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Global research progress on mining wastewater treatment: a bibliometric analysis

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Mining wastewater treatment (MWWT) methods have played a vital role in sustainable water management in recent years. This bibliometric analysis summarized the scientific research improvement on MWWT and the assessment of future research. We employed bibliometric and social network analysis to quantitatively study 1542 research articles (published from 2001 to 2020) related to MWWT. The findings reveal that: (1) publications on MWWT have increased significantly since 2009, and researchers have intensively focused more on the application and optimization of current technologies such as membrane filtration systems, automatic variable filtration, advanced oxidation processes, and UV irradiation; (2) China and USA have the maximum number of research publications as well as are the centers in the international collaboration network, while Canada and European countries have produced a higher quality of papers; (3) through clusters of keywords and treatment technology analysis, the top three keywords are related to adsorption, oxidation, and activated sludge processes, corresponding to three types of mature wastewater treatment categories (physical, chemical, and biological); and (4) scientists have moved their focus to treatment technologies from the conventional to advanced ones for MWWT research. Finally, some problems and perspectives are presented, which might suggest current scientific hotspots and future research guidelines.

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Environmental significance

Modern mines as well as abandoned mines are responsible for significant environmental damage of water throughout the world. The treatment of mining wastewater is a major issue related to sustainable water resources management. Although many wastewater treatment technologies have been used to treat mining wastewater, the diversity of technologies makes it difficult for policy makers or investors to understand the research hotspots and technology development trends in this field. In this study, by bibliometric and social network analysis on recent mining water treatment research articles, it was found that China and U.S.A. have great research flow, and China has the greater international academic research influence, while scientists have moved their focus on treatment technologies from conventional to advanced ones in this field. The finding in this study proposed current scientific hotspots and future research guidelines such as policies, and guidelines cheap, high recovery, energy and time saving, and new treatment technologies.

1. Introduction

Water pollution is a concern for the world due to the presence of various contaminants such as dyes,¹ pesticides, medicines, phenolic compounds,² heavy metals,³ as well as their negative impacts on the ecosystem.^{4,5} Despite being one of the sources of

water pollution, mining industries play economic importance, such as technological innovation, benefits of education, and community improvement projects,⁶ generating much-needed employment and infusing revenue not just into the local community but also the nationwide economy, as can be seen from the statistical data from proceeding years.^{7,8}

Heavy metals seep into rocks, accumulating in raw materials, and releasing pollutants into the environment.³ All of this happens naturally, either as a result of rainfall, melting snow, or groundwater.⁹ Many ores, mining precious metals, such as gold (Au), copper (Cu),¹⁰ arsenic (As), mercury (Hg), cyanide, and uranium (U), contain high amounts of the poisonous metalloid ions.¹¹⁻¹³ For example, arsenic in most cases comes from mine exploitation, as well as excavating, and regularly has connections to treasured minerals, including sphalerite, pyrite, and chalcopyrite.¹⁴ Arsenic generally dissolves during manufacture and then seeps into groundwater. The arsenic wastewater is

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poisonous and easily impacts human internal organs, leading to cancers.¹⁵

Many studies have found that heavy metal absorption in mining areas is extremely high due to mine tailings, disposal of high metal wastes,¹⁶ expanding industrial areas, leaded gasoline and paints,¹⁷ all of which can contaminate natural water bodies, soils, and sediments. Simultaneously, many pollutants can be found in mining effluent, including cyanide, ammonia, and heavy metals.^{18,19} Due to their proclivity for biological accumulation, high toxicity, and carcinogenicity at very low doses.^{20,21}



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Land and Resources Science and Technology Award; the courses he hosted won the Excellent Course Award of the "China Bell (BELL) College Environment and Sustainable Development Education Innovation Project" of the Ministry of Environmental Protection.

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heavy metals as a class of contaminants have gotten increasing attention.²²⁻²⁴ Moreover, mine-derived hard rock and liquid tailings waste can alter the chemistry of water and sediment²⁵ as well as the release of contaminants that endanger aquatic ecosystems and human health.^{26,27} Therefore, mining industries and chemical facilities are considered the primary pollution sources,²⁸ and their wastewater need to be treated before releasing into the environment.²⁹ Hence, wastewater treatment technologies have been improved for MWWT and resulted in three mature types of ways to treat mining wastewater, *i.e.*, physical, chemical, and biological treatment methods.

MWWT is complicated considering various compounds at different concentration levels contained in the wastewater.³⁰ Moreover, the treatment is rather challenging considering that each type of mining wastewater is different even within a mining industry depending on the specific mining process.³¹ At present, researchers have carried out a large number of valuable studies or reviews on MWWT technologies, such as adsorption, membrane filtration, advanced oxidation process, and membrane bioreactors for the treatment of mining



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Dr Jian Lin Chen received his BSc from Tianjin University and PhD from City University of Hong Kong. Between 2008 and 2009, awarded as Marie Curie Host Fellowship, he held a post-doctoral position at Ben-Gurion University of the Negev, Israel. After that, awarded as Faculty Research Development Fellowship from 2010 to 2011, he worked as a post-doctoral fellow in the University of Auckland,

New Zealand. In late 2012, he joined Nanyang Technological University in Singapore as a research fellow. In late 2016, he joined City University of Hong Kong as a Visiting Assistant Professor. In September 2020, he joined Hong Kong Metropolitan University as an Assistant Professor. He is currently a member of State Key Laboratory of Marine Pollution in City University of Hong Kong. His research covers fields of environmental science, material science, and chemical engineering.



wastewater.³² The research involved the performance optimization of technologies, dynamics and mechanism of treatment processes, and removal of specific pollutants such as heavy metals. While there is a lack of quantitative methods to systematically summarize the entire MWWT base literature.³³ It is difficult to understand the research hotspot and future research trends in the field of mining wastewater from a macroperspective.³⁴

Bibliometrics is the use of statistical methods to analyze publications and could provide a solution to comprehensively analyze recent research on MWWT. Originally being used in the field of library and information science, bibliometrics has become an indispensable tool for assessing and evaluating scientific output and offered an up-to-date overview of scientometrics, including data sources, performance analysis, and visualization tools, which can be accordingly separated into three categories: general bibliometric and performance analysis, science mapping analysis, and libraries.³⁵ The purpose of this practice is to classify, establish, and assess the essential fundamentals of a specific research area. Currently, a bibliometric study has been developed into one of the highest level tools for the examination of collected works within the scientific discipline due to a large quantity of present data.^{36,37}

Bibliometrics includes a larger number of approaches that are suited for practitioners, such as Biblioshiny (R-tool), Sci-MAT, Logletlab, CiteSpace, and VOSviewer, which have a wonderful visualization and can load and export data from a variety of sources. SciMAT is the tool with a powerful pre-processing and export capacity, while Biblioshiny (R-tool) is a tool with a powerful pre-processing and export capability. Because of the wide range of features, and variety of capabilities, a researcher must decide on the required analytical results and select the choice that best matches their needs. Scientist Pritchard (1969) introduced the bibliometric method for analyzing books and other forms of communication media. It is now being utilized as a collection of statistical and mathematical approaches to uncover previous literary features, identify current hotspots, and predict future research trends.³⁸ Furthermore, this analytical approach may disclose the essential science and technology's structures, features, and patterns.

To the best of our knowledge, there is so far no study that utilized bibliometric analysis to uncover quantitative features of MWWT as well as research trends in this field. To fill the research gap in previous studies, the objective of this research is to use bibliometric analysis to quantitatively and qualitatively evaluate 1542 research articles (from 2001 to 2020) related to MWWT from the Scientific Citation Index (SCI) and Social Sciences Citation Index (SSCI) databases. Specifically, we (i) analyzed the overall research output of mining wastewater and the research productivity of global countries in this field; (ii) evaluated keywords and summarized research hotspots in this field by using social network analysis; and (iii) identified technological development processes, hotspots, and trends by using S-curve derived from article database, which can provide quantitative and qualitative scientific guidance for the future MWWT technologies.

2. Methodology

2.1 Bibliometric analysis and sample collection

Bibliometric analysis is the primary method used in this research to answer the future objective of MWWT.³⁹ Scopus is the most comprehensive collection of summaries and citations from peer-reviewed scholarly papers. As a more helpful, reliable, and transparent selection process than the Web of Science (WOS),⁴⁰ the Scopus database was selected in this study. The data about MWWT was gathered from the Scopus database core collection, laying the groundwork for subsequent software processing and visualization work. The research work was evaluated using bibliometrics.⁴¹ Several constraints are considered when choosing the sample. The investigation lasted from 2001 until 2020. To avoid duplicates, the selected body of work was scrubbed. Keywords were used to choose the sample of documents on MWWT, which were based on documents title, abstract, and keywords that were TITLE (mining*), ABSTRACT, ("wastewater*" OR "wastewater treatment*" OR "treatment" OR "heavy metals*" OR "mining water*" OR excavating), and KEYWORDS, ("precious metals*" OR "Gold, Coal" OR mining* OR metals*). The total documents, *i.e.*, articles, review articles, letters, reports, book chapters, *etc.*, collected were about 1982 and then further refined, and the result was a final sample of 1542 articles on MWWT. Documents were collected in January 2021. The whole study selection and flowchart of the research are shown in Fig. 1.

2.2 Data processing

The dataset for this study was hybridized and pre-processed using the bibliometrics package^{42,43} to remove all duplicates. In the first step, the data were extracted in two different file arrangements, *i.e.*, Comma-Separated Values (CSV) and Research Information Systems (RIS) because different tools support different file formats, for example, R-tool processes RIS file format and VOSviewer handles the CSV format file. Hence, the number of articles, the year of publication, the topical component, the name and term of the journals, and the top keywords were among the contrasts. The initial step in data analysis was to look at the evolution of the most important variables by calculating the thematic portions in which the forms were classified in the Scopus database. In addition, the most well-known publications, institutes, and authors' journals for MWWT, as well as the most important global relationships, were documented. Furthermore, mapping approaches were employed to illustrate keyword co-occurrence. The tool was VOSviewer (version 1.6. 16. 2020 Leiden University, Leiden, Netherlands).⁴⁴ The software, VOSviewer, utilized in this analysis for country collaborations, was developed in Java language. VOSviewer provides also three types of visualizations for each map created: the network visualization, the overlay visualization and the density visualization. We selected two standards "total citations and total link strength" for understanding the figures and tables results, among different groups of countries, authors, organizations, and keywords, which we will describe briefly.



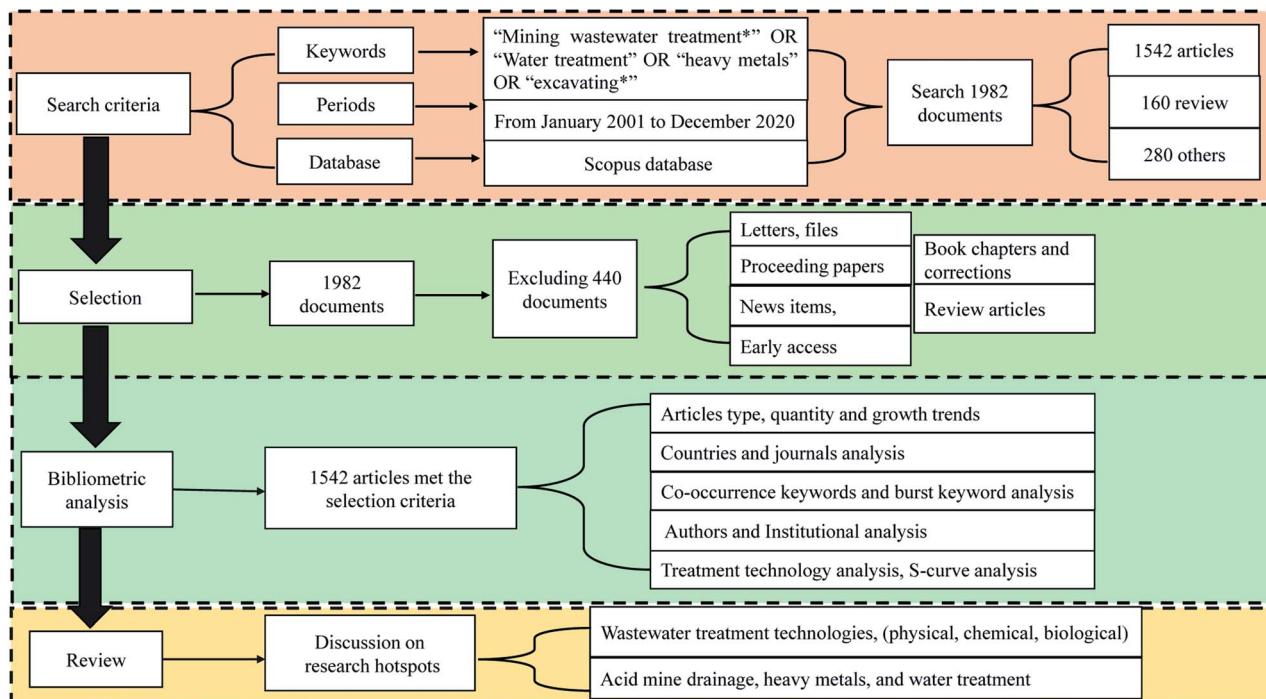


Fig. 1 Document selection and flowchart of the research framework.

2.3 Social network analysis

Social network analysis (SNA) is a measurable tool for assessing and examining the connections and theoretical teamwork among social performers such as countries, writers, and journals. Because of its ability to consistently monitor interactions, grow system concepts, and handle processors, SNA is frequently utilized for checking the influence within the teams and strategic approach to team building.^{45,46} Using social network analysis, we can explore the international collaboration among countries in this study. By showing the interactions between the groups and individual working groups, SNA can show key information about the research, such as the overall activity of collaborations among the countries, authors, and institutions.⁴⁷ By evaluating these networks using Social Network Analysis (SNA), we can learn more about how people are connected, and more crucially, how information flows. This is important for boosting research communication and knowledge activation.

3. Results and discussion

3.1 Analysis of the amount of literature and its growing trends

A total of 1982 records on MWWT research were identified in this study. The papers were classified into 17 types, as shown in Fig. 2(a). The majority of the papers were articles (77.8%), followed by reviews (8.1%). The numbers of articles are the highest and may greatly reflect the development trends and changes in the MWWT research. Therefore, we focused on the analysis and evaluation of research article types of papers (a total of 1542 articles) in the resulting analysis.

The number of publications related to MWWT during the last 20 years is summarized in Fig. 2(b), which shows the number of papers on MWWT research published and the linear trend line during the last twenty years (the red dotted line and the black line). The linear model described the relationship between the publication year and the number of publications. The number of papers has grown gradually, with no more than 11 papers per year before 2010. Since 2011, however, by simple linear regression analysis, the number of papers has increased linearly ($R^2 = 0.98235$). It could also be predicted that the number of scientific papers on MWWT research will increase at a high speed in the near future.

The maximum number of papers published per year was registered in 2020, with a total of 145 papers; while the minimum was registered in 2001 with 26 papers published. Slow growth in the research was observed during the years between 2001 and 2003, while rapid growth was observed continuously from 2010 to 2020.

3.2 International collaboration patterns

International research collaborations have become increasingly important as an emerging area of innovation studies. Fig. 3 shows a graphical representation of various countries that have acknowledged cooperative relationships. The size of the circle on the resulting map represents the number of publications in each country; the lines represent established ties between nations, with the line thickness based on the number of partnerships; and the various colors represent the key groupings of collaboration. China leads the red cluster with the most papers published, followed by Australia, Chile, Colombia, Egypt,



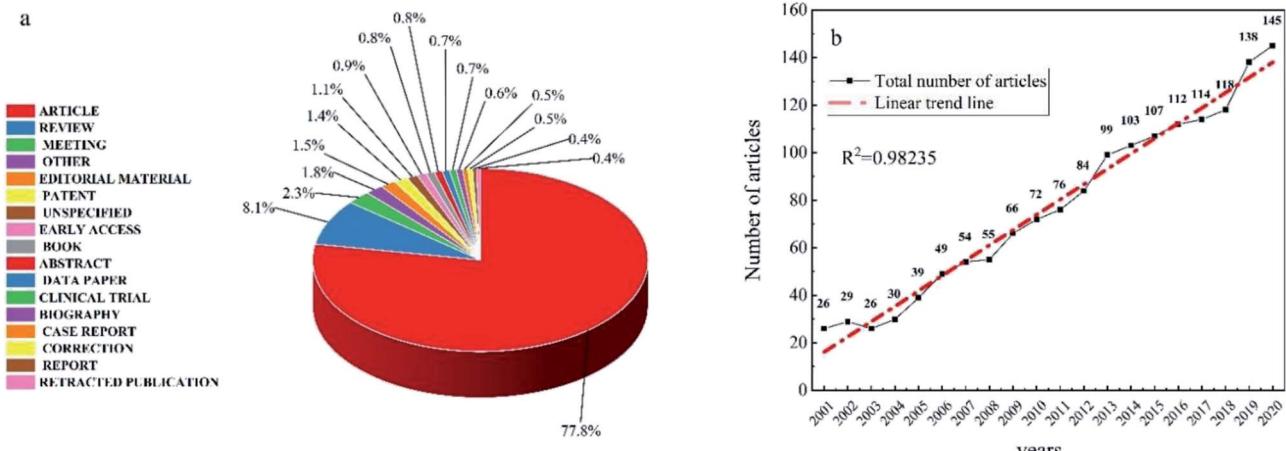


Fig. 2 (a) Document type percentage of reports for mining wastewater research; (b) number of publications on mining wastewater treatment, simple linear regression analysis and evolution during the last 20 years (2001–2020).

Finland, Germany, Greece, Hong Kong, Iran, Italy, Japan, Malaysia, Mexico, Poland, Portugal, Romania, Singapore, South Korea, Spain, Sweden, Switzerland, Turkey, and the United Kingdom. The green cluster is controlled by the USA and Canada, which have the Netherlands, India, and New Zealand as their main collaborators. The third and final cluster is the blue cluster, which is led by the Russian Federation and includes South Africa and Saudi Arabia as significant collaborators.

The number of documents provided by each country, the number of citations accumulated by these documents, and the total link strength (TLS), which is the total sum of all links generated by each document. A higher value of the TLS in proportion to the number of documents is an indicator of greater international collaboration and research publications relevant to the topic. On the other hand, a lower TLS value suggests a low weight on internal scientific production and international collaboration. The values of each country's documents, citations, and TLS are given in Table 1.

Consequently, the results of countries' production indicate that the establishment of MWWT technologies or specific projects from these countries' governments, private sector, and industries will further encourage the future research of MWWT because they are taking a good interest in this research field.

3.3 Journals in MWWT research

A journal is more impactful if a greater number of papers are published in it and more number of citations it possesses. This section shows the most productive journals on MWWT as well as it evaluates their greatest significant variables, as shown in Table 2. The journals recorded in the table cover fields as diverse as hazard materials, environmental science and engineering, water chemistry and technology, environmental water, air, and soil pollution research, and environment management, suggesting that MWWT has received attention from various environment-related fields.

The impact factor (IF) is commonly used to evaluate the relative importance of a journal within its field and to measure the frequency with which the "average article" in a journal has been cited in a particular period. A journal that publishes more review articles will get the highest IF. Moreover, IF is the well-recognized scientometric index to evaluate the position and status of a journal by counting the yearly average number of citations of articles published in the last two years. The higher the IF, the extra highly ranked will be the journal. From Table 2, it can be noticed that numerous articles on MWWT have been published in journals with high IF, such as in *Water Research*, *Journal of Hazardous Materials*, *Environmental Science and Technology*, and *Science of the Total Environment*, all the leading journals in the field of water science and technology, environmental science and engineering, suggesting that some cutting-edge research has been recognized by peers.

There are two standard weight attributes, *i.e.*, total citations and TLS. For a given article, the total citations and TLS indicate the quality and quantity of this published article in a journal, respectively. In case of journal, the citations indicate the

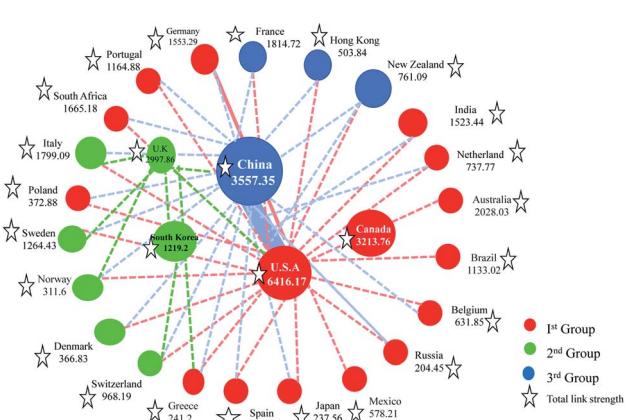


Fig. 3 Main relationships between countries in the MWWT research. The different colors represent the different groups' collaborations and the white color depicts the total link strength value of the individual country.



Table 1 The most active countries in the field of MWWT research include the following features

Rank	Country	Documents	Citations	Total link strength
1	United States	230	7802	6416.17
2	China	228	4189	3557.35
3	Canada	135	2883	3213.76
4	Spain	113	2867	2542.68
5	United Kingdom	100	4329	2997.86
6	Australia	80	1953	2028.03
7	Brazil	78	1498	1133.02
8	India	76	1696	1523.44
9	South Africa	75	1169	1665.18
10	Germany	65	1761	1553.29
11	Russian Federation	63	282	204.45
12	Portugal	49	1223	1164.88
13	South Korea	48	1424	1219.2
14	Finland	42	934	1017.68
15	France	41	1056	1814.72
16	Turkey	38	1156	618.36
17	Italy	37	724	1799.09
18	Poland	28	331	372.88
19	Netherlands	24	1008	737.77
20	Sweden	22	409	1264.43
21	Mexico	21	1373	578.21
22	Belgium	19	611	631.85
23	Chile	19	307	478.03
24	Japan	18	621	237.56
25	Romania	17	501	293.72
26	Iran	17	297	217.39
27	Singapore	16	259	1092.63
28	Switzerland	16	504	968.19
29	Greece	13	353	241.2
30	Malaysia	13	199	206.27
31	Hong Kong	11	339	503.84
32	Egypt	11	199	366.83
33	New Zealand	10	179	761.09
34	Colombia	10	335	311.6

number of articles on this journal linked with articles on other journals, and TLS indicates the link strength of this given journal with other journals.

For instance, with a total of 100 articles, 1588 citations and 110 total link strengths, *The Journal of Hazardous Materials* is the one with the most articles available on MWWT and it shows that it has more influence in this research field than other

journals. The second journal, *Science of the Total Environment*, has a total of 88 articles 3737 citations, and 113 total link strengths. With a total of 67 publications, 1991 citations, and 80 total link strengths on MWWT, *Chemosphere* is the third journal in this classification. Higher citations and TLS show that they are good journals for publications related to MWWT research.

The *Journal of Water Science and Technology*, *Environmental Science and Technology*, and *Journal of Environmental Management* are the oldest and middle-age journals in our sample, with 62 publications, citations of 564 and 28 total link strengths, 55 publications, 3012 citations and 50 total link strengths, and 51 publications, 955 citations and total link strength 51 between 2001 and 2020, respectively.

In addition, 50 articles have been published in *Environmental Science and Pollution Research*. The last three journals are *Water Air and Soil Pollution*, *Water Research*, and *Environmental Pollution*, and two of them have the same numbers of publications, 38 and 38, during the entire period, the last journal in the top ten had 32 publications.

The concept of judging the journal's cooperative distributions can be applied to scientific and technical collaboration. MWWT joint research papers were published in nearly all of the important environment-related journals, at the same time, the collaboration or publication steps of each journal are not easy as we assume, *i.e.*, before the publication of any research material it has to go through many stages, which is not an easy task because each journal has its own criteria, quality, and worth. Finally, there is a good expectation that more collaborative works on MWWT will be published in environment-related journals in the future.

3.4 Keyword analysis

Keyword analysis is a fundamental process to define the field, subfield, topic, and research issues, as well as help researchers, find the information and content of the research. Moreover, the key purpose of keyword analysis is to gain a deeper understanding of hot research topics.

Through keyword analysis, the characteristics and growth trends of the research field can be discovered. Keyword analysis can also tell us how they are correlated with each other and how they can be used for finding the maximum important

Table 2 The most active journals in the field of MWWT research include the following features

Rank	IF	Sources	Documents	Citations	Total link strength
1	10.588	<i>Journal of Hazardous Materials</i>	100	1588	110
2	7.963	<i>Science of the Total Environment</i>	88	3737	113
3	7.086	<i>Chemosphere</i>	67	1991	80
4	1.638	<i>Water Science and Technology</i>	62	564	28
5	9.028	<i>Environmental Science and Technology</i>	55	3012	50
6	4.175	<i>Journal of Environmental Management</i>	51	955	51
7	3.056	<i>Environmental Science and Pollution Research</i>	50	203	12
8	1.900	<i>Water Air and Soil Pollution</i>	38	927	21
9	9.130	<i>Water Research</i>	38	1288	58
10	8.071	<i>Environmental Pollution</i>	32	1430	51



documents between current publications in a scientific field. Table 3 and Fig. 4(a) and (b) show the results of the keywords analysis and the growth of the keywords from 2001 to 2020. The keywords with the maximum frequency were wastewater (frequency = 375), heavy metals (frequency = 360), adsorption (frequency = 315), goldmine (frequency = 296), and coal mine (frequency = 286). Word “frequency” refers to the number of occurrences of words in the documents. We can find some information on the most used keywords in the MWWT research in Fig. 4(a) and (b) and Table 3.

Compared to the entire network, from the perspective of the influence, the system of measurement for keywords in Fig. 4 and Table 3 showed that keywords of coal mining, gold mining, heavy metals, adsorptions, sedimentations, and environmental pollution are more commonly used keywords words during the period (*i.e.*, 2001 to 2020) in MWWT research. Coal mining and gold mining have received more attention because of their higher demand in the business field. On the other hand, the terms “landfill mining” and “passive treatment” are rarely used and we can observe a pink color group in Fig. 4(a). However, this may change in the future depending on scientific advances.

A keyword burst indicates that the scientific community has paid or is paying particular attention to these topics or keywords. In this paper, CiteSpace is used to conduct a visualized analysis of 1542 articles in the extended database, which can identify the references with strong citation bursts. Fig. 4(b) shows the top 20 strongest keyword bursts gaining more attention from the researchers in MWWT research. As seen in Fig. 4(b), the strongest keyword burst is related to a report by “acid mine drainage” (2007–2015), and the second strongest citation burst is “metal” (2007–2014).

3.5 Treatment technology analysis

There are three mature types of technologies to treat wastewater, *i.e.*, physical, chemical, and biological treatment methods. Physical treatment, such as clays, activated carbons, zeolites, biopolymers, silica, lignocellulose, and plants as adsorbents, have been well used to physically remove heavy metals produced by many industries.⁴⁸ Membrane filtering technology, a physical separation method that allows molecules of various sizes and properties to be separated in an aqueous system, produces high metal (*e.g.* mercury) removal ratios and

Table 3 Analysis of the existence of keywords from 2001 to 2020

Rank	Keywords	Frequency
1	Wastewater	375
2	Heavy metals	360
3	Adsorptions	315
4	Gold mine	296
5	Coal mine	286
6	Removal	243
7	Metals	216
8	Absorption	186
9	Groundwater	176
10	Toxicity	145

excellent selectivity characteristics when compared to other treatment choices.⁴⁹ Automated Variable Filtration (AVF) is another physical treatment method. It is a simple process in which the upper flow of influent is cleansed by the downward flow of the filter media.⁵⁰ It meets the requirement for any further filter media cleaning method or freshwater.⁵¹

Chemical treatments, such as chemical precipitation, and ion exchange, neutralization are suggested as the ideal method to treat wastewaters with high chemical toxin contents.³⁸ Cyanide removal from mining wastewater by conventional methods has been broadly described throughout the last decade. Coagulation, as well as electrocoagulation for the removal of cyanide ions from synthetic mining wastewater, were assessed.⁵² Moreover, in a broad sense, advanced oxidation processes (AOPs) are a series of chemical treatments, treatments that use hydroxyl radicals to oxidize organic (and sometimes inorganic) compounds in water and wastewater.⁵³ In addition, ultraviolet (UV) irradiation is a “clean” and commonly used chemical method to remove pollutants from wastewater.⁵⁴ Through photocatalysis, it can break down a range of organic pollutant compounds, microbes, and inorganic compounds.⁵⁵

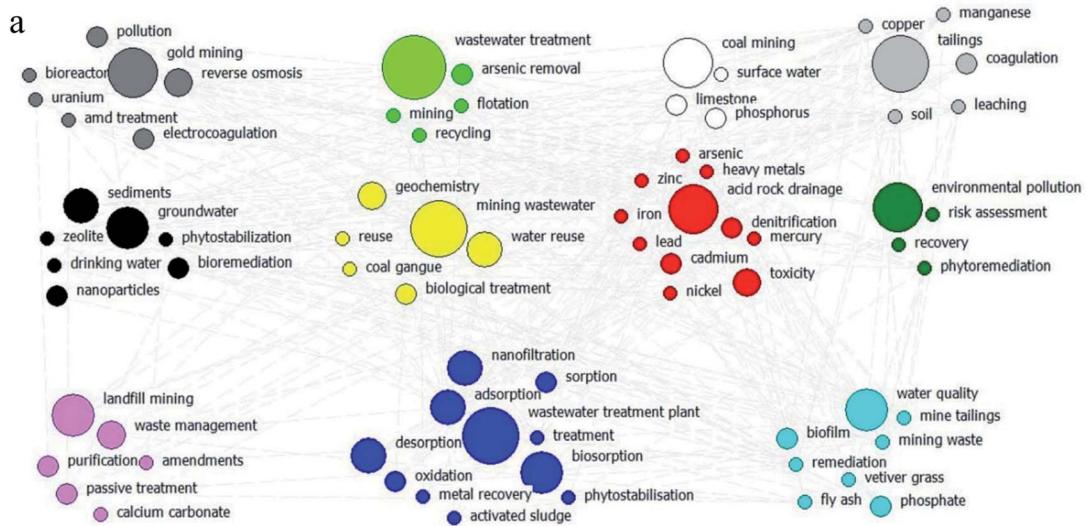
Aerobic/anaerobic treatment is a typical biological method widely used in MWWT.⁵⁶ Under aerobic conditions, bacteria decompose the organic matter and convert it into carbon dioxide. While under anaerobic conditions, groups of micro-organisms transform biomass into biogas. In particular, the sludge treatment method is a hybrid method of combining physical, biological, and chemical methods. As a solid-liquid separation process, different units of adsorption, aerobic/anaerobic treatment, and chemical methods are integrated for different types of wastewater treatment, such as hospital and domestic sewage, industrial wastewater, and mining wastewater.⁵⁷

Moreover, the treatment technology analysis shown in Fig. 5 indicates that adsorption is the major research topic in physical treatment methods with 403 published articles. Its development has shown a clear upward trend and therefore we can make predictions that there is still much scope for the development of adsorption technology. Adsorption is highly efficient, produces high-quality effluents, and is widely used to remove chemical contaminants that are difficult to degrade by conventional biological wastewater treatment.

The adsorption method is one of the most effective methods for the advanced treatment of wastewater, which is usually used to reduce harmful metals. Among them, activated carbon is the most widely used as an adsorbent with a good adsorption capacity for heavy metal ions. In addition, in the study of keyword analysis in Fig. 4 and Table 3, the keywords “heavy metals” and “adsorption” also show a high frequency of co-occurrence.

The adsorption capacity of “activated carbon or fly ash” is related to its porous-sized distribution, large specific surface area, and surface chemistry. However, the use of activated carbon may be expensive depending on its adsorption capacity and the difficulties in reactivation and reuse. Therefore, many researchers have tried to develop cheap and effective adsorbents as alternatives from industry or agriculture *e.g.*, waste carbon





b Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	2001 - 2020
system	2001	4.72	2005	2010	
sulfate reducing bacteria	2001	7.41	2006	2011	
iron	2001	5.49	2006	2013	
metal	2001	9.04	2007	2014	
sulfate reduction	2001	7.11	2007	2010	
sludge	2001	5.12	2007	2015	
constructed wetland	2001	5.12	2008	2014	
zinc	2001	7.15	2010	2015	
biosorption	2001	6.9	2010	2012	
impact	2001	4.79	2010	2013	
acid mine drainage	2001	4.74	2011	2013	
sorption	2001	7.97	2014	2017	
heavy metal removal	2001	4.72	2015	2018	
aqueous solution	2001	11.23	2016	2020	
bioremediation	2001	8.46	2016	2018	
waste water	2001	5.37	2016	2018	
degradation	2001	7.32	2017	2018	
toxicity	2001	7.29	2018	2020	
recovery	2001	7.06	2018	2020	
precipitation	2001	5.97	2018	2020	

Fig. 4 (a) Keyword co-occurrence network map; (b) the keywords with the strong citation burst in articles related to MWWT research published from 2001 to 2020. Strength: illustrate the strength of citation in the research, the red line indicates the starting and end times of the citation period of the keyword.

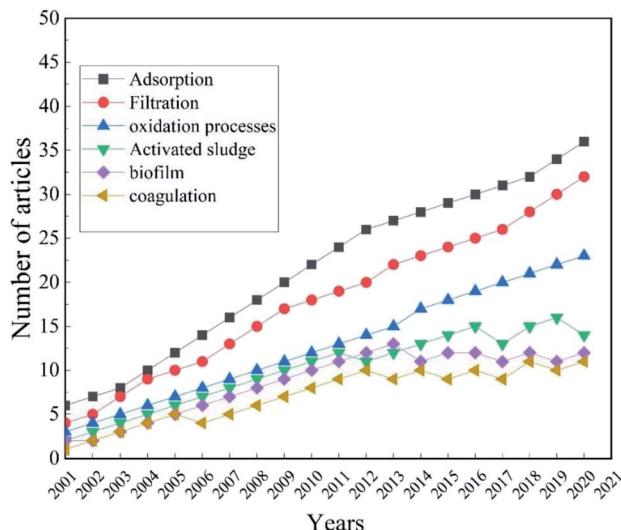


Fig. 5 Annual publication performance of the top six (physical, chemical, biological and sludge), mining wastewater treatment technologies.

slurry, corn cob, coconut shell, recycled cotton waste, nutshells, waste tire rubber, bio-sorbents (chitosan, peat), and so on. Recently "chitosan" has been used for the modification of fly ash for good removal capacity of the adsorbent.

The oxidation processes and coagulation depicted in Fig. 5 indicate that it is a major research topic in chemical treatment methods with 250 and 143 published articles. The oxidation process has shown a clear rising trend, that way we can assume that there is still much scope in chemical treatment technology for the treatment of mining wastewater. Advanced oxidation processes (AOPs), in a broad sense, are a set of chemical treatment procedures designed to remove organic (and sometimes inorganic) materials from water and wastewater by oxidation through reactions with hydroxyl radicals ($\cdot\text{OH}$).

On the other hand, with a total of 143 published articles, coagulation is the least valued MWWT method compared with other treatment techniques studied in Fig. 5. We can see that the progressing trend of coagulation treatment does not go with consistency compared to adsorption, oxidation, and activated sludge treatment technologies. The line of coagulation treatment has gone up a bit from 2001 to 2005, and then it came down between 2005 and 2006. From 2007 to 2012, it went in an ascending order after that it has been fluctuating again. There can be many reasons behind this, one of which may be the cost of operating the process is relatively high than other treatment methods, and secondly, there is an adverse effect of a sudden change in the character of treated water absorption.

The biological treatment techniques "activate sludge and biofilm" were rarely used in treatment techniques. In Fig. 5, activated sludge and biofilm come in number four and five with 200 and 173 published articles, respectively. As seen, in Fig. 5, the progress trend of both "activated sludge and biofilm" was going up consistently from 2001 to 2013, but after 2012, there were sudden fluctuations till the end. Such fluctuations on the topic of activated sludge could be due to the more attention

paid to more efficient ways such as physical and chemical treatment methods.

Physical, as well as chemical methodologies, received extra attention on the laboratory scales and technical or scientific study. However, the applied work uses and patent cover are incomplete because of boundaries in experimental abilities, longer period reserve, higher cost, *etc*. These results present a great opportunity and a large space for development. Meantime although computerized measurement methods such as the internet of things (IoT), wireless sensor networks (WSN), artificial intelligence, swarming drones, and automation have been widely employed in mine water management, it is particularly important for management and decision-makers to find and choose the right technologies to treat mining wastewater in the vast ocean of research on MWWT.⁵⁸ Linking mining wastewater treatments by modifying the relationships between numerous structural classifications, however, must be promising, and the inclusion of the double is still a problem routine that needs to be addressed.

The S-curves derived from the articles show that physical, chemical and biological MWWT methods entered the maturity stage in 2019, 2017 and 2016, respectively. Physical and chemical treatment technologies will have a much longer time before reaching the declining stage and have a greater potential for innovation and development. Among these technologies, adsorption, oxidation, and biofilm could be further developed in the next 5–10 years through academic research and novelty. Differently, biological treatment technologies are closer to the saturation stage, *e.g.*, both biofilm and activated sludge will enter the maturity stage around 2025. Both S-curve and publication output indicated the popularity of the physical and biological treatment methods. Physical treatments have developed rapidly in the past ten years, while biological is an ongoing developing technology.

The composition of mining wastewater became more complicated by including a more non-degradable carbon-based materials with the development of the mining industry.⁵⁹ Physical treatment methods have the advantage of high efficiency, low cost, and convenient operation,⁶⁰ and have played a crucial role in MWWT. With much attention from researchers and a huge number of studies, the maturity of physical treatment technologies such as adsorption and filtration has improved rapidly.⁶¹ In terms of specific technologies, compared with chemical technologies such as "oxidation technology",⁶² and biological "biofilm",⁶³ research on the activated sludge is necessary due to the smaller number of publications it has been presented in the graph.

3.6 Three fields plot of prolific countries, keywords, and journal's network.

A more visualized representation of productive researchers about their countries, keywords, and a particular source of publications in the field of MWWT is shown in Fig. 7. This figure is a three-field plot or Sankey graph of articles offered by countries, keywords, and sources within the field of MWWT. The left-side column represents active countries, the middle



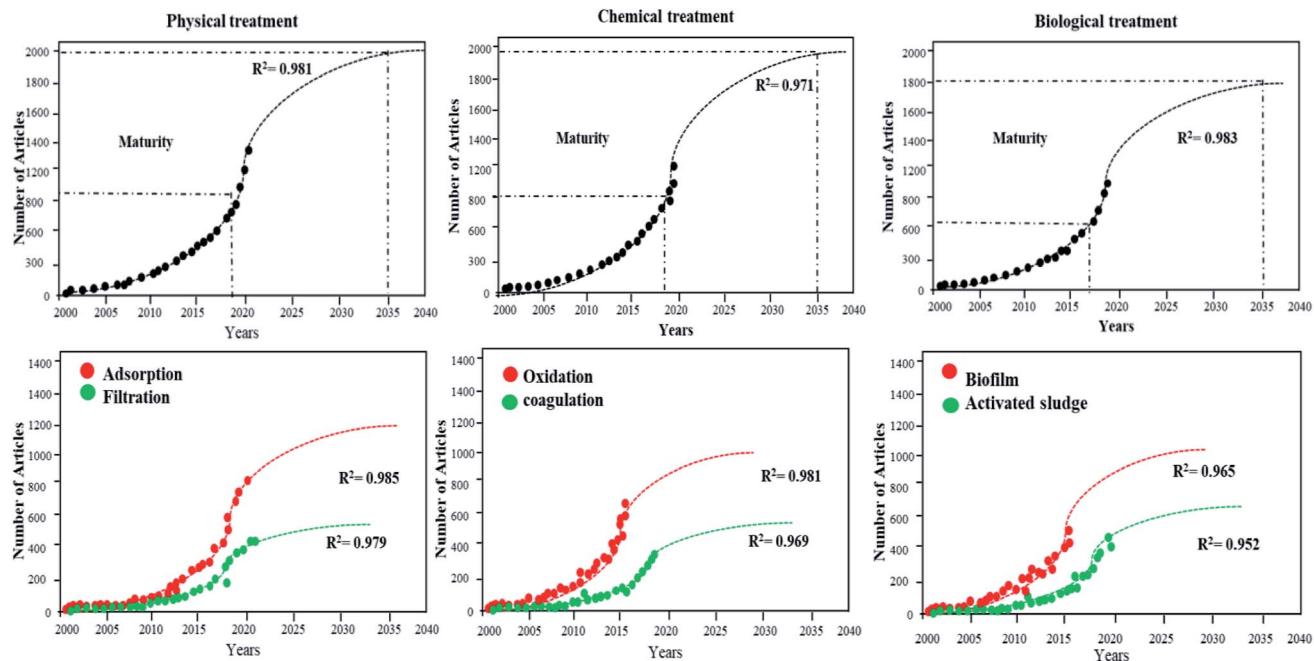


Fig. 6 The S-curve analysis of different mining wastewater treatment methods and technologies as derived from the articles.

column demonstrates the most used keywords by the authors, and the most right column represents the most famous sources relevant to the research field. Note that, the height of the boxes and thickness of the linking lines indicate the proportion of such variables in the total allocation. Across the countries, China has more keyword connections. Even though our previous results discovered that the United States is first concerning scientific invention and citation counts, they came second in affiliation through keywords. In that order, Spain has the next highest volume of keywords, followed by Brazil and South Africa.

From the thickness of the lines going from the countries to keywords, and then publication sources, if the thickness of lines is strong, it will show the higher research on the relevant topic, and if the thickness of lines is weak, it will show low research on the topics. So, here are three field Sankey plots in Fig. 7. We can see the interaction between the three fields with the help of the thickness of the lines and boxes, which is an interesting thing. We can see which countries are working on which topic and publishing in which journals. For example, China has been working a lot on acid mine drainage, adsorption, and heavy metal topics compared to other countries; journals such as *Environmental Pollution*, *Journal of Hazard Materials*, and *Science of the Total Environment* are publishing these research articles. If we see the graph from the right side *i.e.*, on the side of the journal the thickness of the box of the *Journal of Hazard Material* and *Science of the Total Environment* shows that it has higher publications compared to other journals.

The thickness of the line and box of acid mine drainage show that the most important keyword “acid mine drainage” is used in Fig. 6, and China has been working a lot on acid-mine drainage topics, as compared to other countries. Hence, this

shows that acid mine drainage (AMD) is considered to be one of the major environmental issues in the mining industry in China due to high coal mining.^{64,65} The total number of coal mines in China has decreased from more than 80 000 to around 4700 (by the end of 2020) under the guidance of a series of national policies, which is a good initiative for the protection of the world's natural water resources and environment.⁶⁶

While Europe has a long and rich history of mining, there are now significantly more uncontrolled mines than operational mines across the continent and research and development activities across Europe are wide-ranging.⁶⁷ European Union (EU) legislation strongly influences approaches to mine waste/water management in Europe.⁶⁸ Many European countries Estonia, Finland, France, Germany, Hungary, Italy, Macedonia, Netherlands, Norway, Poland, Serbia and Montenegro, Slovakia, Sweden, United Kingdom are facing problems with acid mine drainage and remediation due to minerals or mining exploited,⁶⁹ such problems have been brought into sharp focus by catastrophic events at mining facilities,⁷⁰ as a result, groundwater and surface water pollution are major issues.⁷¹

Acid mine drainage, acid metalliferous drainage (AMD), or acid rock drainage (ARD) are caused due to the outflow of acidic water from coal mines (https://en.wikipedia.org/wiki/Coal_mining) or metal mines.⁷² This acidic water procedure through the chemical reaction of surface water (rainwater, snowmelt, pond water) and shallow subsurface water with rocks that contain sulfur-bearing minerals results in sulfuric acid.⁷³ AMD impacts stream and river ecosystems by increasing acidity, depleting oxygen, and releasing heavy metals such as aluminum (Al^{3+}), iron (Fe^{3+}), manganese (Mn^{2+}), zinc (Zn^{2+}), copper, lead, and mercury, which pollute the ground and surface water.⁷⁴ AMD is one of mining's most serious threats to

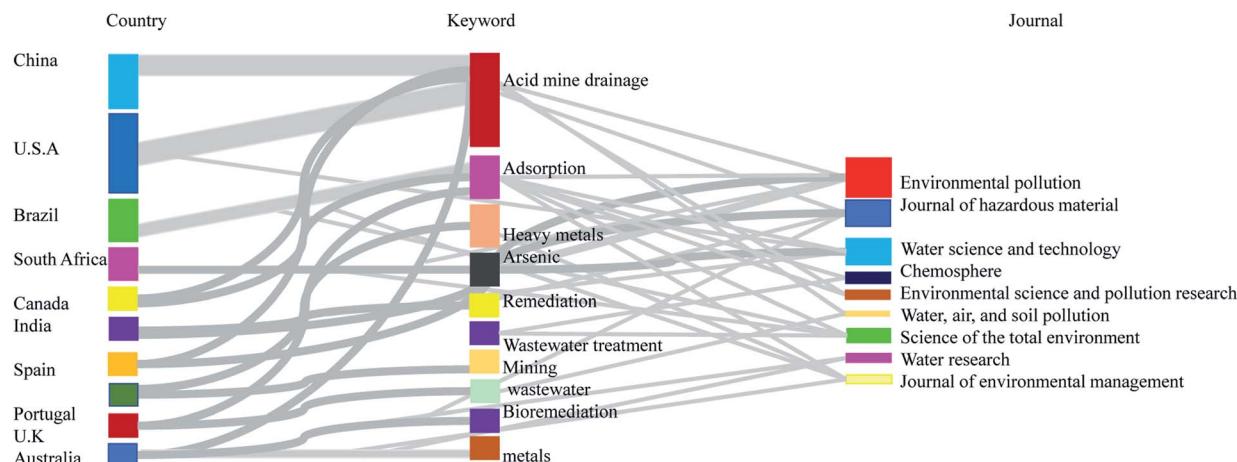


Fig. 7 The three-field Sankey graph of countries, keywords, and sources of mining wastewater treatment: the highlighting is located on the height of all boxes and the thickness of the linking lines; the higher the box, the extra important; and the thicker the lines' relationship, the additional information or size of work was formed.

human and aquatic life. For instance, acid mine draining can devastate rivers, streams, contaminate drinking water, and aquatic life (aquatic plants and animals) for hundreds and, under the "right" conditions, thousands of years.⁷⁰

Numerous adsorption, filtration, and sorption technologies are being used for the treatment of AMD. However, the most prevalent method for treating AMD contamination is the addition of alkaline reagents such as lime, limestone, sodium carbonate, or sodium hydroxide.⁷⁵ This treatment aims at neutralizing acidic water and the precipitation of heavy metals. This includes all necessary pretreatment, ultra-filtration, reverse osmosis, evaporators, and crystallizers.⁷⁶

3.7 Descriptive analysis of most productive authors and institutions

Collaboration distributes resources among academic institutions, creating conditions for partnerships, finding the latest research, and problem solving, bringing innovations in research, improving research practice, and sharing ideas and research. By institutional analysis, we can reveal the ideas of most collaborative institutions in MWWT and find how much they have interacted individually or collectively with each other. In addition, we can find whether individual institutions have decided to work on this topic or if it was government funding or an opportunity from the private sector.

In the sample, 83.87% of the institutions have published ten articles, and 90.88% of institutions have produced ten to fifteen articles. Therefore, we chose at least twenty publications and 30 citations as criteria to extract the most influential institutions in the MWWT field. From Fig. 8(a) and the inserted table, University of Chinese Academy of Sciences, Beijing is ranked as the first in the MWWT area with 43 publications (174 citations and 124 total link strength). The subsequent institutions are the University of Saskatchewan (Canada), and Guangzhou institute of geochemistry (China), with 35 and 31 publications, 111 and 90 citations, 12 and 100 TLS, respectively. In this analysis, the thickness of the line reflects the frequency or TLS of coauthor-

ship collaboration among the institutions. The greater TLS values of Chinese research institutes identified their closer collaborative relationships between institutions. The results show that the University of Saskatchewan, Canada, has the least collaboration in MWWT research due to 12 TLS.

Though institutions with the 31 and 30 publications are Guangzhou institute of geochemistry and Harbin institute of technology (China), respectively, and countries with 28 to 19 publications are Taiwan, South Africa, India, Finland, USA, Spain, Turkey, and South Korea, but these countries have strong collaboration among other institutions because of higher TLS than Canada.

Author productive analysis shows the interest, and role of authors' contributions in the research policies, problem-solving, and research innovation progress of his institutions, company, organization, and country development. Fig. 8(b) and the table downside illustrate some important information related to the authors, which are the following: the different colors represent different clusters. Each node in the cluster represents an author. The node's size represents the number of articles published by the authors, and the nodes with the same color represent the relevant information of cooperation between the authors. In the author's knowledge map and table, the total citations show an indicator of the influence of a researcher's work and cited by another researcher, and the TLS represents the size of collaboration among the authors. The greater the TLS, the stronger the collaboration.

About 84.21% of the authors in the sample have published one paper, and 5.4% of the authors have produced seven or more documents. Hence, we analyze the authors who have published at least seven or more papers. Furthermore, considering the impact of the author, we chose the authors whose papers have been cited at least over 90 times.

To understand the relationships between the table and figure of authors, there are two standard weight attributes, referred to the total citations attribute and TLS attribute for a given item, the total citations and TLS qualities, and quantity



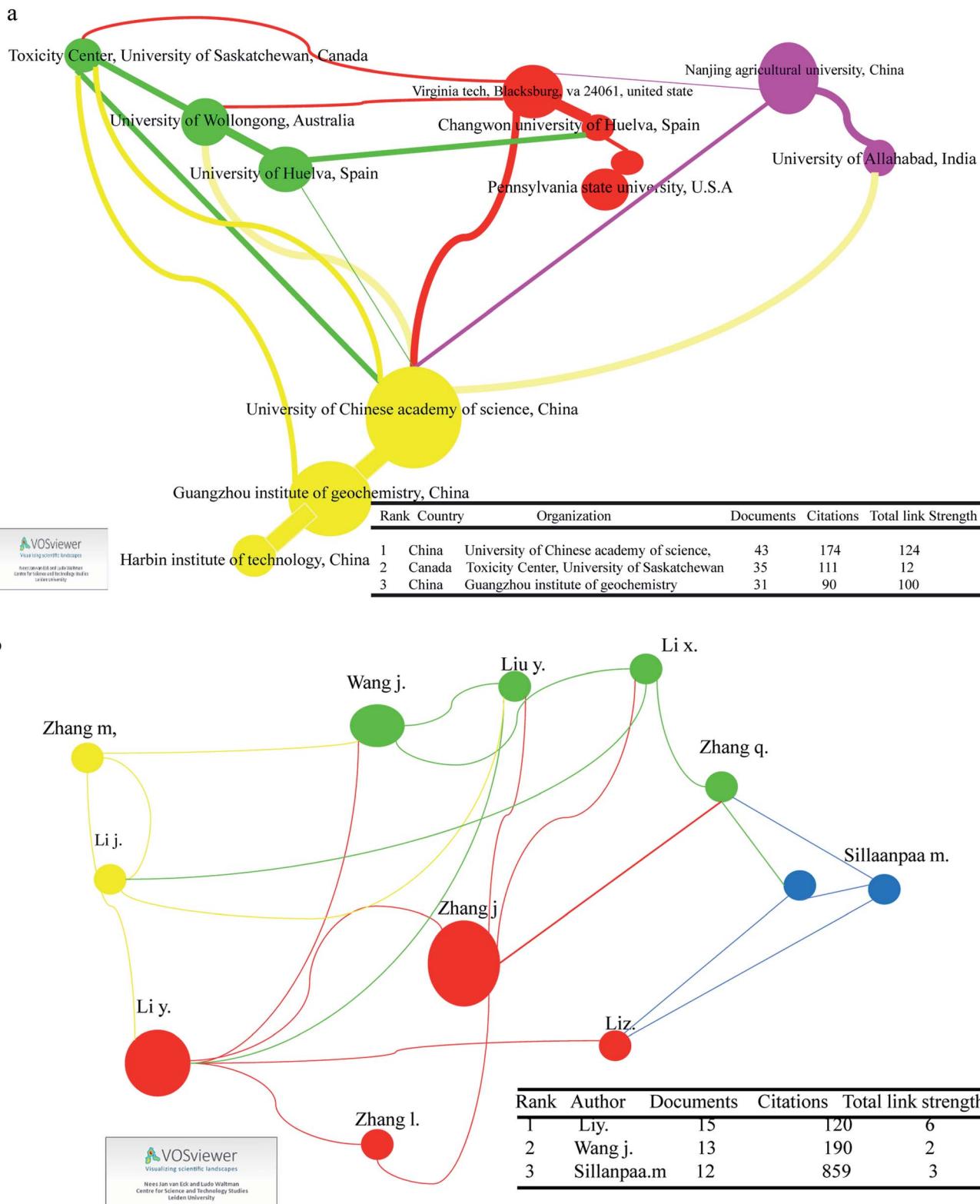


Fig. 8 (a) Most influential institutions in the MWWT research field. Colors indicate the cluster to which an institute was high publications and collaboration with other institutions assigned by the clustering; (b) the knowledge map of some authors in the research of mining wastewater treatment.

show the author's performance in the relevant research field. The number of links of an author with other authors, and total citations of an author's publications with other authors have

different values and standards. For example, to understand the concept of total citations and TLS, in the case of co-authorship, the citations indicate the number of articles linked with other



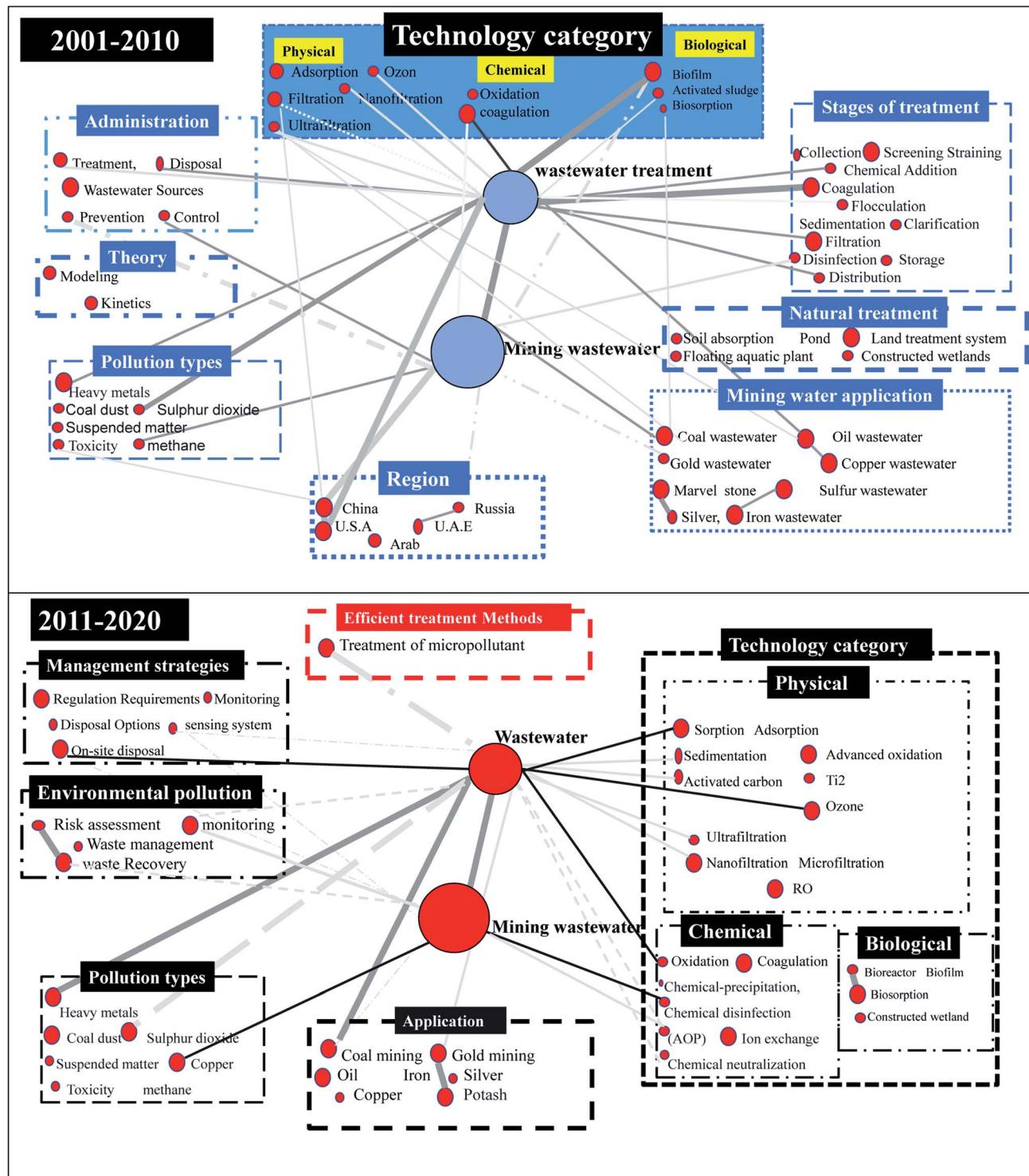


Fig. 9 The interconnection network and evolution of keywords in articles published during 2001–2020. Notes: the relative number of keywords is characterized by the size of the red dots. The larger the red dot is, the more common that keyword appeared or was used in the linked articles. The number of co-occurrences is characterized by the pattern of the gray lines. The thicker and darker the line is, the larger the number of co-occurrences of the two keywords that were used by the authors.

research articles, and the TLS attribute indicates the total strength of the co-authorship links of a given researcher with other researchers.

According to the results shown in the inserted table of Fig. 7(b), with 15 documents, 120 citations, and 6 TLS, Li Y. can be recognized as the most important author, meaning this author is taking more interest and encouraging research in the

MWWT field, and other researcher cited his paper in their research papers. These following authors are Wang J., and Sillanpaa M., the second and third positions authors, respectively, who have published more than ten articles in the field of MWWT research. As a consequence, Li Y. and Wang J. are the authors who are more productive with influential research. Hence, exploration, description, and explanation are the three most influential and common purposes of research among the institutions individually or collectively.

3.8 Evolution processes of MWWT research

Co-word analysis can make good use of the keywords contained in the “time” attribute. Therefore, the dynamic changing process of study discipline study could be presented much more objectively and practically. This work divided the period from 2001 to 2020 into two stages, and the analysis of keywords in each stage is shown in Fig. 9. The domain classification of the two stages is increased. However, the research focused on different directions and the relationship between different fields was also changing over time.

Identified from the co-word analysis, treatment technologies, pollution types, mining water applications, stages, theory, and management strategies have always been crucial points, issues, or topics in the study of MWWT research during the entire period.⁷⁷ In the evolution from stage 1 (2001–2010) to stage 2 (2011–2020), the interconnections of keywords began to become closer. Additionally, there was research concerning China and the U.S.A in this period because of these two countries' size and interconnection, and closeness to each other and with wastewater treatment keywords. In the aspect of the theory, stages of treatment, pollution type, natural treatment, and advanced treatment technologies began to receive attention because of the use of modeling and kinetic theories such as pseudo-first order and second-order kinetics models in treatment research. In both, stage 1 (2001–2010) to stage 2 (2011–2020), new techniques, such as physical, chemical, and biological technologies were introduced into this field,⁶¹ while the specific topic was related to the administration or management of waste and disposal.⁷⁸ In stage 2 (2011–2020), efficient advanced treatment technologies such as ultrafiltration, nanofiltration, revise osmosis (RO),⁷⁹ oxidation, *etc.* continue to be concerned. Moreover, this phenomenon indicated that the related research on biosorption and activated carbon was still very rare.

In the present and near future, there are some solutions for treating wastewater from the mining industry such as the full range of wastewater treatment technologies including biological processes, desalination, clarification, evaporation and crystallization, disinfection, filtration, ion exchange, membrane separation, package plants, sludge dewatering and handling, and zero liquid discharge.⁸⁰ Moreover, integrated steps (conducting a self-assessment, evaluating technology, performing a pump audit, installing smart technology, reviewing data) can help MWWT plants to achieve better water efficiency and realize potential cost savings⁸¹ by reducing water waste.⁸² The analysis of the treatment technologies allows us to understand the current research in MWWT with adsorption, filtration, and

oxidation processes that are mainly focused on an experimental scale.⁸³ The evaluation of real conditions in the continuous flow mode is mandatory for large-scale implementation in the mining wastewater industry.⁸⁴ Portable and fast *in situ* leak detection technologies, such as paper-based chips⁸⁵ and microfluidics,^{86,87} are also necessary to allocate more time for emergency response.

4. Conclusions

The persistence of heavy metals in the environment has attracted the attention of researchers and the public in recent years. With the increasing number of papers on MWWT, bibliometrics helps researchers to understand academic collaboration, research trends, and hot issues. This bibliometrics study looked at 1542 articles from 2001 to 2020 that represented research on MWWT. Through publication analysis, international collaboration analysis, keyword co-occurrence networks, wastewater treatment technology analysis, and authors and institutional analysis have shown that China and the U.S.A have great research flow, while China has the greater international academic research influence. Moreover, the most investigated types of mining wastewater were heavy metal and acid mine drainage, which has sparked a lot of interest due to human and environmental health concerns and can be called research hotspots in recent years. Adsorption processes, membrane filtration processes, oxidation processes, coagulation processes, and activated sludge are the most common joint treatment techniques, which have shown great potential in recent decades because of increased government and social pressure to reduce severe pollution and recover values to preserve the natural environment.

In the recent few years, the term “environment pollution and water” has appeared in journals about MWWT. This means that the impact of mining wastewater on the “environment and water” is unclear. Thus, researchers should consider these points. Also, the impact of mining wastewater and heavy metals on human health and aquatic life is unclear. Further studies are required to understand the majority of the questions that remain unknown.

(a) Potential future directions are expressed based on the bibliometric review of the past and present conditions of MWWT research; researchers should pay close attention to related studies in the coming years. A further research study by advanced-level research investigations should be conducted to map target variables that are affecting public health and the environment. This would permit the improvement of a knowledge base for the water treatment and reuse sector in advanced and under developing mining sectors, particularly in water-scarce regions where the value-added benefits are higher. While the international mining industry puts effort into future development over the expanded production, they must not lose sight of working productivity and total cost optimization.

(b) Upcoming years are expected to see permanent positive and helpful investment trends in the mining and wastewater treatment sector improved treatment levels, resource recovery, and desalination capacities.



(c) Prices, policies, and guidelines are also important key drivers in the business atmosphere. The relationship between advanced technologies, the social dimension of suitability, as well as the rules of regulation and guidelines, will be an intentional hot topic for further exploration at the advanced level of this research field.

(d) Many beneficial possibilities for the treatment and recycling of wastewater in the mining industry have been documented, however, some limits require additional research. Heavy metals in wastewater raise alarms due to their ability to persist in the environment and their serious health repercussions. Moreover, studies have shown that mining and tunneling, alongside population development areas, will lead to higher applications of chemicals in the future, which would be a big problem for securing the natural environment.

(e) Consumption of energy is one of the major technical problem that must be addressed in treatment plants where a limited population exists in towns and small cities because it is difficult to provide facilities at a low cost.

(f) The results and conclusions of scientific facts, beliefs, and opinions of researchers and other users differ significantly, which inhibits the development of wastewater applications due to lack of understanding of the associated benefits. Great efforts must be put into the report such conditions to appropriately disseminate scientific knowledge to society as a whole.

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Author contributions

Aqib Zahoor: investigation, formal analysis, data curation, writing – original draft, writing – review and editing. Mao Guozhu: investigation, conceptualization, resources, supervision, writing – review editing and funding acquisition. Jian Lin Chen: supervision, writing – review editing, investigation, conceptualization and funding acquisition. Xinming Jia: data curation, conceptualization. Xiao Xiao: data curation, writing review and editing.

Conflicts of interest

The authors note that they have no known competing financial or personal interests that could have influenced the findings of this study.

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