Physicochem. Probl. Miner. Process., 60(4), 2024, 192132 | Physicochemical Problems of Mineral Processing

http://www.journalssystem.com/ppmp

ISSN 1643-1049

Research hotspot and trend of resource utilization of phosphorus tailings - based on Citespace and VOSviewer visualization

Dianjun Jiang, Xueping Huang, Lili Liang, Xiaoshan Deng, Liangzhi Huang

Industrial Technology Incubation Center of Guangdong Academy of Sciences, Guangzhou, 510075, China

Corresponding author: 2672749507@qq.com (Xueping Huang)

Abstract: With the development and utilization of phosphorus resources, phosphorus tailings continue to pile up, which has become a serious problem that cannot be ignored, so the resource utilization of phosphorus tailings has extremely significant research significance. This study takes "phosphorus tailings" and "phosphate tailings" as keywords, 989 related research articles were selected from the Web of Science (WOS) database, and the research results were summarized. The research progress and research hotspots of phosphorus tailings resource utilization in the past 23 years were investigated. Citespace and VOSviewer were used to analyze the published literature in this research field. The results show that the research trend exhibits slow growth-fluctuating growth-rapid growth. The research organizations in this field present the form of independent research groups, among which there are more Chinese research teams. This paper systematically introduces the research hotspot of phosphorus tailings resource utilization, including the collaborative extraction of valuable elements from various solid wastes, and the collaborative preparation of functional materials from various solid wastes under the green closed cycle without by-product system. The future research focus is also put forward.

Keywords: phosphorus tailings, secondary resources, Citespace, VOSviewer

1. Introduction

Phosphate ore resources are an important strategic resource that is non-renewable and irreplaceable. At present, almost all phosphate products are obtained from phosphate ores (Karunarathna et al., 2019). Phosphate ore resources can be classified into four categories based on their degree of mineralization: igneous rock deposits, metamorphic deposits, sedimentary deposits, and biogenic deposits (such as bird droppings deposits). Approximately 75% of phosphate ore resources are found in sedimentary deposits (Ruan et al., 2019). According to the classification based on the primary vein minerals found in phosphate ore, it can be categorized into the following types: Siliceous, clayey, calcareous, organic, mixed minerals, igneous rock, and metamorphic rock (with vein minerals predominantly including sulfides, magnetite, carbonates, nepheline syenite, pyroxene, fossil feldspar, etc.) (Abouzeid et al., 1980).

Phosphate ore separation methods mainly include water washing, heavy media beneficiation, and flotation methods. More than 60% of the phosphate ores in the world are purified by flotation technology (Nunes et al., 2019). However, the beneficiation process generates 20-30% of tailings. With the continuous exploitation and utilization of high-grade ores, the development of middle and low-grade phosphate ores has been paid more and more attention. The environmental problems caused by a large amount of tailings accumulation in the production process are becoming more and more serious (Negm and Abouzeid, 2008). Such as heavy metal contamination of soil, groundwater, and radioactive contamination, etc (Wetherill et al., 1983; Chiu and Li, 2016; Soesoo et al., 2020; Khelifi et al., 2022). To reduce the harm of phosphorus tailings to environmental pollution, the research methods of phosphorus tailings resource utilization have gradually attracted attention (Abouzeid et al., 2008).

Phosphorus tailings mainly contain calcium oxide (CaO), magnesium oxide (MgO), and silicon

DOI: 10.37190/ppmp/192132

dioxide (SiO_2), as well as small amounts of phosphorus pentoxide (P_2O_5), iron and aluminum oxides (Mao and Zhang, 2021). The main utilization ways of phosphorus tailings include tailings reclamation (Severov et al., 2022), tailings filling (Xiong et al., 2023), agricultural applications (Babel et al., 2016), and flame-retardant composite materials (Zhou et al., 2019). At present, the key points and difficulties in the field of phosphorus tailings recycling research are summarized and determined mainly through a large number of literature readings. For example, Kinnunen et al. (2018) reviewed the preparation of ceramic materials from recycled tailings, focusing on the analysis of the methods and approaches for the preparation of ceramics from phosphorus tailings. This approach lacks a comprehensive analysis of the research on the resource utilization of phosphorus tailings, a summary and analysis of the development history, research hotspots, and future research directions. Using the method of bibliometrics, this paper summarizes the research on the utilization of phosphorus tailings resources and analyzes the key points of future research. Scientific software can visually analyze massive literature data to understand the development history of a research field, current research hotspots, and future research trends (Zhang et al., 2021). Commonly bibliometrics software includes CiteSpace (Chen et al., 2004), VOSviewer (van Eck and Waltman, 2010), COOC (Qin et al., 2022), etc., which has been widely used by domestic and foreign scholars in medicine, engineering, management, and other research fields.

In this paper, the Web of Science (WOS) database was used as the literature retrieval source, and the published papers related to the utilization of phosphorus tailings resources were taken as the research object. Citespace and VOSviewer were used for statistical and visual analysis of this field. Through quantitative and visual analysis, the research hotspots and research progress of phosphorus tailings resource utilization in the recent 23 years are reviewed, which provides references for the future research direction of phosphorus tailings.

2. Data collection and analytical methods

2.1. Data source

Literature from the WOS Core Collection was searched with the subject keyword TS = (phosphorus tailings or phosphate tailings), and 1,111 documents were obtained. The literature type as research papers, the language limit as English, and the WOS index type as SCI-E (Science Citation Index Extended) were determined in terms of conditions, a total of 1002 valid literature articles were obtained between 2000-2023. After initial review and screening to exclude irrelevant studies, 989 relevant articles were retained. Complete records of these publications, including author names, article titles, publication years, keywords, etc., along with cited references, were downloaded in plain text format. Further, bibliometric analysis was performed using VOSviewer and Citespace.

2.2. Data processing

Based on 989 data retrieval documents collected from the WOS core database, Origin 2019 software was used to statistically analyze the number of publications in different years. In addition, VOSviewer and Citespace software is used for co-occurrence analysis (such as country, institution, and author), research hotspot analysis (keyword co-occurrence), and co-citation analysis (references). Co-citation analysis describes the relationship between two or more authors (journals, references) that are cited by the same author (journal, reference) at the same time. In the keyword co-occurrence analysis network, nodes represent specific keywords. Such as countries, institutions, or keywords, the larger the node, the higher the frequency of occurrence. On this basis, by using EndNote X9, Excel, and Origin 2019, the literature data were deeply mined to visually analyze the research hotspots and development trends of phosphorus tailings resource utilization. The analysis process is shown in Fig. 1.

3. Results and discussion

3.1. Analysis of publications, subject categories, and periodicals

The number of articles published in the research field of phosphorus tailings resource utilization from

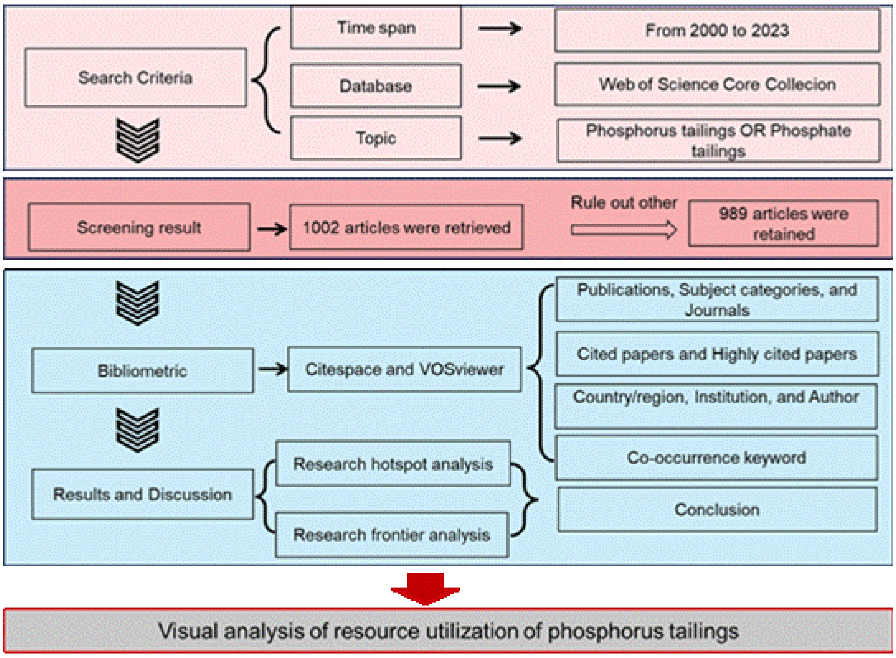


Fig. 1. Scientometric analysis process

2000 to 2023 was counted, as shown in Fig. 2(a). The overall number of publications is all on an upward trend, which is shown in three stages of slow growth-fluctuating growth-rapid growth. From the third stage, it can be seen that the number of articles related to the utilization of phosphorus tailings resources has shown a rapid growth trend since 2018, indicating that the attention of the research on the utilization of phosphorus tailings resources has increased year by year.

From the perspective of the year, the research literature on the resource utilization of phosphorus tailings increased slightly during 2000-2011. From 2005 to 2011, the number of published articles showed a slow growth trend, averaging 11 articles per year. In 2006, the number of published articles reached the highest level in this period. At this time, the phosphorus tailings resource utilization research is in the preliminary exploration stage. The research focuses on (1) the harm of tailings to the environment, and (2) treating waste with waste and simply recycling valuable elements. Silva et al. (2010) studied the relationship between particle size and heavy metal content. The content of exchangeable form element Cd in fine-grained tailings is higher than that in coarse-grained phosphorus tailings. Since phosphorus tailings are alkaline, Hakkou et al. (2009) added phosphorus slag to acidic mine wastewater, which effectively reduced the acidity of water and the content of metal elements in water.

The second phase is 2012-2017, a period of fluctuating growth in the number of publications and small ups and downs, with increasing interest in the resource utilization of phosphorus tailings. The period from 2018 to 2023 is the third stage, showing a trend of rapid growth. The growth rate reached the highest in 2018, with the average annual number of articles reaching 80.16. This was due to the increasing attention paid to the development and utilization of medium and low-grade phosphate ore, which resulted in an increasing tailings stock. The destruction of tailings ponds will cause serious environmental problems. Especially in 2019, the Chinese government launched the Yangtze River "three phosphorus" special investigation and rectification action. Various provinces and cities have taken corresponding measures and introduced several relevant policies to rectify the industry. Gnandi et al. (2009) found that phosphorus tailings contained high concentrations of toxic metal ions such as Cr, Cd, Cu, V, Ni, and Zn, which would cause serious pollution to soil, groundwater, and surface water. For residents living downstream of the tailing's ponds, there is a risk of health hazards from drinking water contaminated with heavy metals and transmission through the food chain (Bouka et al., 2013). Therefore, the treatment of phosphorus tailings is particularly important, and the resource utilization of phospho-

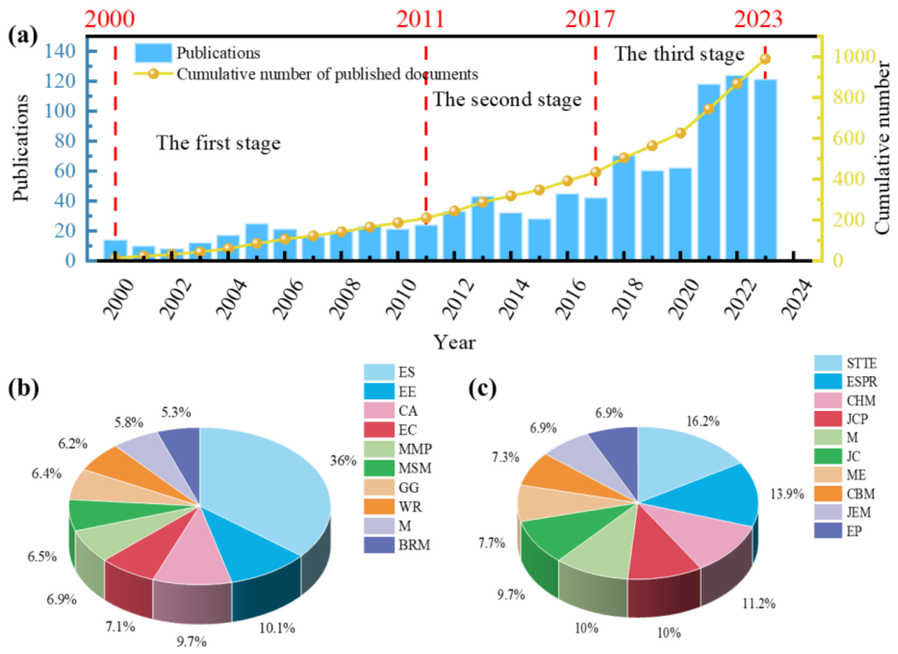


Fig. 2. (a) Changes in the number of publications on research on integrated utilization of phosphorus tailings resources from 2000 to 2023; (b) Top 10 subject categories. ES stands for Environmental Sciences, EE stands for Engineering Environmental, CA stands for Chemistry Analytical, EC for Engineering Chemical, MMP for Mining Mineral Processing, MSM for Materials Science Multidisciplinary, GG for Geochemistry Geophysics, WR for Water Resources, M for Mineralogy, BRM for Biochemical Research Methods; (c) Top 10 productive journals. STTE stands for Science of the Total Environment, ESPR stands for Environmental Science and Pollution Research, Chm stands for Chemosphere, JCP stands for Journal of Cleaner Production, M stands for Minerals, JC stands for Journal of Chromatography A, ME stands for Minerals Engineering, CBM stands for Construction and Building Materials, JME for Journal of Environmental Management, and EP stands for Environmental Pollution

rus tailings is paid more and more attention. This includes the preparation of highly effective soil amendments using microbial-modified phosphorus tailings (Jin et al., 2023). Phosphorus and calcium were recovered from phosphorus tailings by the hydrochloric acid leaching-precipitation method (Yu and Du, 2023). In general, the research of phosphorus tailings resource utilization has made remarkable progress after long-term development.

To conduct a detailed bibliometric analysis of this research field, the collected 989 articles were statistically analyzed in terms of disciplinary categories. Figure 2(b) shows the top 10 disciplinary categories in terms of the number of articles issued in the research field of phosphorus tailings resource utilization, whereas Table 1 lists the specific information of the top 10 disciplinary directions. The discipline of environmental science has the highest number of articles with 384 (38.83%), followed by engineering environment with 108 (10.92%), chemical analysis with 104 (10.52%), and engineering chemistry with 76 (7.68%). The top three disciplines are environmental science, engineering environment, and chemical analysis, which indicates that the research on resource utilization of phosphorus tailings focuses on environmental protection.

3.2. Analysis of co-cited and highly cited articles in the literature

3.2.1. Literature co-citation analysis

Literature co-citation analysis can be used to know the evolution of the research field by analyzing the structure (Xu et al., 2023). The Top N value is set to 50. The paths are pruning the sliced network and pruning the merged network. Figure 3 shows the visualized network mapping of literature co-citation with a total of 5781 nodes and 18828 connecting lines. Among them, the larger the nodes indicate that the literature is more important and closely related to the research field, and the thicker the connecting lines between the nodes explain the closer the connection and the higher the co-citation frequency. As can be seen in Fig. 3, the distribution of the literature co-citation time network is seen to be mainly divided into left, middle, and right segments, indicating that the knowledge structure of phosphorus tailings resource utilization has changed significantly from 2000 to 2023.

Table 1. Top 10 most productive subject categories during 2000-2023

Subject categories	Publications	Percentage (%)
Environmental Sciences	384	38.83
Engineering Environmental	108	10.92
Chemistry Analytical	104	10.52
Engineering Chemical	76	7.68
Mining Mineral Processing	74	7.48
Materials Science Multidisciplinary	69	6.98
Geochemistry Geophysics	68	6.88
Water Resources	66	6.67
Mineralogy	62	6.27
Biochemical Research Methods	57	5.76

Table 2. Top 10 most productive journals during 2000-2023

Rank	Journal	Publications	H-index	Citations	Average citation per paper	Year
1	Science of The Total Environment	42	353	1038	24.71	2005
2	Environmental Science and Pollution Research	36	179	801	22.25	2012
3	Chemosphere	29	311	1011	34.86	2002
4	Journal of Cleaner Production	26	309	938	36.08	2017
5	Minerals	26	58	312	12	2013
6	Journal of Chromatography A	25	250	760	30.4	2000
7	Minerals Engineering	20	136	387	19.35	2000
8	Construction and Building Materials	19	259	441	23.21	2015
9	Environmental Pollution	18	301	998	55.44	2002
10	Journal of Environmental Management	18	243	606	33.67	2013

The cluster analysis of co-cited literature can reflect the evolution law of the topic of the research field and find the potential knowledge structure of the research field. The clustering analysis of the co-cited literature network was carried out by using Citespace, and 15 clusters were extracted by filtering out the clusters with a small number of nodes. The clustering algorithm selects the log-likelihood ratio (LLR). The co-cited clustering information is shown in Table 3. The value of the clustering module was 0.9743, and the average profile value was 0.9839, which indicated that the reliability of the clusters was good. As can be seen from the co-cited clustering diagram in Fig. 4, the structural changes in the knowledge of phosphorus tailings resource utilization are mainly from focusing on its mineralogical and geochemical characteristics. It includes the migration mechanism of pollutants in the environment, the initial recovery of their useful components (#0, #3, #8, #10, #12), to the preparation and application of functional materials (#6, #2, #17). This shows the development of multidisciplinary cross-fertilization of phosphorus tailings resource utilization research and a gradual increase in the number of research topics, from the initial simple recovery of phosphorus to the study of waste for waste or the preparation and application of multifunctional materials

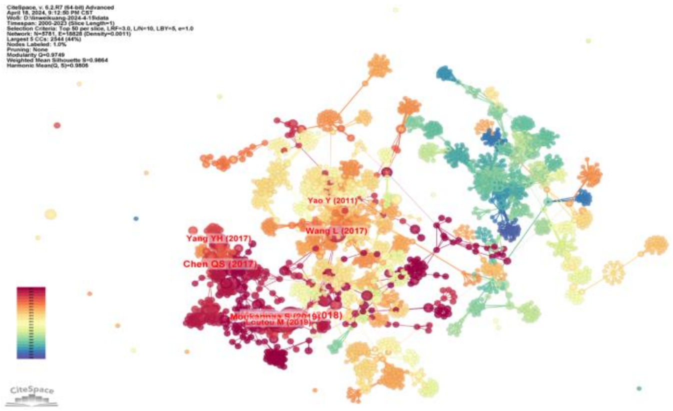


Fig. 3. Literature co-citation network of phosphorus tailings resource utilization during the period of 2000-2023

The cluster analysis of co-cited literature can reflect the evolution law of the topic of the research field and find the potential knowledge structure of the research field. The clustering analysis of the co-cited literature network was carried out by using Citespace, and 15 clusters were extracted by filtering out the clusters with a small number of nodes. The clustering algorithm selects the log-likelihood ratio (LLR). The co-cited clustering information is shown in Table 3. The value of the clustering module was 0.9743, and the average profile value was 0.9839, which indicated that the reliability of the clusters was good. As can be seen from the co-cited clustering diagram in Fig. 4, the structural changes in the knowledge of phosphorus tailings resource utilization are mainly from focusing on its mineralogical and geochemical characteristics. It includes the migration mechanism of pollutants in the environment, the initial recovery of their useful components (#0, #3, #8, #10, #12), to the preparation and application of functional materials (#6, #2, #17). This shows the development of multidisciplinary cross-fertilization of phosphorus tailings resource utilization research and a gradual increase in the number of research topics, from the initial simple recovery of phosphorus to the study of waste for waste or the preparation and application of multifunctional materials.

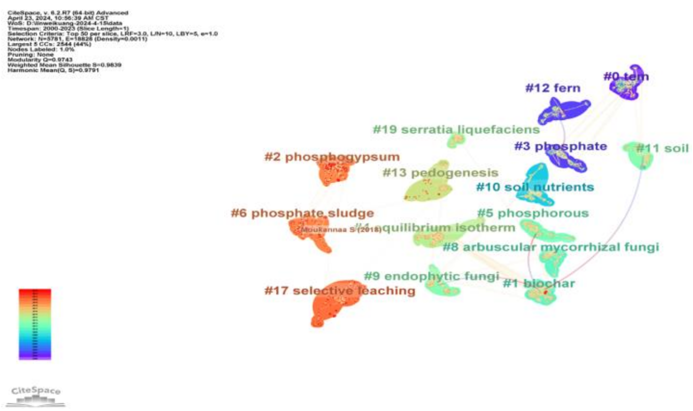


Fig. 4. Clustering mapping of co-cited reference networks

3.2.2. Analysis of highly cited articles

Highly cited articles are representative of the articles in a research field and have a significant impact

Table 3. Clustering information of co-cited references

Cluster-ID	Size	Silhouette	Year	Label (LLR)
0	229	0.968	2001	tem; sem; stormwater; combined sewer overflow; speciation
1	210	0.957	2010	biochar; sorption; nanocomposite; nanocomposites; model
2	136	0.989	2018	phosphogypsum; phosphate tailings; cemented paste backfills; fluoride; layered double hydroxides
3	135	0.978	2002	phosphate (p); soil washing; brassica juncea; liming; tailing waters
4	135	0.985	2013	equilibrium isotherm; granulation; ferric oxides; phosphorus removal; kinetics
5	126	0.988	2010	phosphorous; batch mode; pumice; adsorption; phytoremediation
6	116	0.954	2018	phosphate sludge; geopolymers; valorization; compressive strength; calcination
8	93	1	2009	arbuscular mycorrhizal fungi; c: n: p stoichiometry; revegetation; multiple scales; rare earth elements of mine tailings
9	92	0.989	2012	endophytic fungi; Pb/Zn soil contamination; leaching; soil health; experimental scales
10	87	0.984	2006	soil nutrients; opencast coal mining; velvetgrass; iron; quarry
11	86	0.995	2010	soil; cd; immobilization remediation; ferrihydrite; Pb
12	84	1	2002	fern; pityrogramma calomelanos; arsenic; melastoma malabathricum; pteris vittata
13	81	0.983	2014	pedogenesis; soil enzymes; plant mineral nutrition; chronosequence; soil weathering
17	69	0.997	2020	selective leaching; psb; bacillus subtilis; SiO_2-3CaO
19	64	0.997	2012	serratia liquefaciens; ammonia-oligotrophic; heavy metal resistance; nitrogen fixation; mine tailings

on the development of that research field. The top 10 cited publications were filtered according to the total citation frequency, as shown in Table 4. TOP4 references are as follows: phosphogypsum and phosphorus tailings are used in cemented filling. This paper has been cited 134 times, indicating that this research has made a breakthrough compared with the traditional cemented filling of phosphorus tailings alone, and realized the simultaneous utilization of the two wastes. Geopolymer materials were successfully prepared by partially replacing fly ash and kaolin with phosphorus tailings. The paper has been cited 109 times, which provides a new research idea for the preparation of geopolymers from phosphorus tailings. The paper on the thermal stability, mechanical properties, and microstructure of geopolymer synthesized from alkaline phosphorus tailings has been cited 81 times. Among the publications with TOP 10 citations, the main research directions are (1) material preparation, such as the preparation of geopolymers, cement, and cemented fillers; (2) phosphorus tailings resource recycling, such as tailings reelection, recovery of phosphorus, and rare earths; and (3) utilization of phosphorus tailings to achieve the waste for waste. For example, the use of alkaline phosphorus tailings to treat acidic wastewater produced by magnetite pyrite tailings and mineralogical studies of clay-rich phosphorus tailings to maximize the resource utilization of this type of phosphorus tailings resources.

3.3. Analysis of countries, regions, institutions, and authors

3.3.1. Countries, regions analyzed

Using VOSviewer to extract the country/region information in the WOS database, there are a total of 80 countries/regions, in which the minimum number of articles sent by a country, is set to 5, and the minimum number of citations for a country is set to 0. 40 countries satisfy the thresholds, of which 39

Table 4. Top 10 articles cited in the literature on phosphorus tailings resource utilization

Title of article	Journal	Citation	Year	DOI	Author
Utilization of phosphogypsum and phosphate tailings for cemented paste backfill	Journal of Environmental Management	134	2017	10.1016/j.jenvman.2017.06.027	Chen et al.
Recycling of phosphate mine tailings for the production of geopolymers	Journal of Cleaner Production	109	2018	10.1016/j.jclepro.2018.03.094	Moukannaa et al.
Alkaline fused phosphate mine tailings for geopolymer mortar synthesis: Thermal stability, mechanical and microstructural properties	Journal of Non-Crystalline Solids	81	2019	10.1016/j.jnoncrysol.2018.12.031	Moukannaa et al.
Influences of phosphate tailings on hydration and properties of Portland cement	Construction and Building Materials	60	2015	10.1016/j.conbuildmat.2015.08.115	Zheng et al.
Laboratory Evaluation of the Use of Alkaline Phosphate Wastes for the Control of Acidic Mine Drainage	Mine Water and the Environment	52	2009	10.1007/s10230-009-0081-9	Hakkou et al.
Recovery of apatite from flotation tailings	Separation and Purification Technology	48	2011	10.1016/j.seppur.2011.03.015	Oliveira et al.
Utilizing phosphate mine tailings to produce ceramisite	Construction and Building Materials	43	2017	10.1016/j.conbuildmat.2017.08.070	Yang et al.
An innovative method for simultaneous stabilization/solidification of PO43- and F- from phosphogypsum using phosphorus ore flotation tailings	Journal of Cleaner Production	38	2019	10.1016/j.jclepro.2019.06.340	Li et al.
Rare Earth and Phosphorus Leaching from a Flotation Tailings of Florida Phosphate Rock	Minerals	32	2018	10.3390/min8090416	Liang et al.
Mineralogical and geochemical investigation of clay-rich mine tailings from a closed phosphate mine, Bartow Florida, USA	Environmental Geology	30	2008	10.1007/s00254-007-0971-8	Krekeler et al.

countries/regions have cooperative relationships with each other. The top ten countries/regions in terms of the number of articles issued are shown in Table 5. The network diagram of cooperative relations is shown in Fig. 5(a). The country with the highest number of articles issued is China, accounting for 37.310%. The country with the second largest number of articles is the United States, accounting for 13.347%. The third country with the highest number of articles is Canada with 7.887%. The number of articles published in China is 2.795 times more than that of the United States and 4.731 times more than that of Canada. It can be seen from the number of articles that China has invested the most in research related to the resource utilization of phosphorus tailings. As can be seen from Fig. 5(b), the number of published studies on the utilization of phosphorus tailings in China during 2000-2020 shows a trend of fluctuating growth. In 2020-2023, there was a clear surge in the number of articles. At the same time, due to the domestic environmental protection policies in China in recent years, there has been increasing attention to the research on the resource utilization of phosphorus tailings. The analysis of connection intensity (showing the link with this node; the more connections, the higher the connection intensity, suggesting tight cooperation and communication) reveals that China has the most publications, but the gap with the United States is small. From the relationship network, it can be seen that the connectivity between China and other countries is relatively sparse, in which China and the United States have the closest cooperation (the thicker the connectivity line, the closer the cooperation), followed by Australia and the United Kingdom, and the cooperation with other countries is relatively loose; while the United States in addition to the close cooperation with China is also relatively close cooperation with Canada, France, and Australia. According to the results of the analysis of cooperation intensity and cooperation relationship, it can be seen that the number of publications on the resource utilization of phosphorus tailings is related to the phosphorus resource reserves of each country. Although China has the largest number of publications, it still needs to further strengthen cooperation with other countries (e.g., Germany, France, and Spain).

Table 5. Phosphorus tailings resource utilization research field country number of publications and connection intensity

Country or region	Number of publications	Citations	Link strength
China	369	10424	81
USA	132	7660	79
Canada	78	2504	45
India	52	925	11
Australia	45	1087	30
Brazil	43	506	22
Morocco	42	774	34
French	41	1231	37
Spanish	41	793	33
Japan	33	794	9

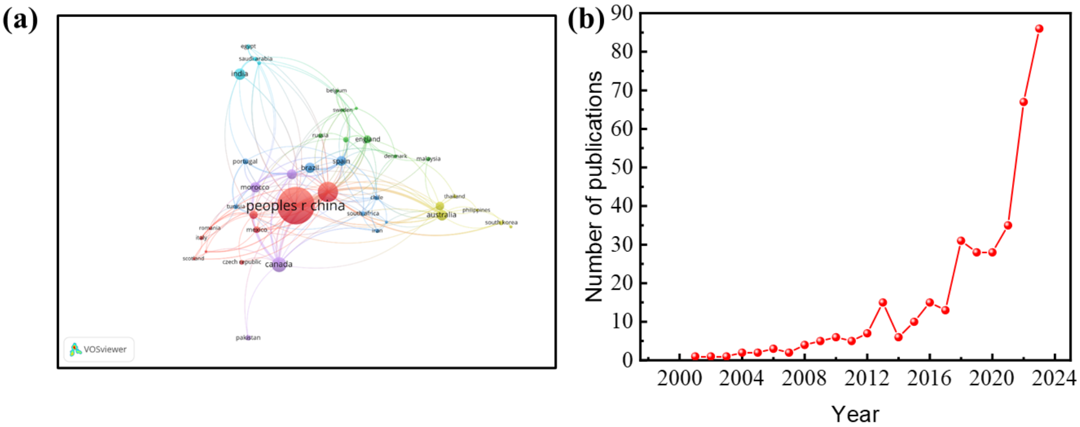


Fig. 5. (a) Network mapping of country/region publication numbers; (b) Trends in the number of publications in China over the period 2000-2023

3.3.2.Analysis of research institutions and authors

The analysis of research institutions identifies the distribution and contribution of research units in the field of research. The authors' analysis can identify the cooperation of researchers in the research field and the authors with more publications, which is an important force in promoting the development and innovation of the research field. In VOSviewer software, 139 authors were extracted by selecting the Author option in Co-authorship, and the minimum number of published articles was set to 3. As shown in Fig. 6(a), the network visualization of the above authors was analyzed. The node size indicates the comparison of the number of published articles, while the connecting line indicates the closeness of the cooperation relationship. As analyzed in Fig. 6(a), the team of Benzaazoua from the University of Quebec has the highest number of publications with 16. Its research areas are acidic wastewater treatment (Ouakibi et al., 2013), non-metallic material preparation (Moukannaa et al., 2018; Oubaha et al., 2023), and other studies of potential economic utilization (Amar et al., 2023; Chlahbi et al., 2023). As can be seen from the authors' collaborative relationships, the research teams mainly show the phenomenon of small aggregation, with authors from the same research team being closely linked and the links between the teams being looser.

As shown in Fig. 6(b), organizations in co-authorship were selected for the analysis of research institution partnerships, and the minimum number of publications was set to 3. A total of 187 institutions met the threshold. Excluding the institutions without partnerships, we get the institutions with partnerships, which is shown in Fig. 6(c). The Chinese Academy of Sciences has the highest number of articles (44) and also has the most connections, indicating that this research institution has the most collaborations with other organizations. Therefore, the institutional network analysis illustrates that the Chinese Academy of Sciences contributes the most to the research field of phosphorus tailings resource utilization, and it also maintains extensive cooperation with other research organizations.

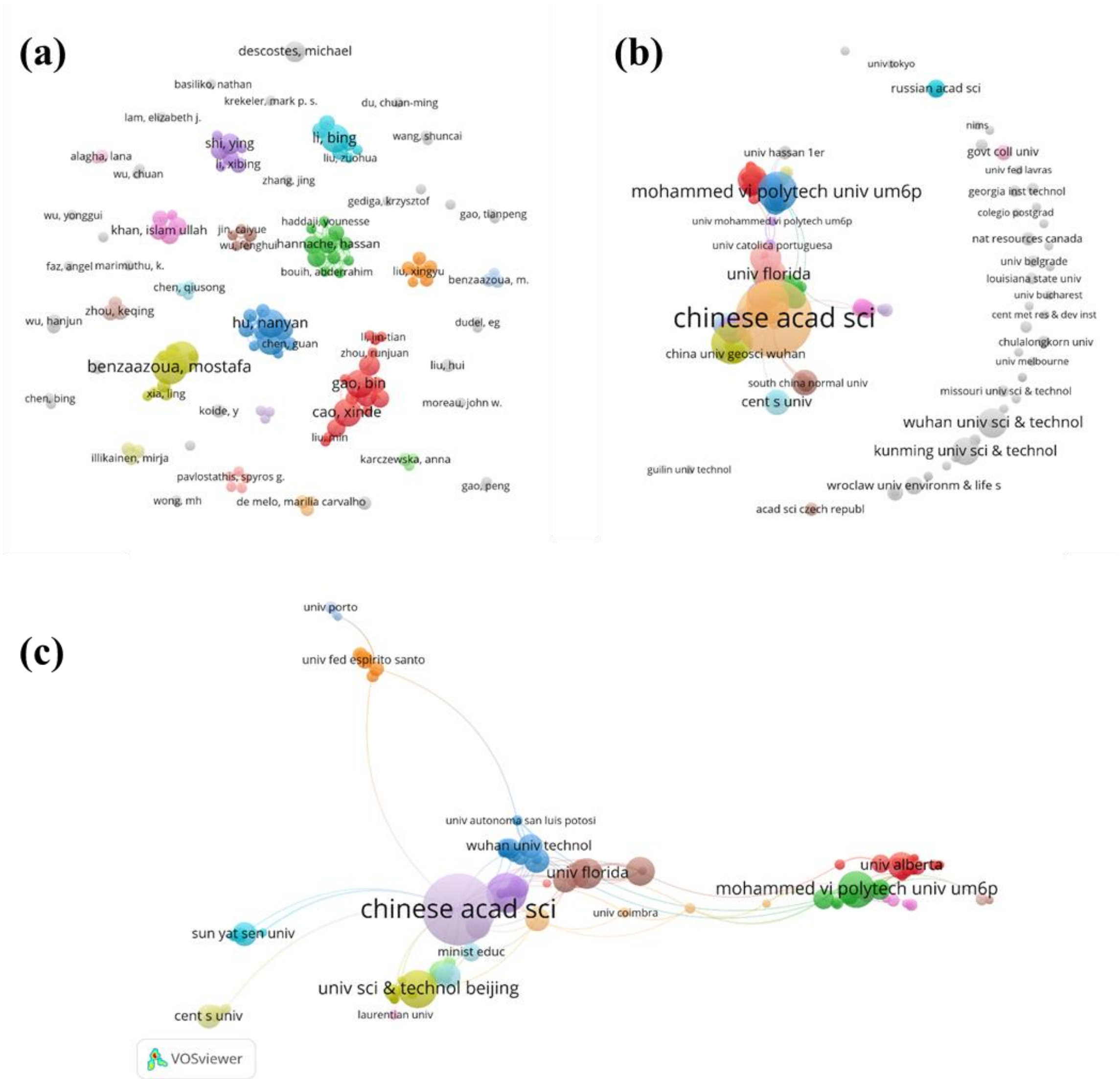


Fig. 6. (a) Author network viewable (b) All organization network viewable (c) Partial organization network viewable

3.4. Analysis of research hotspots

3.4.1. Keyword co-occurrence analysis

Keywords are the author's distillation and summary of the main content of the article, usually used to reflect the research hotspot (Yu et al., 2017). In this paper, we use VOSviewer to perform a co-occurrence analysis of 2784 keywords. The number of occurrences of each keyword is set to 5, and 282 keywords meet the threshold. The keyword co-occurrence network is shown in Fig. 7, where one color represents a cluster, and there are seven clusters in total.

Keywords that appear more frequently in Cluster 1 (red network structure), Cluster 6 (cyan section) and Cluster 7 (orange section) include “phosphorus”, “soil”, “mine tailings”, “toxicity”, “rare-earth-elements”, “geochemistry”, “heavy-metals”, “cadmium”, and “Pb”. This is mainly through mineralogical and geochemical characterization to study the state of valuable elements and the mechanism of migration and toxicity of hazardous substances in soil and other environments. The keywords that appear more frequently in Cluster 2 and Cluster 3 are “recovery”, “separation”, “performance”, “selectivity” and so on. This mainly studies the extraction of valuable elements in phosphorus tailings and its mechanism. For example, rare earth resources are recovered through tailings re-election. Keywords that appear more frequently in Cluster 4 (in yellow) include “strength”, “fly-ash”, “temperature”, “paste backfill”, and so on. “Paste backfill” and so on. This indicates that the main research focuses on the preparation of construction materials and fillers. The keywords that appear more frequently in Cluster 5 are “adsorption”, “flotation”, “mechanism”, “minerals”, “construction materials”, “construction materials” and “filler”. “minerals”, “removal”, “water”, “phosphate “etc. This suggests the study of phosphorus tailings-based adsorption functional materials in the field of environmental remediation and the study of adsorption mechanisms.

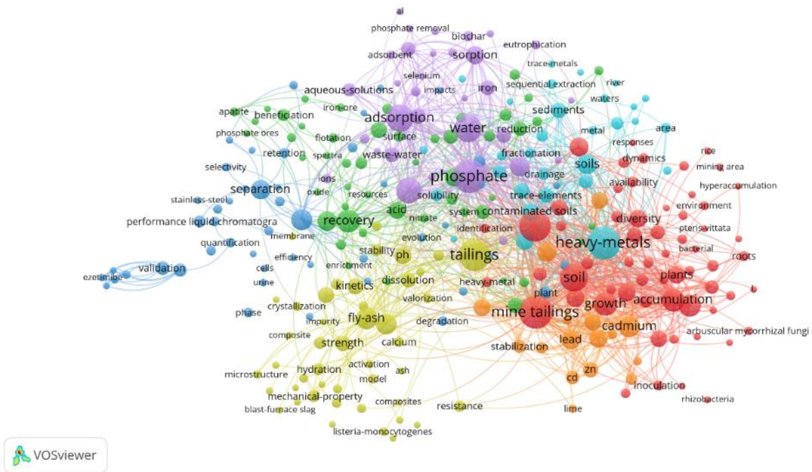


Fig. 7. Keyword network co-occurrence map

3.4.2. Keywords burst analysis

The burst keywords can clarify the evolution trend and emerging direction of a certain research discipline and research field to accurately analyze the research hotspots. As shown in Fig. 8, from 2002 to 2023, the keywords “adsorption”, “sorption”, “removal” and “kinetics” were highlighted. The eruption time is 2018, which indicates that there has been much research on the preparation of adsorption functional materials and adsorption mechanism of phosphorus tailings in the past five years. During the period from 2006 to 2023, the keywords highlighted are “strength”, “compressive strength”, “phosphogypsum “fly ash”. Exploding in 2019, the application of phosphorus tailings in the preparation of building materials has also shown a high level of interest in the past 4 years. Between 2007 and 2023, the keywords “rare earth elements”, “recovery” and “behavior” were emphasized. In addition, the keywords that emerged at the same time include "separation" and "phosphate". This indicates that the research on the recovery and utilization of valuable elements in phosphorus tailings is more enthusiastic.

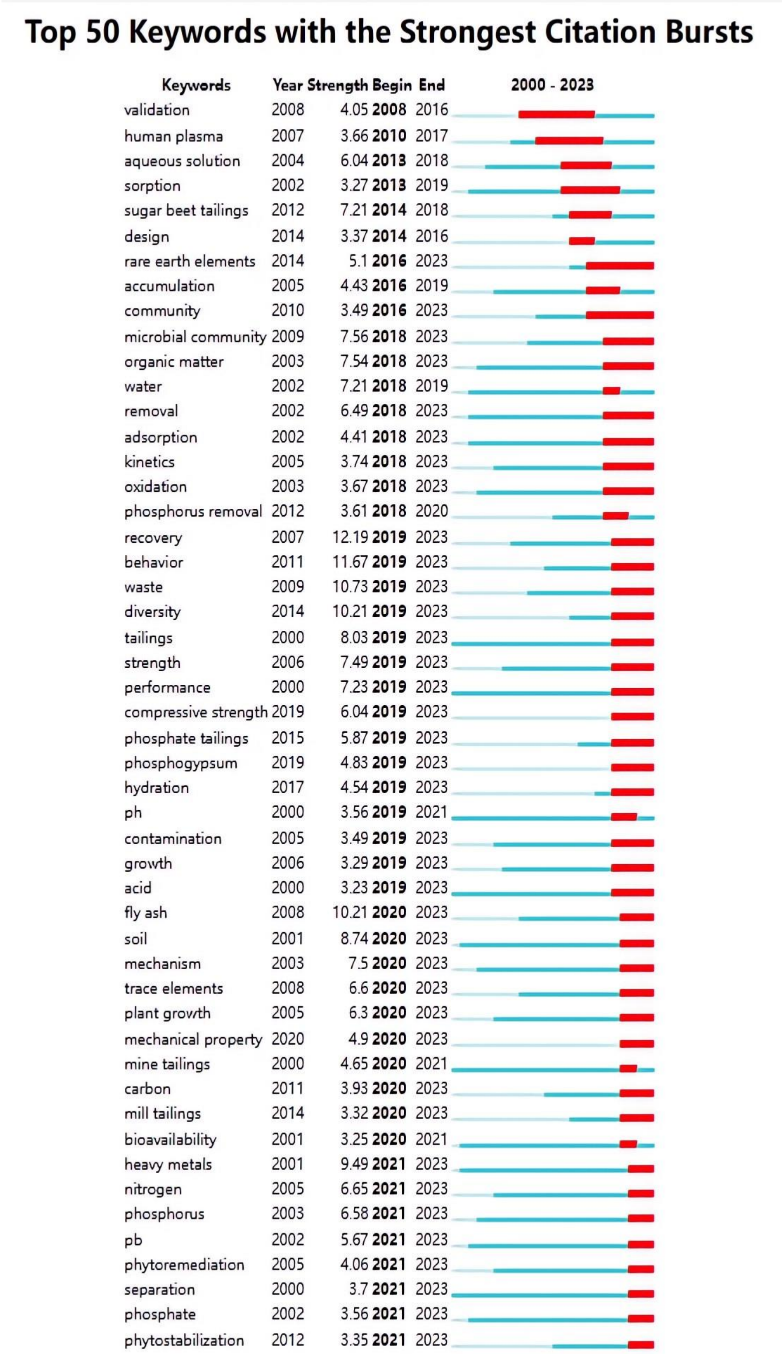


Fig. 8. Analysis of core keyword emergence of phosphorus tailings resource utilization research

4. Research trends analysis

Through the network visualization of phosphorus tailings resource utilization and the analysis of research hotspots, the research on phosphorus tailings resource utilization is comprehensively outlined, and prospects mainly in three aspects: recovery of valuable elements from phosphorus tailings, preparation of adsorbent functional materials and their adsorption mechanism, and preparation and application research of construction materials.

4.1. Valuable element recovery

After chemical multi-element analysis, the main valuable elements in phosphorus tailings are P, Mg, Ca, and rare earth elements. At present, the extraction of valuable elements in phosphorus tailings is mainly through two processing methods: mineral processing and metallurgy.

The beneficiation method mainly recovers the phosphorus element in phosphorus tailings, but due to fine particle size, it is difficult to achieve effective recovery by the conventional flotation method. Therefore, for the reelection of phosphorus tailings, there are two main research directions: new flotation reagents and new flotation process. At present, for the flotation reagents, there are two methods: the combination of reagents and the development of new reagents. Mixing butylene disulfonate with rice oil soap greatly improves the selectivity of apatite in flotation bubbles and the grade of phosphorus (Oliveira et al., 2011). The research obtained re-elected concentrate with recovery and P_2O_5 content of 46.2% and 29.4%, respectively. Novel inhibitor hybridized polyacrylamide grafted nanoparticles of silicate chalcopyrite minerals were synthesized by Alsafasfeh et al. (2018; 2022). The reagent is an organic-inorganic hybrid polymer. It inhibits silicate minerals by adsorbing on the surface of silicate particles through electrostatic attraction, leading to electrically neutralized flocculation (Fig. 9). Apart from developing flotation reagents, researchers have also improved flotation bubble sizes to increase the grade and recovery of concentrates from phosphorus tailings. Taghavi et al. (2022) used microbubbles and nanobubbles in the mechanical flotation unit to improve the grade and recovery of concentrate. It has also been demonstrated that certain phosphorus tailings contain rare earth elements (Yang et al., 2019). Therefore, the extraction of rare earth elements from phosphorus tailings has also become the research focus. The commonly used extraction method is beneficiation enrichment - wet acid leaching, to get the rare earth-rich extract (Thyabat and Zhang, 2016; Arroug et al., 2021). With the continuous development of low-grade phosphate resources and the increasing fineness of grinding, it is becoming more and more difficult to recover phosphate concentrates through flotation methods. In recent years, researchers have extracted valuable elements such as P, Mg, and Ca from the tailings by synergistic leaching and used them as a source of slow-release fertilizer. The leaching slag can be used to prepare building materials without producing any waste (Yu and Du, 2023; Wu et al., 2023; Jin et al., 2023). Besides the direct extraction of valuable elements from phosphorus tailings, other solid wastes can be utilized to interact with the phosphorus tailings. Yu et al. (2023) used scrap steel slag to remelt with phosphorus tailings to enrich the phosphorus mineral phase. Then selective leaching was performed to extract P, Ca, and Si, which can be used as a source of phosphorus-silicon fertilizer. The mixed slag containing Fe phase was reused in metallurgy.

Therefore, for the recovery of valuable elements in phosphorus tailings, suitable extraction methods can be selected according to the mineral composition, chemical composition, particle size characteristics, and the state of valuable elements in phosphorus tailings. It is worth noting that the closed cycle of the whole extraction process to achieve comprehensive utilization through the waste to waste is the key research direction for the recovery of valuable elements in phosphorus tailings in the future.

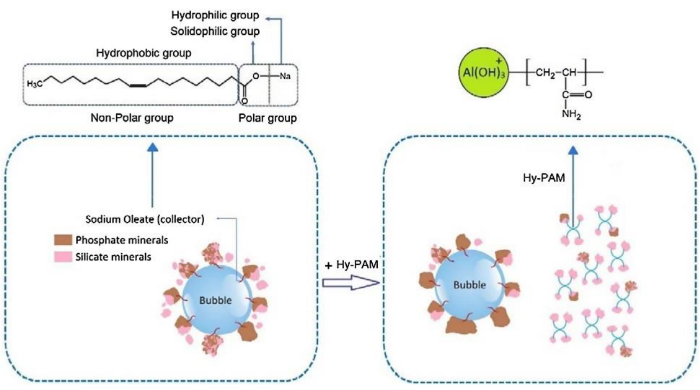


Fig. 9. Mechanism of quartz inhibition by novel hybridized polyacrylamide grafted nanoparticles (Alsafasfeh et al., 2018)

4.2. Research on the preparation and application of phosphorus tailings-based materials

Based on the different chemical and mineralogical compositions of phosphorus tailings, the materials prepared from them are applied for different purposes. Typically, the main components of phosphate tailings are rich in clay minerals, high-silicates, and carbonates, which are commonly used to prepare adsorbent materials and construction materials, demonstrating great potential for application (Idrissi et al., 2021).

4.2.1. Preparation and application of adsorption materials

Various types of minerals such as montmorillonite, quartz, and dolomite in phosphorus tailings can be synthesized into ceramics (Krekeler et al., 2008). It is worth noting that during the calcination process, dolomite decomposes into CaO and CO_2. CaO plays the role of flux. CO_2 increases the porosity of the ceramics, turning ordinary ceramics into porous ceramics, thereby reducing the weight of the ceramics (Skibo et al., 1989; Hajjaji and Mezouari, 2011; Huang et al., 2022; Fu et al., 2023). At the same time, porous ceramics with excellent chemical properties, thermal stability, and low thermal conductivity are considered to be the most promising insulation materials (Duan et al., 2017; Ren et al., 2019). Fu et al. (2023) utilized phosphorus tailings and coal gangue to prepare lightweight foam ceramics by adjusting the roasting time and heating rate. Prolonged roasting time is favorable to the formation of glassy phases and increases the average pore size. A larger heating rate can prevent the ceramics' vitrification. The advantages of lightweight foam ceramics are the very low leaching values of heavy metals and the potential ecological risk. Sun et al. (2023) used phosphorus tailings and bauxite as raw materials to prepare Al_2O_3-SiO_2 porous ceramics. The traditional experimental method requires a large number of tests, while the new method based on a data-driven approach can effectively reduce the number of tests and obtain better target results with high efficiency. A certain dataset is obtained through a small number of tests, and then a regression algorithm is employed to predict the performance characteristics of the ceramics (Fig. 10). The random forest algorithm was found to be suitable for the small sample data set, and the database was constructed using the model of the algorithm. Finally, the experimental program with ideal performance was obtained through the screening of the database. Porous ceramics can be prepared as adsorbent materials due to their rich porosity and low risk of heavy metal leaching (Hu et al., 2023). Lv et al. (2023) modified porous ceramic grains at 70°C using a NaCl solution of 1 mol/dm^3. The modified porous ceramic grains showed micropores and 99% removal of Ag^+ from water.

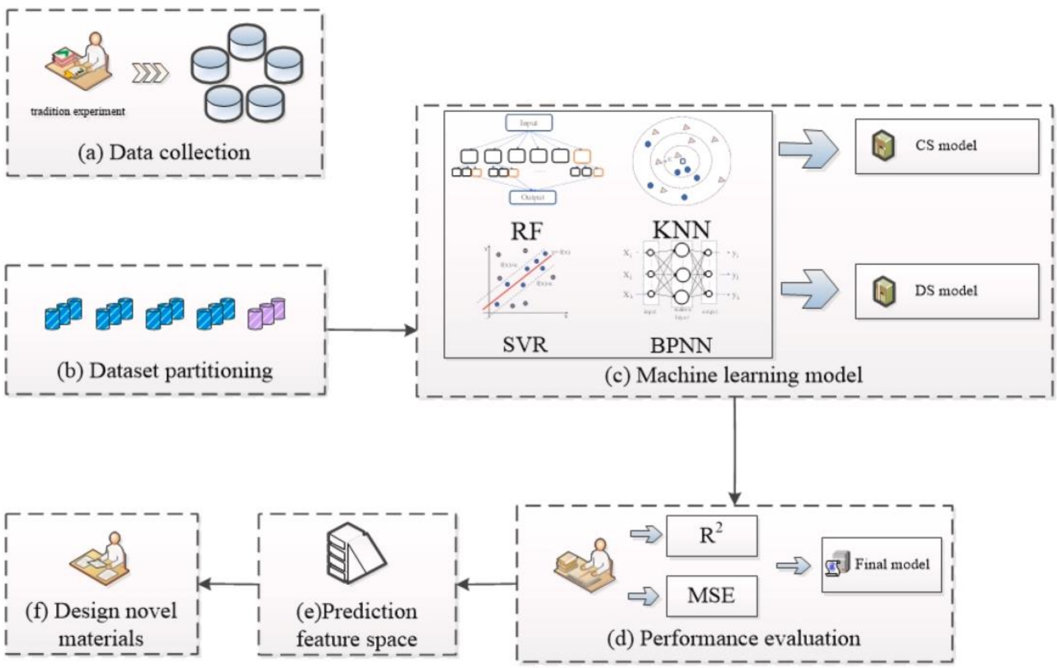
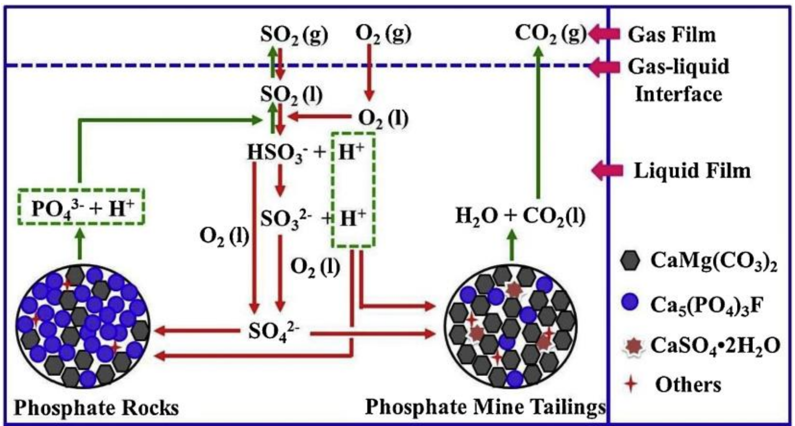


Fig. 10. Design of porous ceramic model framework with small sample machine learning (Sun et al., 2023)

In addition to the use of modified porous ceramics as adsorbent materials, efficient adsorbents can be prepared directly from phosphorus tailings along with other materials. Add phosphate tailings, phosphogypsum, and starch to deionized water in proportions and mix until the solution becomes thick. After drying, it was calcined at 400°C to produce a porous phosphate adsorbent material (Jiang et al., 2023). The adsorbent contained large quantities of calcium sulphate, magnesium oxide, iron oxide, calcium oxide, and silicate. These compounds stimulate phosphate adsorption to a greater level. Phosphorus tailings mixed with wood chips and peanut shells after co-pyrolysis can be created with the adsorption of a variety of metal ions biochar (Yang et al., 2022). Heavy metal ions have been demonstrated to attach to -COOH and -OH on biochar while also reacting with PO_3^- and $P_2O_7^{4+}$ to create precipitates. Notably, hydroxyapatite, with its ability to absorb and solidify heavy metal ions, can also be employed to remediate heavy metal-contaminated soils (Wu et al., 2023). Some studies have discovered that phosphate tailings, due to their high carbonate mineral content, can be employed as an effective adsorbent. Nie et al. (2020) employed a blend of phosphate tailings and deionized water as a sorbent for SO_2. The study found that dolomite in phosphate tailings can improve the desulfurization effect, while Mg^{2+}, Mn^{2+}, and Fe^{3+} in the solution can accelerate the catalytic oxidation of S(IV) and improve the desulfurization effect (Fig. 11). Wu et al. (2023) tested $H_2C_2O_4$ and $Na_2C_2O_4$ modified phosphorus tailings for Mn^{2+} and NH_4^+-N sorption. Mn^{2+} was removed by precipitation, but NH_4^+-N was primarily removed through adsorption and ion exchange using $MgNaPO_4$-$6H_2O$ and $MgHPO_4$-$3H_2O$.



$$SO_2(g) \leftrightarrow SO_2(aq) \quad (1) \qquad SO_2(aq)+H_2O \leftrightarrow H_2SO_3 \quad (2)$$

$$H_2SO_3 \leftrightarrow H^+ + HSO_3^- \quad (3) \qquad HSO_3^- \leftrightarrow H^+ + SO_3^{2-} \quad (4)$$

$$2HSO_3^- + O_2 \rightarrow 2H^+ + 2SO_4^{2-} \quad (5) \qquad 2SO_3^{2-} + O_2 \rightarrow 2SO_4^{2-} \quad (6)$$

$$CaMg(CO_3)_2 + 4H^+ + 2SO_4^{2-} \rightarrow CaSO_4{\cdot}2H_2O\downarrow + Mg^{2+} + SO_4^{2-} + 2CO_2\uparrow \quad (7)$$

$$Ca_5(PO_4)_3F + 10H^+ + 5SO_4^{2-} + 10H_2O \rightarrow 5CaSO_4{\cdot}2H_2O\downarrow + 10H^+ + 3PO_4^{3-} + F^- \quad (8)$$

$$Ca^{2+} + SO_4^{2-} + 2H_2O \rightarrow CaSO_4{\cdot}2H_2O\downarrow \quad (9)$$

$$CaMg(CO_3)_2 + 4H_3PO_4 \rightarrow Ca(H_2PO_4)_2 + Mg(H_2PO_4)_2 + 2CO_2\uparrow + 2H_2O \quad (10)$$

$$Ca_5(PO_4)_3F + 7H_3PO_4 \rightarrow 5Ca(H_2PO_4)_2 + HF \quad (11)$$

$$5Ca(H_2PO_4)_2 + 5H_2SO_4 + 10H_2O \rightarrow 10H_3PO_4 + 5CaSO_4{\cdot}2H_2O\downarrow \quad (12)$$

Fig. 11. Mechanism diagram of desulfurization of phosphate ore and phosphorus tailings as adsorbents respectively (Nie et al., 2020)

In summary, there are two primary methods for producing adsorption functional materials from phosphate tailings: modifying porous materials to adsorb heavy metal ions and adsorbing acidic pollutants directly from the phosphate tailings or by physical and chemical treatment. The use of modern research techniques in the creation of adsorbent functional materials, such as artificial intelligence and machine learning, will also be a future trend. At the same time, the cost of preparing effective materials for the adsorption of radioactive polluted wastewater is significant, such as the modified adsorption of radioactive elements in porous ceramics. However, the utilization of phosphorus tailings and a variety of waste-synergistically generated functional materials for the treatment of radioactively polluted wastewater is an important research avenue to minimize the cost of waste-to-waste.

4.2.2. Preparation and application of building materials

SiO_2 from phosphorus tailings has the potential to be active. Under alkali excitation, it can generate C-S-H gelation products and act as a filler. Simultaneously, calcium oxide in phosphorus tailings can activate SiO_2 (Luan et al., 2019). Gu et al. (2022b) used high-temperature calcination to produce magnesium sulfate cement. Dolomite breakdown products at different calcination temperatures have varying effects on cement strength. Calcination around 700-750°C produces magnesium calcite, brucite, and calcite, whereas beyond 1000°C produces brucite and lime. However, in the reaction system, brucite creates $5Mg(OH)_2$-$MgSO_4$-$7H_2O$, which gives strength together with gypsum and unreacted phosphorus tailings.

Gu et al. (2022) used high-temperature calcination to produce magnesium sulfate cement. Dolomite breakdown products at different calcination temperatures have varying effects on cement strength. Calcination around 700-750°C produces magnesium calcite, brucite, and calcite, whereas beyond 1000°C produces brucite and lime. However, in the reaction system, brucite creates $5Mg(OH)_2$-$MgSO_4$-$7H_2O$, which gives strength together with gypsum and unreacted phosphorus tailings. In addition, some researchers have employed acidic wastewater and phosphorus tailings to make magnesium sulfate cement. F^- in acidic wastewater can be immobilized with cement. Phosphorus in phosphorus tailings contributes to the production of $5Mg(OH)_2$-$MgSO_4$-$7H_2O$ (Chen et al., 2022). The process consumes a large amount of waste and also reduces production costs. The procedure consumes a huge quantity of trash and reduces manufacturing costs. The researchers have also conducted systematic investigations on the synthesis of various types of cementitious materials and the parameters that influence compressive strength. For example, a study on the influence of phosphogypsum and water-cement ratio on the strength qualities and high-temperature resistance of phosphorus tailings-based magnesium sulfate cement (Gu et al., 2023; Zheng et al., 2015). Hamdane et al. (2021; 2023) produced geopolymers from ultrafine phosphorus tailings after activation with NaOH and KOH. This approach substituted 50% of roasted kaolin and achieved a compressive strength of 50 MPa.

The use of phosphorus tailings to make filler materials for mine empty regions is another major research topic. This process can utilize a significant amount of phosphorus tailings, reducing stockpiles. Phosphorus tailings can replace some of the gelling agents, increasing compressive strength. As a result, phosphate tailings and other solid wastes are typically mixed to create cemented filler materials. Chen et al. (2017) studied the role of phosphogypsum and phosphorus tailings in cemented filling. It was discovered that phosphogypsum and phosphorus tailings can be utilized as backfill materials by combining Portland cement as a binder with CaO as an additive. Mei et al. (2019) used phosphorus tailings and water treatment sludge (coarse aggregate) to create a cemented paste filler. The results showed that the compressive strength increased with the increase of coarse aggregate and phosphorus tailings content when the phosphorus tailings content of -20 μm was within 25%. Furthermore, phosphorus tailings offer significant promise in sintered brick preparation (Loutou et al., 2019; Ettoumi et al., 2020).

Research on the use of phosphorus tailings in building materials has shown that there is significant potential for lowering tailings stockpiles and maximizing resource utilization. It is worth mentioning that acceptable proportioning and cost remain the most important determining criteria for successful utilization. The ratios of different materials have a direct impact on the performance of cementitious materials. Future research should focus on the circumstances and mechanisms for the synergistic preparation of cementitious materials from phosphorus tailings and other wastes. Not only does it meet material specifications, but it also lowers production costs and simplifies the synthesis process.

5. Conclusion and prospect

The combination of bibliometrics and the knowledge graph visualization function of VOSviewer and CiteSpace enables researchers to visualize research results and research trends on the utilization of phosphorus tailings during the period 2000-2023. During this period, there was an overall growth trend in the number of publications related to the utilization of phosphate tailings. In order to realize the high-value utilization of phosphorus tailings, researchers have explored ways to mix phosphorus tailings with other wastes, extract valuable elements at the same time, and jointly synthesize efficient adsorption functional materials and building materials. Among them, treating waste with waste is also the research hotspot and trend of resource utilization of phosphorus tailings in recent years.

Significantly, advanced methodologies such as artificial intelligence and machine learning promise to accelerate further advancements in this research domain. Techniques such as flocculation flotation and micro/nano bubble flotation hold promise for enhancing the recovery of phosphorus concentrate from tailings and merit deeper investigation. Concurrently, the pyro-hydrometallurgical processes for recovering Ca, Mg, Fe, and rare earth elements from phosphorus tailings require further exploration of their mechanisms and operational efficiencies.

In the process of extracting valuable elements from phosphorus tailings, the primary objective is to minimize the generation of secondary waste. This necessitates not only further research in order to optimize the process and elucidate the underlying mechanisms, but also the investigation of innovative applications for the secondary waste products generated following the recovery of the valuable elements. The potential of utilizing phosphorus tailings in the production of building materials offers a compelling avenue to reduce inventory and maximize resource utilization. However, addressing gaps such as long-term environmental monitoring and toxicity testing of materials necessitates further optimization of synthetic conditions and mechanistic analysis.

References

ABOUZEID, A., El-JALLAD, I., ORPHY, M., 1980. *Calcareous phosphates and their calcined products*. Minerals Science and Engineering. 12, 73-83.

ABOUZEID, A., 2008. *Physical and thermal treatment of phosphate ores — An overview*. International Journal of Mineral Processing. 85, 59-84.

ALSAFASFEH, A., KHODAKARAMI, M., ALAGHA, L., MOATS, M., MOLATLHEGI, O., 2018. *Selective depression of silicates in phosphate flotation using polyacrylamide-grafted nanoparticles*. Minerals Engineering. 127, 198-207.

ALSAFASFEH, A., ALAGHA, L., ALZIDANEEN, A., NADENDLA, V.S.S., 2022. *Optimization of flotation efficiency of phosphate minerals in mine tailings using polymeric depressants: Experiments and machine learning*. Physicochemical Problems of Mineral Processing. 58, 150477.

AL-THYABAT, S., ZHANG, P., 2016. *Extraction of rare earth elements from upgraded phosphate flotation tailings*. Minerals and Metallurgical Processing. 33, 23-30.

AMAR, H., BENZAAZOUA, M., ELGHALI, A., TAHA, Y., EL GHORFI, M., KRAUSE, A., HAKKOU, R., 2023. *Mine waste rock reprocessing using sensor-based sorting (SBS): Novel approach toward circular economy in phosphate mining*. Minerals Engineering. 204, 108415.

ARROUG, L., ELAATMANI, M., ZEGZOUTI, A., AITBABRAM, M., 2021. *Low-grade phosphate tailings beneficiation via organic acid leaching: process optimization and kinetic studies*. Minerals. 11, 492.

BABEL, S., CHAUHAN, R., ALI, N., YADAV, V. 2016. *Preparation of phosphate mine tailings and low grade rock phosphate enriched bio-fertilizer*. Journal of Scientific and Industrial Research, 75, 120-123.

BOUKA, E., LAWSON-EVI, P., EKLU-GADEGBEKU, K., AKLIKOKOU, K., GBÉASSOR, M., 2013. *Heavy metals concentration in soil, water, Manihot esculenta tuber and Oreochromis niloticus around phosphates exploitation area in Togo*. Research Journal of Environmental Toxicology. 7, 18.

CHEN, Q., ZHANG, Q., FOURIE, A., XIN, C., 2017. *Utilization of phosphogypsum and phosphate tailings for cemented paste backfill*. Journal of Environmental Management. 201, 19-27.

CHEN, C., 2004. *Searching for intellectual turning points: Progressive knowledge domain visualization*. Proceedings of the National Academy of Sciences. 101, 5303-5310.

CHIU, Y., LI, Y., 2016. *Study on heavy metal characteristics of soil in phosphorus tail*. Journal of Residuals Science and Technology. 13, 1-7.

CHLAHBI, S., BELEM, T., ELGHALI, A., ROCHDANE, S., ZEROUALI, E., INABI, O., BENZAAZOUA, M., 2023. *Geological and geomechanical characterization of phosphate mine waste rock in view of their potential civil applications: a case study of the Benguerir mine site, Morocco*. Minerals. 13, 1291.

DUAN, P., SONG, L., YAN, C., REN, D., LI, Z., 2017. *Novel thermal insulating and lightweight composites from metakaolin geopolymer and polystyrene particles*. Ceramics International. 43, 5115-5120.

ETTOUMI, M., JOUINI, M., NECULITA, C.M., BOUHLEL, S., BENZAAZOUA, M., 2020. *Characterization of phosphate processing sludge from Tunisian mining basin and its potential valorization in fired bricks making*. Journal of Cleaner Production. 124750.

FU, F., HU, N., YE, Y., CHEN, G., 2023. *The foaming mechanism and properties of SiO_2–Al_2O_3–CaO-based foamed ceramics with varied foaming agents*. Ceramics International. 49, 32448-32457.

FU, F., HU, N., YE, Y., CHEN, G., JIA, J., 2023. *Production of lightweight foam ceramics by adjusting sintering time and heating rate*. Construction and Building Materials. 394, 132063.

GNANDI, K., REZAIE BOROON, M., EDORH, P., 2009. *The Geochemical characterization of mine effluents from the phosphorite processing plant of Kpémé (Southern Togo)*. Mine Water and the Environment. 28, 65-73.

GU, K., LANG, L., LI, D., CHEN, B., 2022. *Preparation of magnesium oxysulfate cement with calcined phosphate tailings*. Journal of Materials in Civil Engineering. 34, 04022358.

GU, K., CHEN, B., YAN, P., WANG, J., 2022. *Recycling of phosphate tailings and acid wastewater from phosphorus chemical industrial chain to prepare a high value-added magnesium oxysulfate cement*. Journal of Cleaner Production. 369, 133343.

GU, K., CHEN, B., JIANG, Z., 2023. *Properties and high-temperature resistance of tailing-based magnesium oxysulfate (MOS) cement affected by phosphogypsum and water-binder ratio*. Construction and Building Materials. 405, 133341.

HAJJAJI, M., MEZOUARI, H., 2011. *A calcareous clay from Tamesloht (Al Haouz, Morocco): Properties and thermal transformations*. Applied Clay Science. 51, 507-510.

HAKKOU, R., BENZAAZOUA, M., BUSSIÈRE, B., 2009. *Laboratory evaluation of the use of alkaline phosphate wastes for the control of acidic mine drainage*. Mine Water and the Environment. 28, 206-218.

HAMDANE, H., TAMRAOUI, Y., MANSOURI, S., OUMAM, M., BOUIH, A., EL GHAILASSI, T., BOULIF, R., MANOUN, B., HANNACHE, H., 2021. *Statistical modeling of geopolymers from dual-alkali activation of un-calcined phosphate sludge and their potential applications as sustainable coating materials*. Journal of Cleaner Production. 283, 125421.

HAMDANE, H., OUMAM, M., MHAMDI, H., BOUIH, A., EL GHAILASSI, T., BOULIF, R., ALAMI, J., MANOUN, B., HANNACHE, H., 2023. *Elaboration of geopolymer package derived from uncalcined phosphate sludge and its solidification performance on nuclear grade resins loaded with 134Cs*. Science of The Total Environment. 857, 159313.

HU, N., LV, Y., LUO, B., YE, Y., FU, F., JIA, J., OU, Z., LI, J. 2023. *Preparation and performance of porous ceramsite for Ag^+ removal in sewage treatment with total phosphorus tailings*. Journal of Cleaner Production, 413, 137515.

HUANG, Y., HU, N., YE, Y., OU, Z., SHI, X., 2022. *Preparation and pore-forming mechanism of MgO–Al_2O_3–CaO-based porous ceramics using phosphorus tailings*. Ceramics International. 48, 29882-29891.

IDRISSI, H., TAHA, Y., ELGHALI, A., EL KHESSAIMI, Y., ABOULAYT, A., AMALIK, J., HAKKOU, R., BENZAAZOUA, M., 2021. *Sustainable use of phosphate waste rocks: From characterization to potential applications*. Materials Chemistry and Physics. 260, 124119.

JIANG, W., JIANG, Y., LI, P., LIU, D., REN, Y., LI, D., LIU, Z., CHEN, Y., YE, Y., 2023. *Reuse of phosphogypsum and phosphorus ore flotation tailings as adsorbent: The adsorption performance and mechanism of phosphate*. The Journal of Physics and Chemistry of Solids. 178, 111313.

JIN, C., CHEN, B., QU, G., QIN, J., YANG, J., LIU, Y., LI, H., WU, F., HE, M., 2023. *$NaHCO_3$ synergistic electrokinetics extraction of F, P, and Mn from phosphate ore flotation tailings*. Journal of Water Process Engineering. 54, 104013.

JIN, C., YANG, J., CHEN, B., QU, G., LI, H., WU, F., LIU, X., LIU, Y., KUANG, L., LI, J., 2023. *Soilization utilization of solid waste: Ecological regulation of phosphorus tailings-based soil with physicochemical improvement and Bacillus_cereus-addition*. Environmental Research. 236, 116856.

KARUNARATHNA, M.H.J.S., HATTEN, Z.R., BAILEY, K.M., LEWIS, E.T., MORRIS, A.L., KOLK, A.R., LAIB, J.C., TEMBO, N., WILLIAMS, R.A., III, PHILLIPS, B.T., ASH, B.L., MIDDEN, W.R., OSTROWSKI, A.D., 2019. *Reclaiming phosphate from waste solutions with Fe(iii)–polysaccharide hydrogel beads for photo-controlled-release fertilizer*. Journal of Agricultural and Food Chemistry. 67, 12155-12163.

KHELIFI, F., MOKADEM, N., LIU, G., YOUSAF, B., ZHOU, H., NCIBI, K., HAMED, Y., 2022. *Occurrence, contamination evaluation and health risks of trace metals within soil, sediments and tailings in southern Tunisia*. International Journal of Environmental Science and Technology. 19, 6127-6140.

KINNUNEN, P., ISMAILOV, A., SOLISMAA, S., SREENIVASAN, H., RÄISÄNEN, M., LEVÄNEN, E., ILLIKAINEN, M., 2018. *Recycling mine tailings in chemically bonded ceramics – A review*. Journal of Cleaner Production. 174, 634-649.

KREKELER, M.P., MORTON, J., LEPP, J., TSELEPIS, C., SAMSONOV, M., KEARNS, L., 2008. *Mineralogical and geochemical investigation of clay-rich mine tailings from a closed phosphate mine, Bartow Florida, USA*. Environmental Geology. 55, 123-147.

LOUTOU, M., TAHA, Y., BENZAAZOUA, M., DAAFI, Y., HAKKOU, R., 2019. *Valorization of clay by-product from Moroccan phosphate mines for the production of fired bricks*. Journal of Cleaner Production. 229, 169-179.

LUAN, X., LI, J., LIU, L., YANG, Z., 2019. *Preparation and characteristics of porous magnesium phosphate cement modified by diatomite*. Materials Chemistry and Physics. 235, 121742.

LV, Y., HU, N., YE, Y., LV, Y., LIU, H., 2023. *Adsorption of Ag^+ with NaCl modified ceramsite prepared from total phosphorus tailings: performance and adsorption mechanism*. Water, Air, and Soil Pollution. 234, 784.

MAO, S., ZHANG, Q., 2021. *Mineralogical characteristics of phosphate tailings for comprehensive utilization*. Advances in Civil Engineering. 5529021.

MEI, F.D., LI, Y.J., HU, C.Y., MEI, Z.H., YE, F., 2019. *Utilization of flotation phosphate tailings and water treatment sludge in cemented paste backfill based on phosphate tailings*. Science of Advanced Materials. 11, 1306-1314.

MOUKANNAA, S., LOUTOU, M., BENZAAZOUA, M., VITOLA, L., ALAMI, J., HAKKOU, R., 2018. *Recycling of phosphate mine tailings for the production of geopolymers*. Journal of Cleaner Production. 185, 891-903.

NEGM, A., ABOUZEID, A., 2008. *Utilization of solid wastes from phosphate processing plants*. Physicochemical Problems of Mineral Processing. 42, 5-16.

NIE, Y., DAI, J., HOU, Y., ZHU, Y., WANG, C., HE, D., MEI, Y., 2020. *An efficient and environmentally friendly process for the reduction of SO_2 by using waste phosphate mine tailings as adsorbent*. Journal of Hazardous Materials. 388.

NUNES, A., PERES, A., CHAVES, A., FERREIRA, W., 2019. *Effect of alkyl chain length of amines on fluorapatite and aluminium phosphates floatabilities*. Journal of Materials Research and Technology. 8, 3623-3634.

OLIVEIRA, M., SANTANA, R., ATAÍDE, C., BARROZO, M.A., 2011. *Recovery of apatite from flotation tailings*. Separation and Purification Technology. 79, 79-84.

OUAKIBI, O., LOQMAN, S., HAKKOU, R., BENZAAZOUA, M., 2013. *The potential use of phosphatic limestone wastes in the passive treatment of AMD: a laboratory study*. Mine Water and the Environment. 32, 266-277.

OUBAHA, S., TAHA, Y., LOUTOU, M., MGHAZLI, M.O., BENZAAZOUA, M., HAKKOU, R., 2023. *Fired brick production using phosphogypsum and phosphate mining waste*. Construction and Building Materials. 403, 133149.

QIN, F., LI, J., ZHANG, C., ZENG, G., HUANG, D., TAN, X., QIN, D., TAN, H., 2022. *Biochar in the 21st century: A data-driven visualization of collaboration, frontier identification, and future trend*. Science of The Total Environment. 818, 151774.

REN, X., MA, B., SU, C., QIAN, F., YANG, W., YUAN, L., YU, J., LIU, G., LI, H., 2019. *In-situ synthesis of Fe_xSi_y phases and their effects on the properties of SiC porous ceramics*. Journal of Alloys and Compounds. 784, 1113-1122.

RUAN, Y., He, D., CHI, R. 2019. *Review on Beneficiation Techniques and Reagents Used for Phosphate Ores*. Minerals, 9, 253.

SEVEROV, V., FILIPPOVA, I., FILIPPOV, L., 2022. *Use of fatty acids with an ethoxylated alcohol for apatite flotation from old fine-grained tailings*. Minerals Engineering. 188, 107832.

SILVA, E., MLAYAH, A., GOMES, C., NORONHA, F., CHEREF, A., SEQUEIRA, C., ESTEVES, V., MARQUES, A., 2010. *Heavy elements in the phosphorite from Kalaat Khasba mine (North-western Tunisia): Potential implications on the environment and human health*. Journal of Hazardous Materials. 182, 232-245.

SKIBO, J., SCHIFFER, M., REID, K., 1989. *Organic-tempered pottery: an experimental study*. American Antiquity. 54, 122-146.

SOESOO, A., VIND, J., HADE, S., 2020. *Uranium and Thorium Resources of Estonia*. Minerals. 10, 798.

SUN, Z., HU, N., KE, L., LV, Y., LIU, Y., BAI, Y., OU, Z., LI, J., 2023. *Machine learning-assisted design of Al_2O_3–SiO_2 porous ceramics based on few-shot datasets*. Ceramics International. 49, 29400-29408.

TAGHAVI, F., NOAPARAST, M., POURKARIMI, Z., NAKHAEI, F., 2022. *Comparison of mechanical and column flotation performances on recovery of phosphate slimes in presence of nano-microbubbles*. Journal of Central South University. 29, 102-115.

VAN ECK, N., WALTMAN, L., 2010. *Software survey: VOSviewer, a computer program for bibliometric mapping*. Scientometrics. 84, 523-538.

WETHERILL, J., 1983. *Significance of radium in gypsum tailings from phosphate fertilizer plants in Alberta*. Health Physics. 44(6), 717.

WU, S., LIU, Y., SHANG, L., ZHOU, W., LI, Y., SUN, J., LI, J., LONG, H., NING, Z., LIU, C., 2023. *Recycling of phosphate tailings for an efficient hydroxyapatite-based adsorbent to immobilize heavy metal cations*. Environmental Science and Pollution Research. 30, 72160-72170.

WU, Y., SHU, J., CAO, W., LI, Z., LI, B., XU, Z., CHEN, H., CHEN, M., DENG, Z., 2023. *Adsorption removal of Mn^{2+} and NH^{4+}–N from electrolytic manganese metal wastewater by modified phosphate ore flotation tailings*. Environmental Science: Water Research & Technology. 9, 125-133.

WU, Z., SHE, L., YE, P., ZHU, T., LI, J., ZHANG, X., MA, J., WANG, T., 2023. *Extraction of H_3PO_4 from low-grade phosphate rocks leachate of HCl-route by the mixture of TBP and IPE: Optimization, mass transfer and mechanism*. Journal of Molecular Liquids. 370, 120681.

XIONG, S., LIU, Z., MIN, C., SHI, Y., ZHANG, S., LIU, W., 2023. *Compressive strength prediction of cemented backfill containing phosphate tailings using extreme gradient boosting optimized by whale optimization algorithm*. Materials. 16, 308.

XU, R., WU, D., WANG, Z., DENG, Y., CHENG, Q., PANG, H., WEI, W., LIU, Y., 2023. *Knowledge mapping analysis of the track and hotspot of water lubrication: A scientometrics review*. Friction. 11, 1557-1591.

YANG, X., MAKKONEN, H., PAKKANEN, L., 2019. *Rare earth occurrences in streams of processing a phosphate ore*. Minerals. 9, 262.

YANG, F., LV, J., ZHOU, Y., WU, S., SIMA, J., 2022. *Co-pyrolysis of biomass and phosphate tailing to produce potential phosphorus-rich biochar: efficient removal of heavy metals and the underlying mechanisms*. Environmental Science and Pollution Research International. 30, 17804-17816.

YU, D., XU, Z., PEDRYCZ, W., WANG, W., 2017. *Information sciences 1968–2016: A retrospective analysis with text mining and bibliometric*. Information Sciences. 418, 619-634.

YU, Y., DU, C., YANG, X., 2023. *Recovery of phosphorus from steelmaking slag and phosphate tailings by a collaborative processing method*. Separation and Purification Technology. 313, 123499.

YU, Y., DU, C., 2023. *Leaching of phosphorus from phosphate tailings and extraction of calcium phosphates: Toward comprehensive utilization of tailing resources*. Journal of Environmental Management. 347, 119159.

ZHANG, Y., GOH, K., NG, Y., CHOW, Y., WANG, S., ZIVKOVIC, V., 2021. *Process intensification in micro-fluidized bed systems: A review*. Chemical Engineering and Processing-Process Intensification. 164, 108397.

ZHENG, K., ZHOU, J., GBOZEE, M., 2015. *Influences of phosphate tailings on hydration and properties of Portland cement*. Construction and Building Materials. 98, 593-601.

ZHOU, Q., GONG, K., ZHOU, K., ZHAO, S., SHI, C., 2019. *Synergistic effect between phosphorus tailings and aluminum hypophosphite in flame-retardant thermoplastic polyurethane composites*. Polymers for Advanced Technologies. 30, 2480-2487.