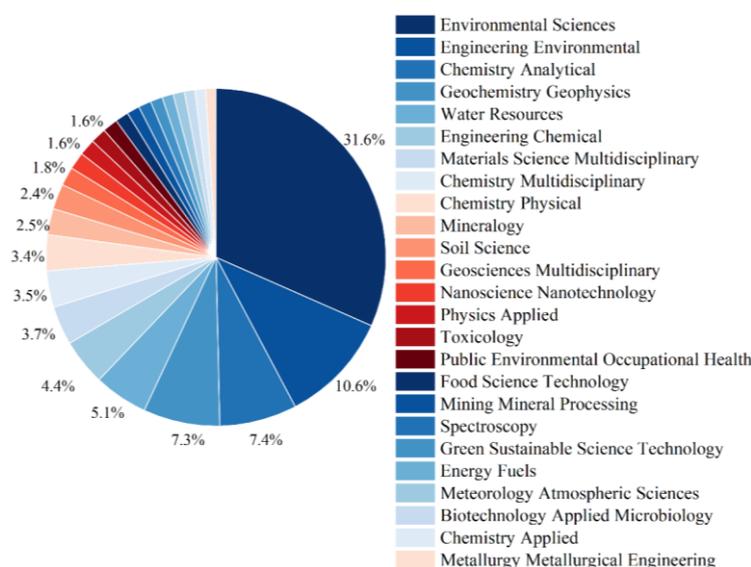


Figure 2. The percentage of subject distribution of papers

Overall, the number of papers on antimony biogeochemical processes has shown a significant growth trend over the past few decades. Especially after 2001, the research enthusiasm has been continuously increasing, reflecting the academic community's continuous attention and emphasis on the issue of antimony biogeochemical processes.

Main research forces

National and international cooperation

The amount of papers from different countries not only intuitively reveals their level of activity in Sb research, but also helps researchers grasp the global distribution of Sb research, which provides a reference for investigations and cooperation (Chen et al., 2020). According to the analysis of the WoS database, it can be known that 71 countries have conducted research on the biogeochemical process of Sb (Figs. 3 and 4). Among them, the number of papers from China is 393, accounting for 35% of the total global papers. The proportions of papers from the United States and Germany are 8.5% and 5.2%, respectively. This indicates that Chinese researchers pay extremely high attention to scientific issues related to Sb.



Figure 3. Geographical distribution of published papers by countries. (The connection represents the cooperative relationship between the two countries)

The Scimago Graphica and VOSviewer were used to analyze and obtain the visualization map of the cooperation network among countries (Fig. 5) and the superimposed visualization map (Fig. 6). In Figure 5, the node size represents the number of papers issued by a country. The lines connecting the nodes indicate that there is a cooperative relationship between the two countries. The color of the element represents the cluster to which it belongs. Different clusters are represented by different colors. This view can be used to view each individual cluster. In Figure 6, different colors correspond to the average start time of the study, with bluer colors indicating earlier study times and yellower colors indicating later study times.

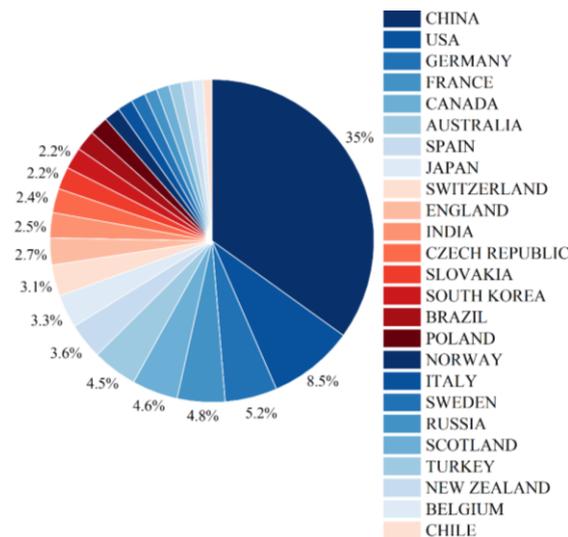


Figure 4. Proportion of published papers by countries

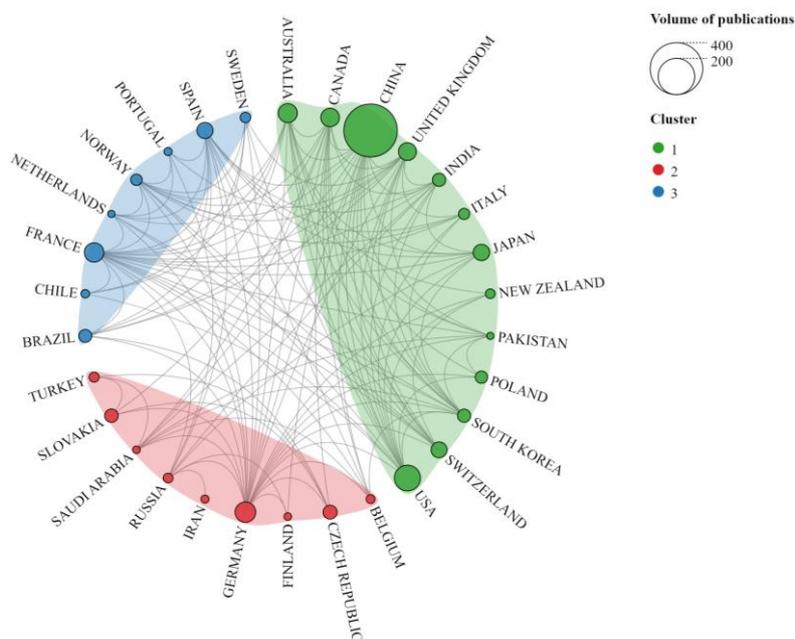


Figure 5. Proportion of published papers by countries

Based on the analysis conducted using SCImago Graphica, countries can be categorized into the following three groups according to the intensity of their cooperation with other nations (Fig. 5): the first green cluster includes countries such as China, the United States, Australia, Canada, Japan, and the United Kingdom; the second red cluster includes countries such as Germany, the Czech Republic, the Slovak Republic, Belgium and Finland; the third blue cluster includes countries such as France, Spain, Norway, and Sweden. Countries within the same group may share similar research directions or have deep collaborations. China is the country that has conducted the most cooperation with other countries, followed by the United States, Germany, and Canada. Slovakia is also active in this research field, but most of its published papers are authored domestically,

with limited collaboration with other countries or regions. From the perspective of time span, Chile, Japan and New Zealand conducted earlier research in the field of Sb, followed by France, the United States and Germany, while China, South Korea and Italy conducted the research relatively later (Fig. 6).

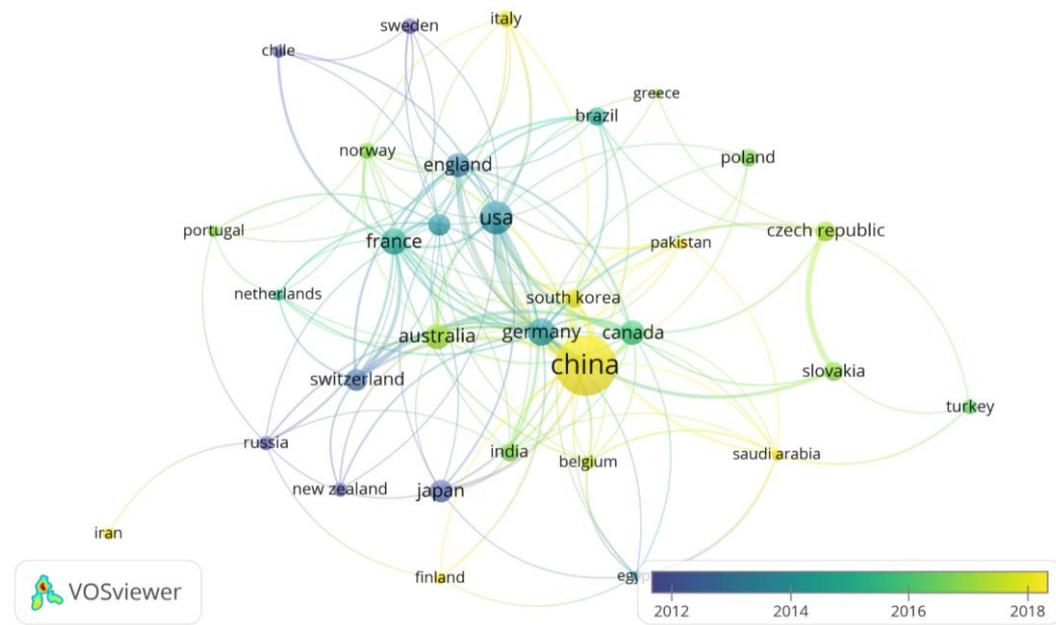


Figure 6. Visualization of time evolution of international cooperation

Focus analysis of main research institutions

Based on the collaborative research conducted by the organization, we can gain a deeper understanding of the most influential institutions in the field of Sb biogeochemical processes (Zhang et al., 2020). In VOSviewer, we set the analysis type as “Co-authorship” and the node type as “Organizations”, and thus obtained the top 10 research institutions that have published the most articles in domestic and foreign journals (Table 1).

Table 1. Average number of citations per article for the top 10 research organizations in terms of papers

Institutions	Country	Number of papers	Total citations	Number of citations per article
<i>Chinese Academy of Sciences</i>	China	88	2768	31.45
<i>Beijing Normal University</i>	China	35	2036	58.17
<i>University of Chinese Academy of Sciences</i>	China	35	757	21.63
<i>China University of Geosciences</i>	China	26	465	17.88
<i>Guizhou University</i>	China	21	156	7.43
<i>Chinese Research Academy of Environmental Sciences</i>	China	20	399	19.95
<i>Comenius University in Bratislava</i>	Slovak Republic	19	642	33.79
<i>Southern Cross University</i>	Australia	17	667	39.24
<i>ETH Zurich</i>	Switzerland	16	1244	77.8
<i>University of New England</i>	Australia	12	408	34

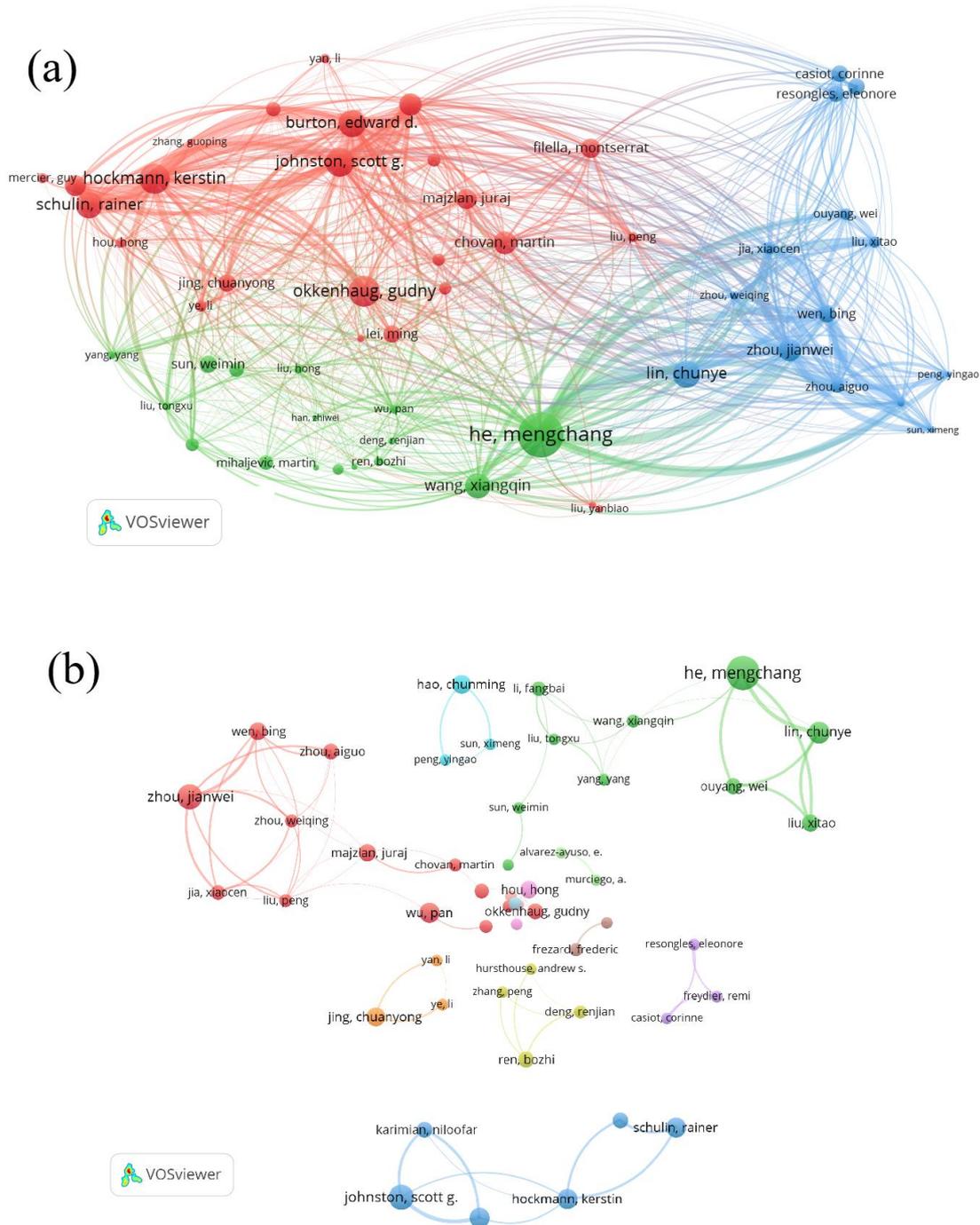


Figure 7. (a) Author citation network mapping. (b) Author collaboration network mapping

Through analyzing the collaborative relationships among authors, it was found that authors affiliated with the same institution have a higher frequency of collaboration, indicating a high likelihood that they belong to the same research teams (Fig. 7a and b).

The larger the node, the more citations the author has in the field and the stronger the academic influence (Fig. 7a). Different colors represent different clusters, which indicates different research teams, and larger nodes suggest that the author is a major contributor to the research field of their team (Fig. 7b). Six out of ten institutions are from

China, representing China's main research force in this field. In *Table 1*, the Chinese Academy of Sciences (CAS) has the highest number of papers and total citation frequency, followed by Beijing Normal University (BNU). However, Swiss Federal Institute of Technology in Zurich (ETH Zurich) has the highest average citation frequency per article, indicating that the average level of articles published by ETH Zurich in this field is relatively high. The author with the largest number of citations is He Mengchang (BNU), followed by Hockmann, Kerstin (ETH Zurich) and Johnston, Scott G (ETH Zurich), indicating that their study have important academic influence (*Fig. 7a*). Here, we mainly identify three representative groups, and each group has one largest contributor. The first group (green) is mainly a scientific research team composed of researchers such as He Mengchang, Lin Chunye and Wang Xiangqin, affiliated with BNU. The second group (red) is mainly a research team composed of researchers such as Hockmann, Kerstin and Schulin, Rainer, affiliated with ETH Zurich. The third group (blue) is mainly a research team composed of researchers such as Zhou Jianwei, Zhou Aiguo and Wen Bing, affiliated with China University of Geosciences (CUG). The biggest contributors of these three scientific research teams in the field of Sb research are He Mengchang, Schulin, Rainer and Zhou Jianwei, respectively. Considering the number of papers and average citation frequency per article, we selected CAS, ETH Zurich, BNU and CUG as representative institutions, and analyzed their representative articles to summarize the key research directions of these institutions.

The development of CAS in this research field can be divided into three stages, reflecting a progressive innovation from basic science to multidisciplinary integration. In the basic research stage, the institution mainly focused on the development of analytical methods and material design at the laboratory level, laying the technical foundation for the research. Yu et al. proposed the adsorption performance of thiol cotton fiber (TCF) for Sb(III) and explored the adsorption kinetics and selective separation (Yu et al., 2002). Zhang et al. developed electrochemical hydride generation atomic fluorescence spectrometry (EHG-AFS) for high-sensitivity detection of arsenic (As) and Sb in traditional Chinese medicine (Zhang et al., 2005). Zhang et al. studied the oxidation state of antimony (Sb(III) and Sb(V)) in polyethylene terephthalate (PET) bottles by X-ray absorption fine structure spectroscopy (XAFS) and found the chemical form change and migration risk of Sb in polymer (Takahashi et al., 2008). In the mid-term stage, institutional research expanded from the laboratory to the soil, plants and Sb mining environment, and focused on the form transformation, toxic effects and adsorption removal technology of Sb. Zhang et al. studied the migration law of Sb in mining environment (water, sediment, soil) and revealed the release mechanism of Sb during the extraction of gold by cyanide (Zhang et al., 2009). Xu et al. proposed the synergistic mechanism of Fe-Mn binary oxide (FMBO) for the oxidation adsorption of Sb(III), which became a classic material for efficient removal of Sb (Xu et al., 2011). Qi et al. found that copper doping into magnetite (Cu-Fe₃O₄) can significantly improve the oxidation adsorption capacity of Sb(III) (maximum adsorption capacity 43.55 mg/g) (Qi et al., 2016). Lou et al. designed a three-dimensional reduced graphene oxide/Mn₃O₄ (RGO/Mn₃O₄) composite material to achieve efficient removal of Sb(III) and Sb(V) (maximum capacity 151.84 and 105.50 mg/g) (Zou et al., 2016). In the later stage, the institution added interdisciplinary research such as isotope technology, microbiology and molecular simulation. For instance, it focused on the effects of microorganisms (such as sulfate-reducing bacteria and nitrate-reducing bacteria) on the oxidation-reduction, methylation and sulfide precipitation of Sb, and also explored the mechanism of

interaction between Sb and organic matter in complex environmental systems. Xiao et al. analyzed the microbial community structure in antimony-contaminated soil and found the correlation between specific bacterial communities and Sb forms, and proposed the possibility of microbial driven oxidation reduction of Sb (Sun et al., 2017). Ye et al. revealed that sulfate reducing bacteria promote the release of Sb through the formation of thioantimonate, and underscore the significance of biological sulfide generated by sulfate-reducing bacteria in determining the fate and migration of Sb (Ye et al., 2019). Zhang et al. studied the possibility of nitrate-dependent Sb oxidation in antimony-contaminated rice fields and identified nitrate-dependent Sb (III) oxidation bacteria (Zhang et al., 2021). The Chinese Academy of Sciences has undergone an evolution in the field of Sb research, from fundamental analysis to environmental behavior, and then to the innovation of molecular mechanisms and remediation technologies. The research focus has gradually shifted from the development of a single technology to the collaborative regulation of multiple processes in complex environmental systems. By integrating materials science, microbiology and geochemistry, it has promoted the development of research from the laboratory to practical applications. The developed composite materials and other technologies have international influence in the remediation of Sb pollution.

ETH Zurich mainly focuses on the adsorption, redox transformation and migration mechanism of Sb in soil. Among the 16 papers published by the Institute, 13 papers were on the migration and transformation of Sb in soil, accounting for 81.25%, and most of the research objects were shooting ranges contaminated with Sb. The main research directions include: 1) the effect of flooding on the dissolution, mobility and redox state of Sb in soil; 2) The absorption of Sb with different valence state by plants under different conditions. With the extension of flooding time, the environment in the soil will change from oxidation condition to reduction condition, and Sb (V) in the soil will be reduced to Sb (III), which will cause the change of valence state and reduce the solubility of sb, but will cause the change of Sb absorption of plants, which will increase the risk of sb entering the food chain from the soil (Wan et al., 2013a, b). Hydroxides of Fe and Mn are important adsorbents for Sb in soils and sediments, but the mineral surface can also catalyze the oxidation process, thereby activating Sb and increasing its mobility. It is difficult whether goethite can fix Sb by adsorption or whether the adsorbed Sb (III) is oxidized to Sb (V) and released. "Sorption of Sb(III) and Sb(V) to goethite: Influence on Sb(III) oxidation and mobilization" (2006) has an impact factor (IF) of 10.8 and a citation frequency of 434. It is a representative article of the institution in this research field. Schulin, Rainer et al. found that the mobilization of Sb(III) under Fe-reducing conditions may significantly increase (eco)toxicological risks arising from Sb-contaminated soils that are prone to flooding or waterlogging. Therefore, ETH Zurich's research achievements have improved the research on the migration and transformation of Sb in soil and the absorption of Sb by plants, and have guiding significance for future researchers.

BNU ranks high in both the number of papers and the average citation per article. The main research directions include: (1) migration and transformation of antimony in the mining environment; (2) The change of antimony adsorption capacity under different conditions. BNU has conducted relevant research in many river basins and mining areas in China, such as Xikuangshan, Zijiang River and the Three Gorges Reservoir. Its research results are rich and have further filled the gap in this field. It has made an in-depth study on the form, distribution and geochemical behavior of Sb in rivers and soils in the Xikuangsha. A systematic analysis of the morphological distribution of Sb in water bodies and sediments in mining areas found that Sb is mainly Sb(V), and its migration is

regulated by oxidation and adsorption processes (Guo et al., 2018). In addition, sediment retention in reservoirs and dams near mining areas will lead to secondary release of Sb, and iron/aluminum oxides in sediments play a dominant role in the solid phase adsorption of Sb (Guo et al., 2018; Liu et al., 2023). Studies have shown that the release of Sb in sediments is closely related to redox conditions, and the release amount under anaerobic conditions is significantly higher than that in aerobic environments (Wang et al., 2011). In cutting-edge research, researchers have found that Sb isotope analysis has great potential for tracing the source of Sb and biogeochemical processes in the environment (Liu et al., 2024). In terms of adsorption and fixation of antimony, it focuses on the adsorption capacity of different substances for Sb under different environmental conditions (such as Kaolinite, Iron (hydr)oxides, Goethite). The adsorption of Sb (V) by kaolinite is closely related to pH, but it is not resistant to humic acid (Xi et al., 2010). Some anions will affect the adsorption of Sb, and there is a competitive relationship at the adsorption point. PO_4^{3-} significantly reduced the adsorption of Sb (III) by goethite, while NO_3^- and SO_4^{2-} had no such effect (Xi et al., 2013). By studying the characteristics of antimony migration, designing appropriate proportions of Fe-Mg modified biochar and Fe-Al-Based Amendments will reduce the migration rate of antimony in contaminated soil, play a fixed role, and play an important role in environmental governance (Jiao et al., 2022; Wang et al., 2022). He Mengchang et al. mainly focus on studying the migration and transformation mechanism of Sb in soil, water and sediment, focusing on its occurrence form, bioavailability and geochemical cycle process in different environmental media, revealing the impact of natural and human activities on the distribution of Sb, and providing model support for clarifying the reaction kinetic mechanism of Sb at the environmental interface (such as soil-water, mineral-organic matter) and predicting its long-term environmental behavior. In recent years, Sb pollution in Sb mining areas has attracted more and more attention in various countries. There is often long-term mining in this area, which leads to serious Sb pollution. At the same time, it involves the migration and transformation of Sb in different environmental media such as water (surface water-groundwater), soil and sediment. There are many pollution pathways and it is difficult to control, so it has become a key research area for researchers. In addition, the research directions of their research team include: the kinetics and mechanism of light-promoted Sb_2O_3 oxidation and dissolution, the adsorption capacity of new materials for Sb, the Sb isotope composition and enrichment characteristics of water sediments in mining areas, etc. (Hu et al., 2014; Jiao et al., 2022; Liu et al., 2024).

The papers of CUG are relatively few, and its research started relatively late, but it has many latest research achievements. As early as 2016, Zhou Jianwei et al. began studying the Hydrogeochemical Characteristics of Groundwater at the Xikuangshan Antimony Mine in South China (Nyirenda et al., 2016). The research team used Sb isotope characteristics to provide new insights into the source and geochemical processes of Sb in the Xikuangsha (Wen et al., 2016, 2022, 2023b). Zhou Jianwei et al. focused on the occurrence form, migration and transformation laws and driving factors of Sb in the mining area and surrounding environment (soil, groundwater, surface water), studied the effects of natural weathering, mining activities and anthropogenic emissions on the diffusion of Sb, and revealed its geochemical cycle characteristics in a multimedia environment.

In summary, all three teams studied the migration and transformation of Sb, including the effects of different factors (pH, temperature, ionic strength, light, etc.) on the dissolution and release of Sb, the adsorption of Sb by different substances or materials, and the mobility of Sb in different environmental media. He Mengchang et al. focused

more on the adsorption capacity of different materials or minerals for Sb and related influencing factors. Schulin, Rainer et al. release of antimony induced by redox changes, laying the foundation for early research. However, they have not produced any latest research findings in recent years. Zhou Jianwei et al. conducted more in-depth research on the sources, migration and transformation of Sb pollution in Sb mining areas, and used isotope characteristics to study the characteristics of Sb migration and transformation in the mining area's water systems. Although the research focus of each research team is different, with the passage of time, the research has gradually deepened, carried out the research on the migration and transformation of Sb in various Sb polluted environments, actively explored the distribution, migration and transformation, repair and toxic effects of Sb, and comprehensively promoted the research progress of Sb biogeochemical processes by combining the research advantages and technologies of different disciplines.

Co-cited analysis

Co-cited analysis of references

When two articles are simultaneously cited by other articles, a co-cited relationship is formed between them. The number of times they are co-cited is called the co-citation strength. The greater the co-citation strength, the more similar the research topics and the closer the research contents of the two articles. By constructing a co-citation network, the thematic content relationships among articles can be visually displayed, helping researchers identify the research frontiers and hotspots in a discipline. In *Figure 8*, larger nodes indicate that the article has received a higher degree of approval. The paper entitled "Antimony in the environment: a review focused on natural waters I. Occurrence" by Dr. Filella in 2002 has the highest co-citation frequency, with a total citation frequency of 266 times and co-citation frequency of 1192 times. This article reviews 420 papers on freshwater, seawater, estuaries, soils and sediments, summarizes the distribution characteristics and chemical behavior of Sb in the environment, and focuses on the existence form and migration law in natural waters, soils and sediments (Filella et al., 2002a). The paper entitled "Antimony in the environment: a review focused on natural waters II. Relevant solution chemistry" by Dr. Filella in 2002 has a total citation frequency of 175 times and co-citation frequency of 643 times. This article discusses the main characteristics of Sb solution chemistry related to the behavior and fate of Sb in natural waters (Filella et al., 2002b). The second is Professor Wilson SC's 2010 paper titled "The chemistry and behavior of antimony in the soil environment with comparisons to arsenic: A critical review", which has a total citation frequency of 204 times and co-citation frequency of 772 times. This paper focuses on the environmental chemical behavior of inorganic Sb in soil. Through a systematic comparison with arsenic, it reveals the difference between the two in the soil system and their environmental significance (Herath et al., 2017). Through the analysis of these three articles, it can be concluded that Sb has a relatively low abundance in the Earth's crust, but is significantly enriched due to geological and human activities. It mainly exists as Sb(V) in an oxidizing environment, and its chemical properties in different media are also affected by factors such as pH, iron/manganese oxides, chlorides and sulfides. Further research is needed on the redox kinetics of Sb, its methylation mechanism, its bioavailability in the environment, and the influence of microorganisms and organic matter. Together, these papers provide a comprehensive theoretical basis and research direction for the study of the environmental behavior of Sb, which is of great guiding significance for subsequent research.

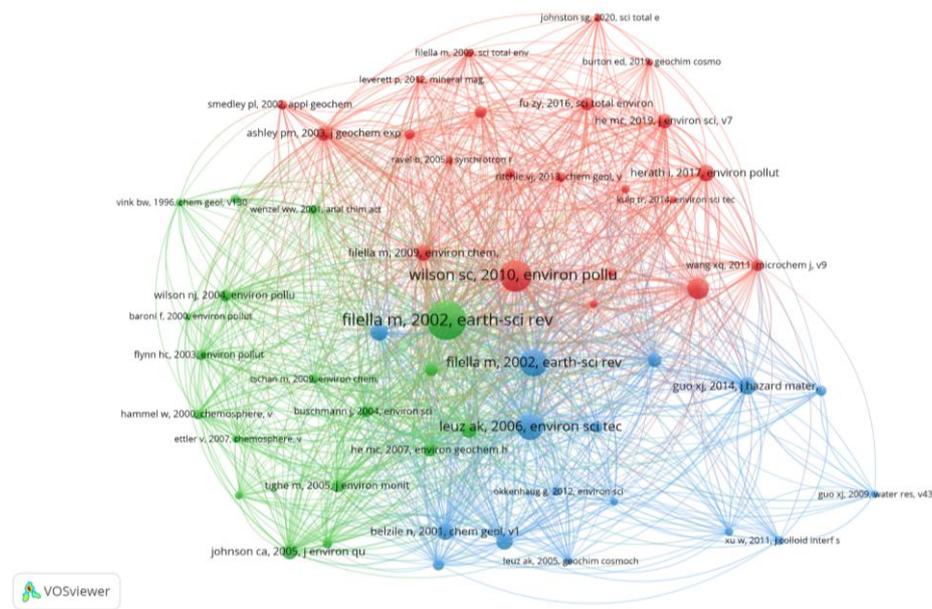


Figure 8. Visual analysis of co-cited references (cited frequency > 65)

Co-cited analysis of journal

Journal analysis is a method for quantitative analysis of literature and is widely used in various disciplines. By analyzing the source distribution of papers on the core data set, researchers can quickly find literature (Han et al., 2006). The WoS database was analyzed to obtain the top 5 journals in terms of the number of papers published in this research field over the past 30 years from 1895 to 2025 (Table 2). It was found that total citations of the top 5 journals with the most citations was 9403. These journals cover multiple disciplines such as environmental science, environmental engineering, ecotoxicology, geochemistry, chemistry, and materials, indicating that research in this field is popular and can be published in mainstream journals in multiple fields. The journals with the largest number of papers and the highest citation frequency per article are *Science of The Total Environment* and *Environmental Science & Technology*, involving 56 and 30 articles respectively (Table 2). The papers included in this journal include popular research directions in this research field. In the papers related to this research field published in the journal *Environmental Science & Technology* in the past 10 years, keywords show that 40% of papers focus on the redox process of Sb (Leuz et al., 2006; Hu et al., 2014; Arsic et al., 2018), 40% of papers focus on the relationship between microbial respiration and Sb (Wang et al., 2018; Ye et al., 2022), and 20% of papers focus on the adsorption characteristics of Sb (Okkenhaug et al., 2016; Yan et al., 2022). Based on the analysis of the citation frequency per article and its research content, it can be known that the current focus of Sb research still leans towards the study of the mechanism of Sb biogeochemical processes.

Keywords analysis of co-occurrence and burst

High frequency keywords co-occurrence analysis

The keywords co-occurrence graphs generated by CiteSpace and VOSviewer can be summarized into 4 clusters (Fig. 9a and b). Cluster 1 (blue) includes the following key words: environment, water, mine, As, groundwater, pollution, natural-waters, etc. This

cluster mainly studies the pollution mechanism and ecological impact of Sb on the water environment, and focuses on the migration behavior of Sb in environmental media (such as dissolution and redox processes) and its potential risks to ecosystems and human health. Cluster 2 (green) includes the following key words: adsorption, removal, oxidation, mechanism, aqueous-solution, nanoparticles, etc. This cluster mainly studies the removal mechanism of heavy metals and antimonates with adsorption (such as nanomaterials and organic matter) and oxidation technology as the core, focusing on chemical processes and technical optimization in wastewater treatment. Cluster 3 (red) includes the following key words: speciation, soil, mobilization, metals, organic-matter, sediment, bioavailability, etc. This cluster mainly reveals the occurrence forms, migration and transformation mechanisms and bioavailability of Sb in soil/sediment, and emphasizes the risk assessment and remediation of sites contaminated by Sb. Cluster 4 (yellow) includes the following key words: temperature, drinking-water, selenium, release, pH, mobilization, etc. This cluster mainly explores the influence of environmental conditions such as temperature and pH on the release behavior of Sb in drinking water or sediments, focusing on the dynamic migration of pollutants under extreme environments (such as high temperature and acidic conditions) and their potential threats to human health. The pollutant removal technology of cluster 1 and the environmental effect research of cluster 2 jointly support the pollution control in mining areas; the morphological analysis of cluster 3 and the release mechanism of cluster 4 provide a theoretical basis for risk assessment. The results of the four cluster analyses indicate that the transformation of Sb forms in the environmental medium and its biological availability are the key difficulties in cross-category research, and they need to be comprehensively addressed by integrating geochemistry, environmental chemistry and engineering technology.

Table 2. Impact factor of co-cited journals (Top 5)

Journal	Number of articles	Total citations	IF (2023)
<i>Environmental Science & Technology</i>	30	2856	10.9
<i>Science of The Total Environment</i>	56	1972	8.2
<i>Journal of Hazardous Materials</i>	37	1621	12.2
<i>Environmental Pollution</i>	26	1512	7.6
<i>Geochimica Et Cosmochimica Acta</i>	14	1442	4.5

The overlay visualization map of keywords co-occurrence (*Fig. 9c*) can intuitively observe the time points of keywords concentration, so as to analyze the research topics at each stage and recent research hotspots, and provide reference for later scientific researchers to choose research directions. Based on the summary of the keywords in *Figure 9c*, *Table 3* is drawn as a reference. From the key word information of the first period (1985~2000), it can be identified that there are not many research directions for Sb. It mainly focuses on the exploration of detection technology (Chattopadhyay et al., 2004) and the mobility of Sb with other trace elements (selenium, bismuth) in the environment (Hou et al., 2005). The terms “drinking water” and “toxicity” indicate that people began to pay attention to the toxicity of Sb and the safety of drinking water during this period. In the second period (2001~2012), the keyword nodes of “water”, “soil” and “sediment” are large, which are the environmental media of most studies. From the perspective of node size, there are more studies on the migration and transformation of Sb in the water environment, followed by soil and sediment. Sb, As and Bi belong to the fifth group of elements in the

periodic table and have relatively similar chemical properties. Researchers usually study them together. The keywords “transport, oxide, reduction, adsorption, bioavailability” indicate the main geochemical behavior of Sb in water-soil-sediment environmental media. Organic matter, as one of the main influencing factors of Sb migration and transformation, has received continuous attention from the scientific community in related research. Interactions of Sb with natural organic matter also are important portion for the fate, mobility and transformation of Sb in aquatic systems (Herath et al., 2017). Sb can be combined with carboxylic acids, alcohols, phenols and amino acids in organic matter. Common humic acids, such as humic acid, have high adsorption capacity for Sb (Pilarski et al., 1995). In addition, humic acid can catalyze the oxidation of Sb (III) to Sb (V), which affects the mobility of Sb in the surrounding environment. The influence of dissolved organic matter (DOM) on the enrichment mechanism of Sb at the molecular level needs to be further improved (Hao et al., 2024). In the third period (2012~2024), the keywords “Xikuangshan, ferrihydrite, ground water, contaminated soil, microbial community” reveal the important research objects in this research field in recent years. Xikuangshan is located in the northeast of Lengshuijiang City, Hunan Province, and is the largest Sb deposit in the world. Mining, mineral processing, smelting and other mining activities in the past century have caused a series of mine geological environmental problems. Sb pollution in soil, surface water and groundwater is particularly prominent, and has also become the key research object of domestic researchers. Iron minerals are the most common minerals in nature, with a wide variety, which will occur complex mineral phase transformation and chemical reactions in the environment, and are important factors affecting the behavior of Sb and other heavy metals in the environment. Microbial oxidation and reduction process can directly affect the type, mobility and migration of Sb in the environment (Han and Park, 2020; Deng et al., 2021). In general, the research is changing from the past single environmental medium research to the complex environment, and the research direction is also changing from the simple chemical behavior of dissolution, adsorption and precipitation to the complex chemical behavior of oxidation, reduction and transformation. The influence of multiple factors on the migration and transformation of Sb is also one of the focuses of future research.

Table 3. Summary of keywords in different periods

Periods	Keywords
The first period (1985~2000)	Trace-element, Selenium, Bismuth, Hydride generation, Solubility, Environmental mobility, Drinking water, Toxicity
The second period (2001~2012)	Water, Soil, Sediment, Shooting range, Speciation, As, Transport, Oxide, Reduction, Adsorption, Pollution, Bioavailability, Organic-matter
The third period (2012~2025)	Behavior, Xikuangshan, Ferrihydrite, Ground water, Removal, Contaminated soil, Transformation, Microbial community

The density visualization map of keywords co-occurrence (*Fig. 9d*), showing the hot spot intensity of different keywords. The warm red color represents the hot spot area, and the cold blue color represents the cold area (Zhang et al., 2020). The keywords with high density are: water, specialty, soil, metal, mobility, As, adsorption, oxide. It is worth noting that, different from the previous analysis, the keywords “removal”, “Sb(III/V)”, “mechanism”,

“aqueous-solution”, “waste-water”, “degradation” are relatively clustered, indicating that the research on the removal technology of Sb pollution in water is a hot direction, including the research and development of nano adsorbents and electrochemical degradation.

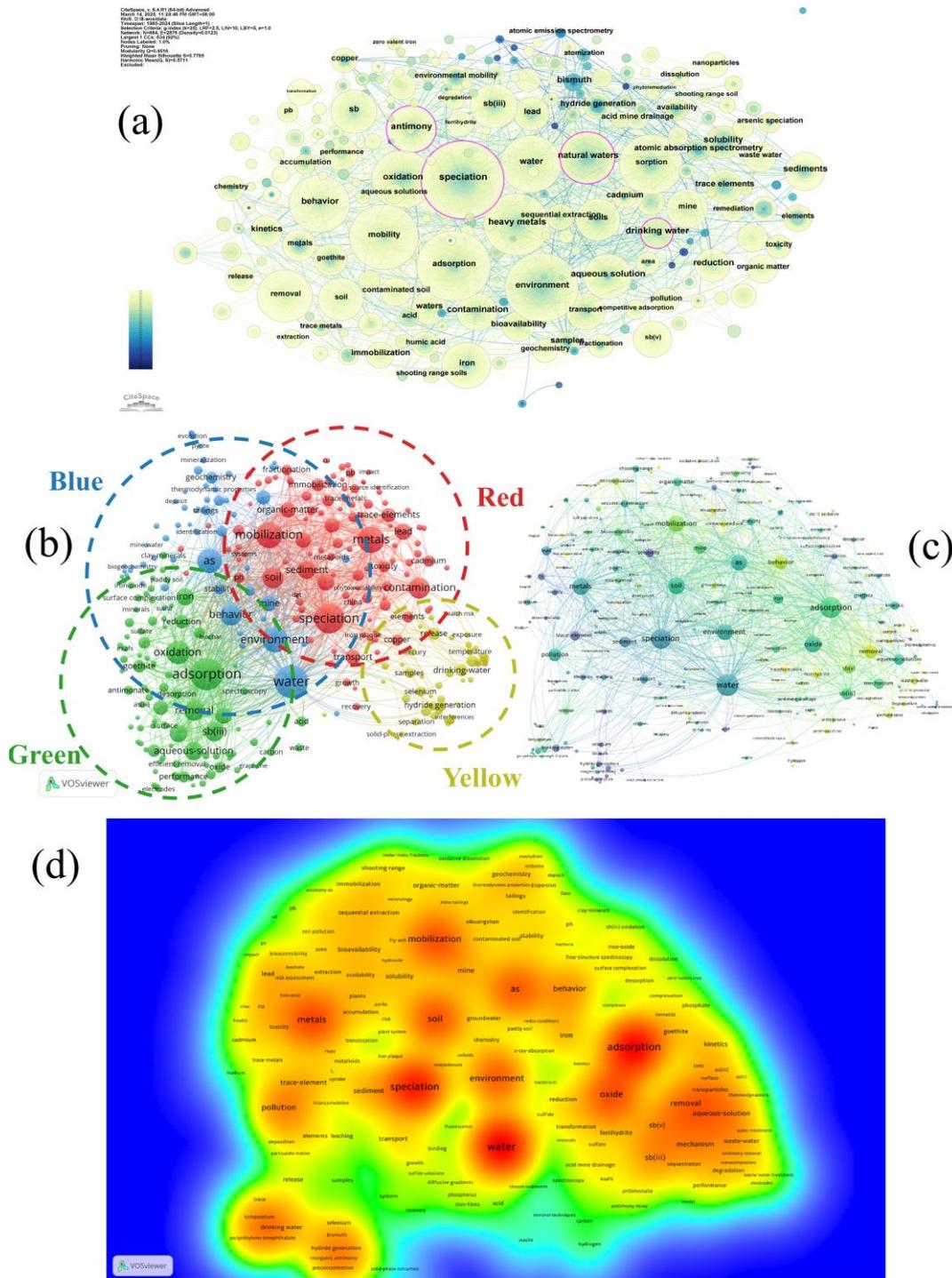


Figure 9. (a) Visualization of keywords co-occurrence. (b) Visualization of keywords co-occurrence. (c) The overlay visualization map of keywords co-occurrence (the colors represent the time when the keyword appeared). (d) The density visualization map of keywords co-occurrence. (The warm red color represents the hot spot area, and the cold blue color represents the cold area)

Burst keywords detection analysis

The high-frequency keywords time series analysis function of CiteSpace is mainly used to track the changing trend of keywords in the research field over time, revealing the evolution path of topic hotspots, the emergence of emerging directions and the decline of traditional topics. By identifying keywords that surge in a short period of time, using burst word detection analysis to observe rapidly growing topics, we can understand the changes in topics in recent years. By constructing a keywords co-occurrence network for the study of Sb biogeochemical processes from 1985 to 2025, the top 20 emergent keywords are shown in *Figure 10*. This research has gone through decades of development, and its research focus has been constantly evolving with technological progress and environmental needs. It can be divided into three main stages.

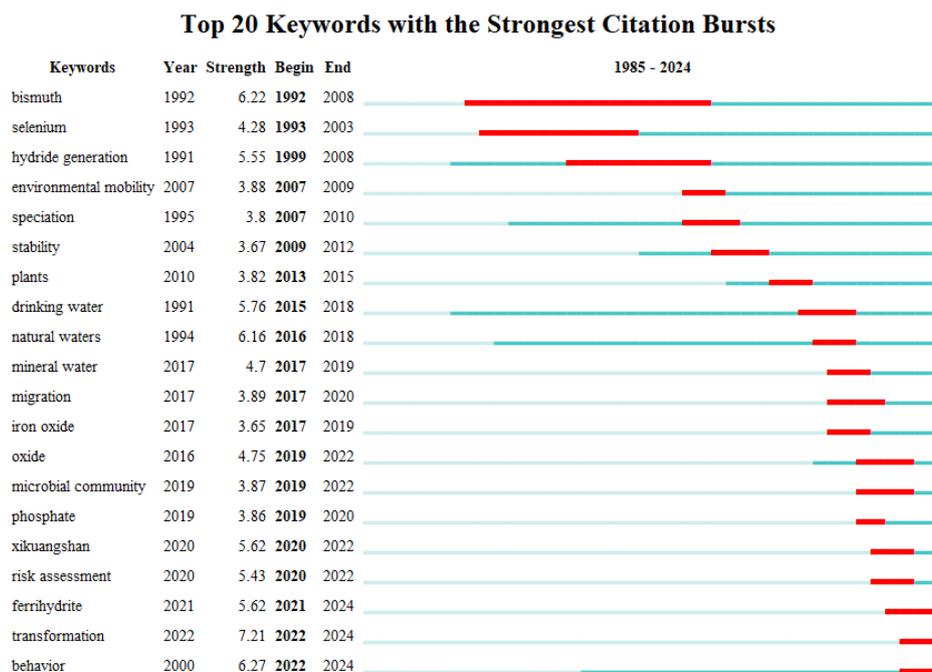


Figure 10. The top 20 keywords with the strongest citation bursts. (The red lines in the diagram are heat bars, representing the time period with the strongest citation bursts; the green bars were keywords cited infrequently)

The early stage (1992-2010) focused on analytical methods and basic mobility research. “hydride generation” as a key technology for Sb detection, promotes the morphological analysis of Sb and clarified the dominant role of chemical forms such as Sb(III) and Sb(V) in its environmental behavior. In the early stage, there were many researches on the distribution and detection technology of heavy metals such as “sb”, “bismuth” and “selenium”, such as “hydride generation ICP-AES” (Morrow et al., 1997) and “gas phase molecular absorption spectroscopy” (Cabredo et al., 1998). So these keywords appeared more frequently in this period.

In the mid-term stage (2010-2017), the research scope expanded to multimedia pollution and ecological risks. The emergence of “natural waters” and “drinking water” reveal the threat of industrial emissions and geological enrichment to water safety, and indicate that the research in this period mainly focused on the migration and

transformation of Sb in water. The emergence of “plant” indicates that the study of plant absorption mechanism focuses on the ecological risk of Sb transmission through the food chain. This stage began to pay attention to multimedia interactions, but it is still mainly based on phenomenon description and lacked microscopic mechanism support.

In the recent stage (2017-2025), the research turned to the microscopic mechanism and interfacial process of Sb migration and transformation. The “iron oxide” and “ferrihydrite” have become hot topics due to their efficient adsorption of Sb (Garau et al., 2019). The emergence intensities of “phosphate” and “microbial community” represent that the competitive adsorption of phosphate and the redox reaction driven by the microbial community revealed the complex transformation pathways of the solid-liquid-biological interface (Biver et al., 2011; Sun et al., 2017). The case of Xikuangshan, the world’s largest Sb mining area, highlights the need for mining area restoration. The high emergence intensities of “transformation” (7.21) and “behavior” (6.27) indicate that the morphological dynamics and multimedia coupling effects of Sb have become cutting-edge directions. The term “behavior” represents the migration and transformation of Sb in different environmental media, including dissolution and precipitation, adsorption and desorption, oxidation and reduction etc. It shows that more and more attention has been paid to the study of the migration and transformation process of Sb.

Suggestions and prospects

Sb is an important participant in the geochemical cycle, and its geochemical process involves multiple spheres such as atmosphere, water, rock and soil. In view of the fact that studying the migration, transformation and enrichment of Sb in different media is helpful to improve its environmental geochemical process, so as to effectively evaluate the impact of Sb pollution on the ecological environment and provide a scientific basis for the formulation of environmental quality standards and pollution prevention and control measures, several suggestions are put forward for future research. First, the current treatment methods for Sb pollution control are still immature. According to the adsorption, desorption and redox characteristics of Sb in different media, new adsorbents or remediation materials should be developed to remove Sb pollutants in the environment and improve the efficiency and effect of pollution control. Second, the interaction between Sb and microbial communities can affect its fate in the natural environment. Microbial communities interact with the dissolution, oxidation, reduction, methylation, bioaccumulation and mobility of Sb. In turn, Sb will have ecological effects on microbial communities (such as biomass, basic respiration rate, enzyme activity, community structure and biochemical processes). Under realistic environmental conditions, the dissolution and redox reactions of Sb(III) may be caused by chemical and microbial interactions. Therefore, the combined effects of these two factors should be considered. Third, current research on Sb forms and their transformation laws is mainly based on indoor simulations, but the ionic strength, impurities, pH and other conditions of natural water bodies are more complex. The transformation laws of Sb forms in natural water bodies need to be further verified, especially the mineral particles and natural organic matter rich in natural water bodies interact with different forms of Sb, thereby affecting its form, toxicity, migration and transformation, and biological effectiveness. These mechanisms need to be further explored. Fourth, Sb isotopes are a powerful tool for tracing Sb pollution sources and biogeochemical processes. To date, many studies have reported the Sb isotope composition in different environments and anthropogenic

samples, but few studies have reported the Sb isotope composition in mining water environments where Sb pollution is ubiquitous. The composition and fractionation mechanism of Sb isotopes in environmental systems need to be further clarified.

Conclusion

Based on 1089 articles in Web of Science, this study used Citespace and VOSviewer to conduct a bibliometric analysis of the evolution and development of research on the migration and transformation of Sb in water, soil and sediment. Based on the above analysis, the following conclusions were drawn.

(1) The number of papers on Sb in China ranks first globally, but the number of highly cited articles in these papers still lags behind that of the European Union and the United States. Currently, China leads in terms of the number of papers and international influence, which is based on the fact that China is a country with a large Sb reserve. However, the highly cited research in this field still focuses on institutions in Europe and America.

(2) In terms of research time, CAS and ETH are earlier than BNU and CUG. In terms of research content, CAS is more comprehensive, ETH is more focused on the migration and transformation of Sb in soil, while BNU and CUG are more concerned about it in mining areas.

(3) The hot spots in each period are different, which is related to the research topics and cognition of scholars on Sb in this period. The emergent words in each period can clearly reflect the research direction and hot spots of that stage, and thus know the development trend. At present, the emergent words such as “microorganism”, “phosphate”, “ferrihydrite” and “iron oxide” indicate that the current research focus is mainly on the influence of microorganisms on the speciation and mobility of Sb, the competition of phosphate for Sb adsorption sites, the efficient adsorption of Sb by ferrihydrite, and the phase change risk.

(4) The research focus has shifted from a single medium to multi-interface processes such as soil-water and water-sediment. The migration and transformation of Sb in the environment rarely occur in a single medium. For example, mining area pollution: Sb bearing tailings are washed by rainwater, Sb migrates from soil to water, and adsorption/desorption and oxidation-reduction reactions occur at the water sediment interface. Agricultural activities: after fertilization of Sb containing sludge, Sb migrates at the soil groundwater interface and may enter the food chain. The research focus from single medium to multi-interface processes such as soil water and water sediment can help to assess the risk more accurately and guide the design of efficient remediation technology.

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