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Application and development of sludge-based materials for environmental pollution remediation: a bibliometric review from 2004 to 2024

Fangyuan Jin,[a] Jinxia Lu,[b] Fei Sun,[b] Fang Yang *[a] and Zhonghong Li *[c]

In recent years, considerable attention has been directed towards the development of high-value materials derived from various types of sewage sludge (SS) including adsorbents, catalysts, and soil amendments, for their potential in environmental pollution remediation. To investigate the current research status, hotspots, and development trends of sludge-based materials for environmental pollution remediation, this study adopted bibliometric tools, such as Bibliometrix, VOSviewer, and Citespace, to conduct a quantitative analysis of the related literature published between 2004 and 2024, collected from the Web of Science Core Collection (WOSCC) database. The results indicated a consistent annual increase in publication numbers, with a marked acceleration observed over the past six years. China significantly outperforms other countries in terms of publication quantity and institutions, and forming a country cooperation network centered around China. Keyword co-occurrence and burst analyses revealed that the current research hotspots in the field of sludge-based materials for environmental pollution remediation primarily focused on the preparation methods, particularly pyrolysis, and the performance and mechanisms studies of the sludge-based materials as adsorbents and catalysts. Future research should prioritize exploring modification methods and materials to develop further high-performance sludge-based materials, such as sludge-based electrode materials. Moreover, in-depth investigations into the impacts of sludge-based soil amendments on soil physical, chemical, and biological properties should be emphasized. By utilizing bibliometrics to evaluate the current state and future trends of sludge-based materials for environmental pollution remediation, this article provides valuable insights into the field's evolution for researchers.

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1. Introduction

Sewage sludge (SS) is a by-product of the wastewater treatment process with a considerable yield and complex composition that has significantly heightened societal interest in its treatment. SS consists of suspended solids, microorganisms, and microbial metabolites, and contains toxic substances including heavy metals (HMs) and organic pollutants (OPs) like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), surfactants, hormones, and pharmaceuticals, *etc.*[1] This complex composition necessitates robust treatment strategies to address environmental and health risks. Compared with traditional SS treatment and disposal technologies such as sanitary landfill, agricultural reuse, sludge incineration, anaerobic digestion, and composting, sludge pyrolysis has become a research hotspot in recent years due to its characteristics of highly efficient reduction, harmlessness, and resource utilization.[2] Sludge-based materials prepared through methods like pyrolysis, loading, and hydrothermal synthesis, possess properties such as high specific surface area, adsorption capacity, adaptable pore structure, resource utilization, and cost-effectiveness, making them suitable for applications as adsorbents,[3] catalysts,[4] and soil amendment,[5] *etc.*, which have a wide range of application progress in the field of environmental remediation.

In recent years, there has been an increasing number of publications on the research of sludge-based materials for environmental pollution remediation, with numerous research directions being pursued. For instance, Liu *et al.* conducted a comprehensive analysis of sludge-based activated carbon (SBAC), highlighting the critical impact of chemical activation on enhancing porosity and adsorption potential for OPs and HMs in wastewater, while also noting future research areas, such as activation efficiency optimization, process mechanism clarification, and HM stabilization strategy development.[6] Zhang *et al.* presented an innovative strategy for SS reduction

[a]State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China. E-mail: yang.fang@craes.org.cn
[b]Basin Research Center for Water Pollution Control, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China
[c]School of Environment and Energy Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, China. E-mail: pl_lizhh@163.com

and resource utilization by preparing biochar-based catalytic materials for aqueous environments, focusing on their exceptional properties, applications in advanced oxidation processes, and catalytic uses, while also discussing key active sites, mechanisms, and future development directions.[7] Goldan *et al.* highlighted the mounting global issue of sludge disposal, advocating for sludge pyrolysis as an economically and ecologically viable approach that concurrently reduces sludge volume, removes harmful compounds, and generates nutrient-rich biochar with diverse applications.[8] Xiao *et al.* comprehensively explored the pretreatment, modification, and multiple applications of sludge-derived biochar, assessing numerous technologies and proposing future directions to convert SS from an environmental concern into a valuable resource.[9] However, traditional literature reviews involve subjective analysis by reading, summarizing, and engaging in qualitative discussions, which may not objectively reflect the current research status and development trends in the field. Although the number of publications on sludge-based materials for environmental pollution remediation has been increasing, there is a lack of comprehensive macro-scale analysis in this field. Therefore, the use of bibliometric methods is warranted to systematically analyze the research progress and accurately grasp the research vein in this field.

As an interdisciplinary field that fuses mathematics and statistics, bibliometrics employs objective and quantitative analysis of knowledge carriers to evaluate the current state of development in specific fields, drawing on historical publication data to forecast future research trends and hotspots.[10] In recent years, bibliometric methods have been widely employed due to their advantages of objectivity, quantification, and visualization, making them valuable tools for evaluating the current status and future development trends in various research fields. Bibliometrics has been extensively applied in various fields, such as the application of silver nanoparticles-based materials in wastewater treatment,[11] the application of zero-valent iron materials in environmental remediation,[12] cyclodextrin-based adsorbents for pollutant removal from wastewater,[13] the treatment of environmental pollutants by humic acid,[14] and the application of porous geopolymers as adsorbents for dyes.[15] To date, there has been no reported study that employs bibliometrics to systematically analyze the development trends and frontier directions of sludge-based materials in the field of environmental pollution remediation.

To comprehend the current trends and development tendency of sludge-based materials for environmental pollution remediation, literature from the Web of Science Core Collection (WOSCC) database was retrieved and analyzed using bibliometric methods, quantitatively organizing and systematically analyzed in terms of authors, countries, research institutions, and keywords. The main contributions of this paper are as follows:

(1) Bibliometrix was employed to analyze the number of publications, annual trends, primary research contributors, major publishing journals, and highly-cited literature in the field of sludge-based materials for environmental pollution remediation.

(2) Employing CiteSpace and VOSviewer, this study analyzed keywords' co-occurrence and burst analysis to evaluate research hotspots' evolution, forecast future trends, and elucidate current hotspots and trends of sludge-based materials for environmental pollution remediation.

(3) This study summarized the preparation methods of sludge-based materials and their application as adsorbents and catalysts in environmental remediation, while also systematically reviewing the research developments and challenges associated with the application of sludge-based materials for environmental pollution remediation.

2. Method

2.1 Data source and collection

To gain a deeper understanding of the current status and future trends of sludge-based materials for environmental pollution remediation, this study employed the Web of Science Core Collection (WOSCC) as its data source. WOSCC is the largest and most comprehensive academic information resource database, covering numerous subject areas, and is recognized as the most influential platform for natural sciences research.[16] The search formula used was TS = ("sludge derived" OR "sludge based"), with a period ranging from January 1, 2004, to December 31, 2024, and a retrieval time of Feb 21, 2025. Limiting the literature type to "Article" and "Review", the search yielded 1919 literature records. After removing duplicates and excluding irrelevant literature, the final count of obtained records was 1228. The literature was selected and downloaded in the "Full Record and Cited References" format, then saved as plain text files to facilitate subsequent bibliometric analysis.

2.2 Data analysis and visualization

The technical roadmap of the bibliometric research was illustrated in Fig. 1. These publications were submitted to Bibliometrix, VOSviewer, and Citespace for analysis. Bibliometrix is an R tool for scientific mapping and analysis, streamlines descriptive statistical analysis of literature elements, including paper count, citations, author information, and keyword distribution.[17] VOSviewer enables analysis of literature elements, while also performing network visualization, overlapping and crossing visualization, and density visualization based on the data characteristics.[18] Citespace's Burst Analytics helps researchers in identifying emerging trends, research hotspots, and shifts in scholarly influence within a given field, providing valuable information for decision-making and resource allocation.[19]

Bibliometrix was employed to statistically analyze main indicators, including annual publications, literature types, disciplines, journals, authors, institutions, countries, highly cited literature, and keywords. VOSviewer was utilized to perform keyword co-occurrence frequency and visualization analyses revealing the current research hotspots in the field of sludge-based materials for environmental pollution remediation. CiteSpace software was concurrently utilized to conduct burst analysis aiming to uncover development trends in the

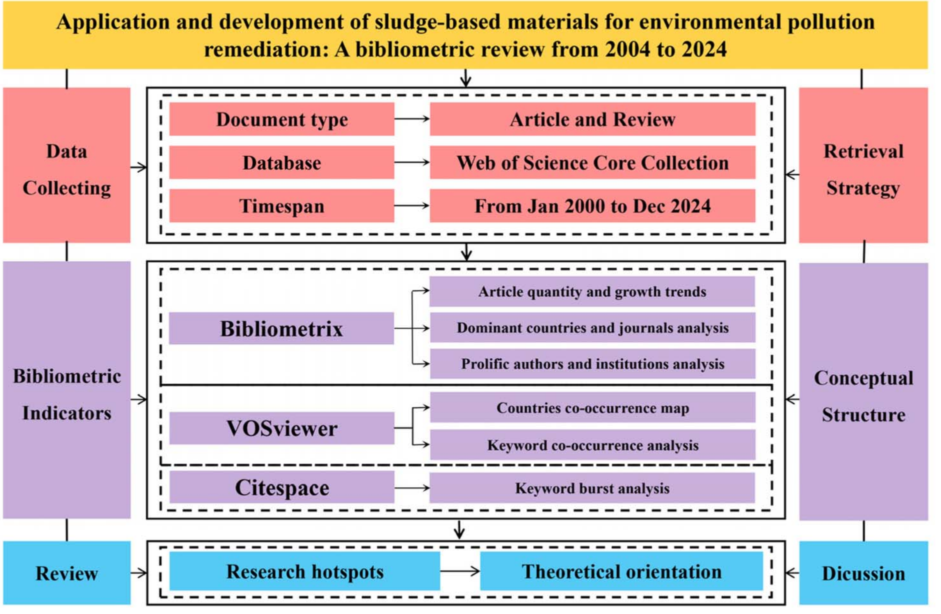

Fig. 1 Technical roadmap of the bibliometric research.

field of sludge-based materials for environmental pollution remediation.

3. Results and discussion

3.1 Annual publication and subject distribution

The number of publications serves as a general indicator of interest levels within the scientific community and may provide an approximation of a field's development trajectory.[20] Among these publications, 1141 research papers accounted for 92.92% and 87 review papers for 7.08%. The number of publications revealed an overall growth trend, with the field's development divided into three distinct stages based on this growth pattern (Fig. 2).

The initial stage (from 2004 to 2010) is characterized by limited attention and a relatively low output of publications in the field, averaging 7.57 publications per year. The sludge treatment industry, which began relatively late and initially relied on low-tech methods like landfilling and simple composting, initially prioritized reduction and harmlessness over resource utilization. However, the early research established a robust theoretical foundation for preparing, optimizing, and applying sludge-based materials, which expanded their potential use in practical applications such as water purification and air quality improvement. For instance, Bagreev *et al.* discovered that sludge-derived materials can serve as adsorbents for hydrogen sulfide in air. The adsorption capacity of material carbonized at 950 °C was found to be twice as high as that of coconut shell-activated carbon, with the capacity of sludge-derived material increasing alongside carbonization temperature.[21]

During the second stage (2011–2018), there was a steady increase in the number of publications, which reflects the

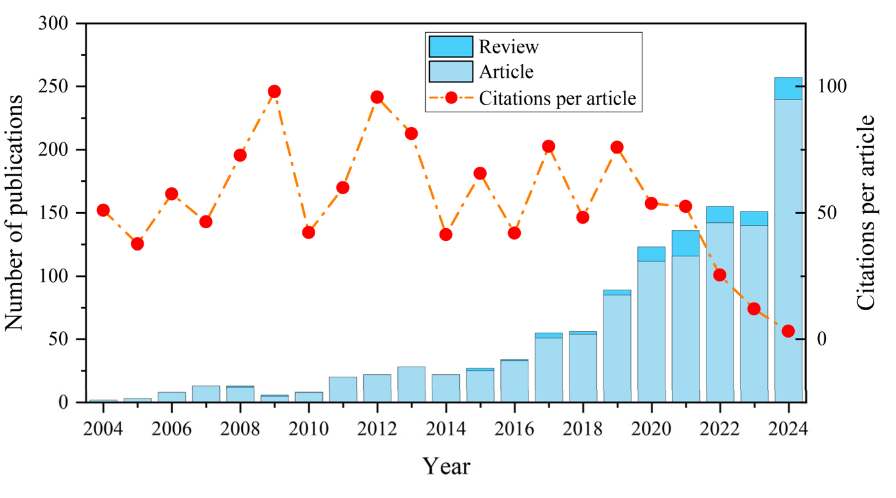

Fig. 2 Number of publications in the field of sludge-based materials for environmental pollution remediation from 2004 to 2024.

escalating interest in the application of sludge-based materials for environmental pollution remediation. The number of published papers rose from 20 in 2011 to 56 in 2018. As urbanization accelerates, increasing sludge production and the demand for environmental remediation have spurred the application of sludge-based materials, with developed countries like those in the EU introducing policies such as the "Sewage Shudge Directive" to promote resource utilization of sludge. In this stage, researchers sought to further optimize the preparation process of sludge-based materials to enhance their performance and effects in environmental remediation while also delving into the adsorption, desorption, and transformation mechanisms of sludge-based materials. For instance, Xu *et al.* summarized three commonly used preparation methods for sludge-based adsorbents (carbonization, physical activation, and chemical activation), investigating the effects of critical parameters such as pyrolysis temperature, residence time, heating rate, activator, and raw material type on sludge-based adsorbent preparation. They also summarized that the adsorption efficacy of sludge-based adsorbents for pollutants depends on factors like surface area, pore size distribution, surface functional groups, and ion exchange capacity.[22]

During the third stage (2019–2024), the field of sludge-based materials for environmental pollution remediation experienced an unprecedented surge in the number of publications. In the past six years, an average of 151.8 publications per year were produced, accounting for 74.19% of the total number of publications. During this stage, Policies like China's "Implementation Plan for Harmless Disposal and Resource Utilization of Sewage Sludge" and the EU's "Circular Economy Action Plan" are enhancing harmless sludge treatment and resource utilization, while the adoption of new technologies such as thermal hydrolysis, carbonization, and gasification has significantly improved the resource efficiency and environmental performance of sludge-based materials. The researchers have concentrated their efforts on developing efficient methods for preparing sludge-based materials, while simultaneously evaluating the associated environmental risks and safety concerns. They also assessed the environmental, economic, and social impacts of the sludge treatment process to guide policy formulation and optimize resource use. For instance, Lv *et al.* reviewed the risk control of HMs leaching from sludge-derived biochar, identifying increased pyrolysis temperature combined with stepwise pyrolysis or co-pyrolysis as an effective method to reduce the risk of HMs leaching in the system.[23] Projected to surpass USD 50 billion by 2030, the global sludge treatment market underscores the promising application of sludge-based materials in environmental remediation.

3.2 Major research forces

3.2.1 Prominent countries/regions and international cooperation. By analyzing the countries/regions of author affiliations, the overall scientific research investment and influence of a country/region in a specific research field can be visualized.[24] In total, 84 countries/regions have contributed to research on sludge-based materials for environmental pollution remediation. Fig. 3 summarizes the top 10 countries/regions based on the number of published papers. China leads with the most research papers (776 papers, 63.19%). This dominance highlights China's commitment to sludge-based material research for environmental pollution remediation, with substantial scientific research efforts yielding fruitful results. China's citations per article average 40.86, a figure surpassed only by Spain, Brazil, and the USA among the top 10 countries. China's rapid economic development and urbanization have made it the world's largest SS producer, generating 65 million tons of sludge (80% moisture content) in 2020, with global sludge production anticipated to reach approximately 103 million tons by 2025, offering abundant and sustainable resources for sludge carbon-based materials.[25] As a novel environmentally-friendly material leveraging sludge resources, sludge-based materials can alleviate disposal pressure while offering innovative solutions in fields such as environmental remediation, catalyst carriers, and energy conversion and storage.

The analysis of the global publication trends and international collaborations in the field of sludge-based materials for environmental pollution remediation was conducted using VOSviewer software and Scimago Graphica visualization software. The size of the circles in the graph represents the number

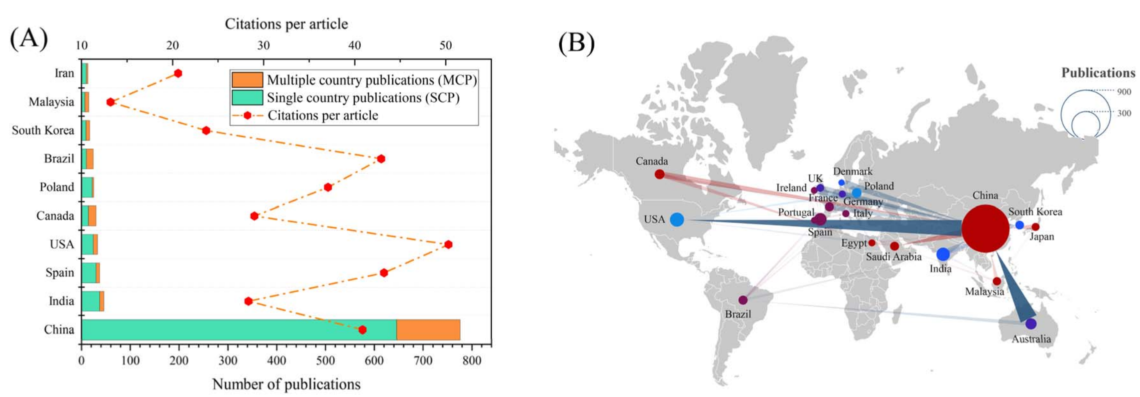

Fig. 3 (A) Publication numbers of (B) cooperation between countries/regions in the field of sludge-based materials for environmental pollution remediation.

of articles published by countries/regions, while connecting lines indicate collaboration, with more connections reflecting closer cooperation between countries/regions. China has emerged as a pivotal node in the international network, engaging in extensive collaborative research with countries including Australia and the USA. Moreover, due to cultural and linguistic similarities, European and North American countries exhibit more collaborative activities, while Asian countries maintain fewer academic connections with other countries.

3.2.2 Major research institutions analysis. A total of 1371 institutions contribute to global research in the field of sludge-based materials for environmental pollution remediation. The top 10 institutions have collectively published 319 articles, accounting for 25.98% of the total number of articles in the field (Fig. 4). The top 3 institutions were the Chinese Academy of Sciences (64 articles, 5.21%), Harbin Institute of Technology (51 articles, 4.15%), and Tongji University (36 articles, 2.93%), indicate that research in the field of sludge-based materials for environmental pollution remediation is not concentrated within a few institutions. When analyzing both the total number of citations and citations per article, Hunan University, Sun Yat-sen University, and Harbin Institute of Technology demonstrate substantial expertise in the field of sludge-based materials for environmental remediation.

3.2.3 High productivity authors analysis. Analyzing the high-productivity authors helps identify prominent researchers in the field and their areas of interest, fostering academic exchanges and collaborations suited to individual research needs.[26] Statistically, a total of 4482 authors have contributed to research in the field of sludge-based materials for environmental pollution remediation, among whom 205 authors (4.57%) have published ≥5 papers, illustrating their significant contributions to this field (Fig. 5). Li J.'s team from Beijing University of Technology leads in terms of publication count, with a total of 25 papers primarily focusing on the removal and recovery of phosphorus from wastewater using sludge-based materials in recent years.[27–29] Zhang J. from Shanghai University have published 23 articles exploring the use of sludge-based materials for environmental pollution remediation. His recent research endeavors have concentrated on the application of electroplating sludge as a catalyst in atmospheric remediation.[30–32] Chen Y., from Zhejiang Gongshang University, is ranked jointly third in terms of publication output on the topic of sludge-based materials. His research primarily focuses on the utilization of these materials as adsorbents for the removal of HM ions from wastewater.[33–35]

3.3 Prominent journals analysis

Bibliometric analysis of research fields covered by issuing journals effectively assists researchers in identifying influential

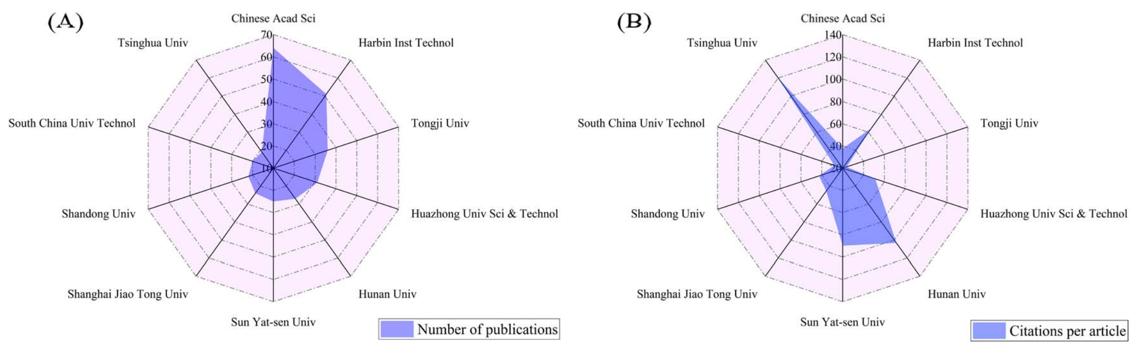

Fig. 4 (A) Publication numbers (B) citations per article of the top 10 institution in the field of sludge-based materials for environmental pollution remediation.

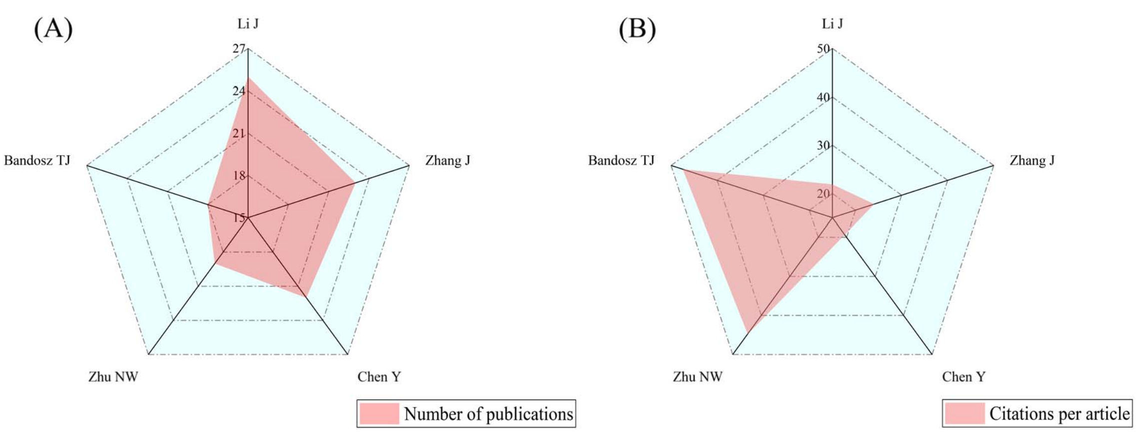

Fig. 5 (A) Publication numbers (B) citations per article of the top 5 authors in the field of sludge-based materials for environmental pollution remediation.

Table 1 Publication numbers of the top 10 journals in the field of sludge-based materials for environmental pollution remediation

Rank	Journals	Publications	%	IF_{2023}	Total cited citations	Average cited citations
1	*Chemical Engineering Journal*	74	6.03	13.3	6948	93.89
2	*Journal of Hazardous Materials*	64	5.21	12.2	3298	51.53
3	*Science of The Total Environment*	63	5.13	8.2	3077	48.84
4	*Journal of Cleaner Production*	48	3.91	9.8	2583	53.81
5	*Bioresource Technology*	42	3.42	9.7	3019	71.88
6	*Journal of Environmental Management*	40	3.26	8.0	1486	37.15
7	*Journal of Environmental Chemical Engineering*	39	3.18	7.4	1379	35.36
8	*Journal of Water Process Engineering*	32	2.61	6.3	415	12.97
9	*Water Research*	31	2.52	11.4	3192	102.97
10	*Separation and Purification Technology*	30	2.44	8.2	575	19.17

journals related to their field.[36] From 2004 to 2024, 270 journals have published articles related to sludge-based materials for environmental pollution remediation, with the top 10 journals listed in Table 1. The top 3 journals in the field, *Chemical Engineering Journal*, *Journal of Hazardous Materials*, and *Science of The Total Environment*, account for 41.46% of the total number of articles, with respective contributions of 6.03%, 5.21%, and 5.13%. This distribution highlights their significant academic influence and prominence within the discipline. The top 10 journals in the field of sludge-based materials for environmental pollution remediation boast an average impact factor of 9.45, with the *Chemical Engineering Journal* holding the highest impact factor among them.

3.4 Highly cited documents

Highly cited articles in high-level journals often reflect leading or innovative work, and their research content and conclusions typically attract the attention of scholars in related fields.[37] Table 2 presents the top 10 cited articles in the field of sludge-based materials for environmental pollution remediation. The most cited article is H. L. Lu's "Relative distribution of Pb^{2+} sorption mechanisms by sludge-derived biochar", published in *Water Research* in 2012 with 826 citations. The article explored the adsorption capacity and mechanisms of sludge-derived biochar for Pb, demonstrating that biochar from sludge pyrolysis effectively removed Pb^{2+} from acidic solutions. The removal rates were between 16.11 and 30.88 mg g^{-1} at initial pH levels from 2 to 5. The primary adsorption mechanisms included organic hydroxyl and carboxyl coordination, accounting for 38.2–42.3% of the total adsorbed Pb, and co-precipitation or complexes on the mineral surface, which constituted 57.7–61.8%.[38] The second most cited article is "Removal of methylene blue from aqueous solution by sewage sludge-derived biochar: adsorption kinetics, equilibrium, thermodynamics and mechanism" by Fan *et al.* published in *Journal of Environmental Chemical Engineering* in 2017. The study investigated the adsorption performance of methylene blue by sludge-derived biochar, analyzing the effects of adsorbent dosage, contact time, pH, and temperature, while attributing the adsorption mechanism to electrostatic interactions, ion exchange, hydrogen bonding interactions, and n–p interactions.[39] Ranked third is K. M. Smith's review "Sewage sludge-based adsorbents: a review of their production, properties and use in water treatment applications", published in *Water Research* in 2009. The review explored the application of sludge-based adsorbents in wastewater treatment, highlighting that carbonized sludge-based adsorbents typically possess high metal cation capacity, while chemical activation with alkali metal hydroxides and acid washing, especially combined with physical activation, has proven effective in creating high surface area SBAs with enhanced Brunauer–Emmett–Teller (BET) surface area.[40]

3.5 Keyword analysis

3.5.1 High-frequency keyword analysis. Keywords concisely summarize an article's main idea and accurately capture its essence, assisting in the identification of research hotspots and trends within a particular field.[41] High-frequency keywords indicate a greater level of attention from scholars in that field. A total of 4838 keywords are found within the 1228 papers searched in the WOSCC database. After merging synonyms and eliminating meaningless keywords, the top 25 keywords were identified (Fig. 6). In addition to "sewage sludge", "activated carbon", and "sludge-derived biochar" that relate to the search topic, other frequent keywords include "pyrolysis", "temperature" and "hydrothermal carbonization" related to the preparation of sludge-based materials have been discussed. Furthermore, keywords related to sludge-based adsorbents ("adsorption", "adsorbents", "kinetics", "equilibrium", "mechanism") and sludge-based catalysts ("degradation", "oxidation", "peroxymonosulfate", "persistent free-radicals") are prevalent, along with pollutant-specific keywords such as "heavy metals" and "methylene blue". This observation suggests that recent research in the field of sludge-based materials primarily revolves around material preparation methods, particularly pyrolysis, and the investigation of adsorption and catalytic processes for pollutants such as HMs and dyes. Analyzing high-frequency keywords reveals their significant role in this field, providing guidance for further study and shedding light on the research focus and trends of sludge-based materials for environmental pollution remediation.

3.5.2 Keyword co-occurrence analysis. Keyword co-occurrence analysis elucidates the interconnections between

Table 2 Top 10 cited publications in the field of sludge-based materials for environmental pollution remediation from 2004 to 2024

Title	First authors	Year	Journal	Article type	Total citation
Relative distribution of Pb^{2+} sorption mechanisms by sludge-derived biochar	H. L. Lu	2012	*Water Research*	Article	826
Removal of methylene blue from aqueous solution by sewage sludge-derived biochar: adsorption kinetics, equilibrium, thermodynamics and mechanism	S. S. Fan	2017	*Journal of Environmental Chemical Engineering*	Article	499
Sewage sludge-based adsorbents: a review of their production, properties and use in water treatment applications	K. M. Smith	2009	*Water Research*	Review	429
Magnetic nitrogen-doped sludge-derived biochar catalysts for persulfate activation: internal electron transfer mechanism	J. F. Yu	2019	*Chemical Engineering Journal*	Article	411
Singlet oxygen-dominated peroxydisulfate activation by sludge-derived biochar for sulfamethoxazole degradation through a nonradical oxidation pathway: performance and mechanism	R. L. Yin	2019	*Chemical Engineering Journal*	Article	388
A critical review on preparation, characterization and utilization of sludge-derived activated carbons for wastewater treatment	P. Hadi	2015	*Chemical Engineering Journal*	Review	339
Characterization of sewage sludge-derived biochars from different feedstocks and pyrolysis temperatures	H. L. Lu	2013	*Journal of Analytical and Applied Pyrolysis*	Article	301
Activation of peroxymonosulfate by sludge-derived biochar for the degradation of triclosan in water and wastewater	S. Z. Wang	2019	*Chemical Engineering Journal*	Article	300
Efficient elimination of organic and inorganic pollutants by biochar and biochar-based materials	B. W. Hu	2020	*Biochar*	Review	284
Tetracycline removal from water by adsorption/bioadsorption on activated carbons and sludge-derived adsorbents	J. Rivera-Utrilla	2013	*Journal of Environmental Management*	Article	276

diverse research topics, methods, and concepts, facilitating the identification of core themes and research hotspots in a given field.[42] Vosviewer software was employed to analyze the keywords related to the field of sludge-based materials for environmental pollution remediation, resulting in three distinct clusters: Cluster I, Cluster II, and Cluster III (Fig. 7 and Table 3).

The primary keywords in Cluster I, including "pyrolysis", "biochar", "temperature", "co-pyrolysis", and "gasification" predominantly focus on the preparation methods of sludge-based materials. Various thermochemical techniques, such as direct pyrolysis, microwave pyrolysis, and hydrothermal carbonization, are employed to convert SS into biochar materials, with pyrolysis being the most widely utilized method.[43] Pyrolysis involves heating SS or other biomass under anoxic or anaerobic conditions at high temperatures effectively eliminating pathogenic microorganisms significantly reducing its volume and degrading organic matter into gases liquids and solid residues such as syngas bio-oil and biochar. The pyrolysis of SS begins with dewatering at 200 °C, during which free and bound water is vaporized, releasing water vapor and a small amount of volatile matter. The primary degradation reactions occur between 200 °C and 350 °C, producing alcohols, hydrocarbons, and releasing gases such as carbon dioxide, methane, and hydrogen. At temperatures ranging from 350 °C to 550 °C, the intermediates undergo secondary degradation and are transformed into smaller alcohols and hydrocarbons. Complete degradation of intermediates takes place between 550 °C and 900 °C, where more complex organic matter is converted into lighter gases, liquid products (bio-oil), and solid products (biochar). During the pyrolysis process, the inorganic minerals present in municipal SS undergo degradation, catalysis, and reduction, ultimately volatilizing into the bio-oil or becoming embedded within the carbon structure. This transformation significantly alters the properties and potential applications of the resulting biochar.[44] The quality of sludge-based biochar is determined by a variety of factors such as the pyrolysis method, temperature settings, the equipment employed, heating rate, the type of protective gas used, and the inherent characteristics of the SS itself. Temperature exerts a significant influence on

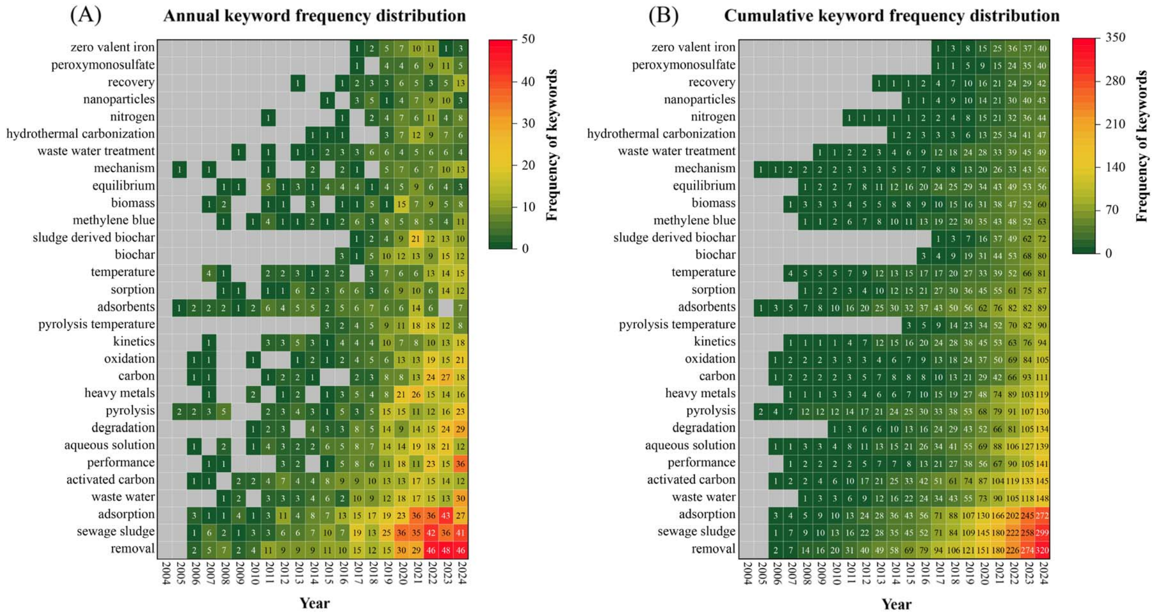

Fig. 6 (A) Annual frequency and (B) cumulative frequency of keywords in the field of sludge-based materials for environmental pollution remediation from 2004 to 2024.

the physicochemical properties of biochar. Insufficient temperatures do not adequately alter the chemical structure of the organic matter, while higher temperatures promote secondary pyrolysis. This enhanced thermal decomposition facilitates the release of volatiles from the surface of sludge-based biochar, resulting in increased porosity and surface area. For instance, Bandosz *et al.* prepared sludge-based adsorbents for removing hydrogen sulfide from moist air by pyrolyzing SS, waste oil sludge, and their 50 : 50 mixtures at 650 °C and 950 °C for durations of half an hour or one hour, finding that the capacity and selectivity of the adsorbents depended on the pyrolysis temperature, duration, and specific chemical properties of the sludge precursor, as determined through characterization and performance analysis.[45]

In addition to the modulation of pyrolysis parameters that can influence the quality of sludge-based materials, researchers have explored the efficacy of co-pyrolysis to enhance both the efficiency of the pyrolysis process and the properties of the resultant products. Co-pyrolysis treats two or more feedstocks within the same pyrolysis system, synergistically combining their diverse compositions under high temperatures to enhance the characteristics of the resulting biochar, often surpassing the yield and quality achieved through conventional pyrolysis. The synergistic effects of co-pyrolysis may manifest as increases in yield and enhancements in biochar quality, or as amplifications of specific properties attributable to the mixed feedstocks, with these effects categorized into positive synergistic and negative, or antagonistic effects.[46] For instance, Hu *et al.* demonstrated

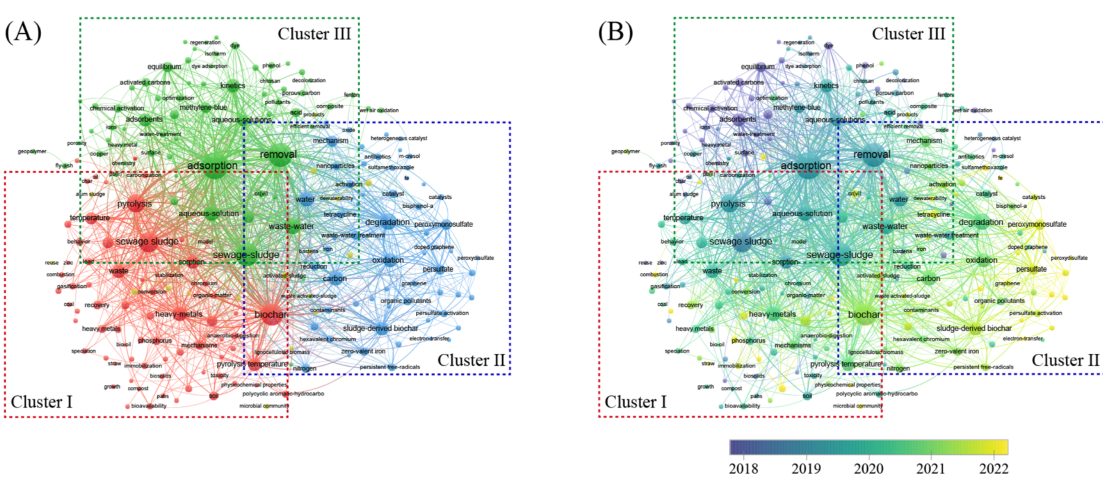

Fig. 7 Co-occurrence network of keywords in the field of sludge-based materials for environmental pollution remediation from 2004 to 2024.

Table 3 Main keywords in the field of sludge-based materials for environmental pollution remediation from 2004 to 2024

Cluster	Main keywords
Cluster I	Pyrolysis, biochar, temperature, biomass, co-pyrolysis, bioavailability, amendments, gasification, hydrothermal carbonization, organic matter, polycyclic aromatic-hydrocarbon
Cluster II	Oxidation, persulfate, peroxymonosulfate, degradation, advanced oxidation process, persulfate activation, catalyst, mechanism, generation, sulfamethoxazole degradation, peroxydisulfate, heterogeneous catalyst
Cluster III	Adsorption, adsorbent, desulfurization, porous carbon, pharmaceuticals, phenol, dye, thermodynamics, equilibrium, kinetics, modification

significant enhancements in biochar properties through co-pyrolysis of sludge with wind turbine blade waste (WTBW) and KOH at 600 °C. Increasing the WTBW mass ratio from 0 to 40% reduced the apparent activation energy from 53.5 to 33.1 kJ mol^{-1}, increased the maximum BET surface area to 498.3 m^2 g^{-1}, and enhanced microporosity by 36%.[47]

Cluster II focuses on the keywords "oxidation", "catalyst", "persulfate", "peroxymonosulfate", and "advanced oxidation process" emphasizing the utilization of sludge carbon-based catalysts in environmental remediation. Particularly rich in HMs such as Cu, Fe, and Al, industrial sludge promotes the formation of metal oxides on the surfaces of sludge-derived activated carbon. Concurrently, the intrinsic hydrogen and oxygen in the sludge react with carbon to form oxygen-containing organic functional groups on these surfaces. This dual modification significantly enhances the catalytic potential of the sludge-based activated carbon, offering a sustainable method to valorize waste while advancing catalytic technologies.[48] Characterized by their readily available raw materials, dispersed active sites, easily modifiable surface chemical functional groups, and high specific surface areas, catalysts and carrier materials derived from SS are well-suited for application in diverse catalytic systems designed for environmental pollution remediation. Notably, sludge-based catalysts have been extensively employed in persulfate systems,[49] Fenton-like systems,[50] photocatalytic systems,[51] and ozone-catalyzed oxidation systems,[52] demonstrating their versatility and effectiveness in addressing environmental challenges.

Although sludge-based catalysts currently exhibit catalytic activity that is inferior to that of commercial catalysts, leading to lower reaction rates and a diminished overall catalytic effect, researchers are actively pursuing a range of strategies to enhance their performance. Researchers have investigated preparation techniques such as pyrolysis, gasification, and ball milling to optimize the catalysts' surface area, pore structure, and functional groups. This optimization involves adjusting parameters like temperature, pressure, and atmosphere, while also developing a range of modification methods to further enhance their performance. These methods, including surface functionalization and the integration of nanomaterial composites, not only augment the activity and selectivity of the sludge-based catalysts but also enable the introduction of active groups tailored for specific reactions. For instance, Shi *et al.* enhanced the photocatalytic efficiency of sludge-derived activated carbon (SDAC) through physical mixing and hydrothermal methods, resulting in TiO_2-SDAC composites that achieved methylene blue removal efficiencies of 70.13% and 95.48% under visible light at a concentration of 40 mg L^{-1}, attributed to the incorporation of carbon atoms into the TiO_2 lattice that modulated its band gap and extended its optical response to the visible spectrum.[53] Velumani *et al.* developed a sludge-based biochar-metal oxide nanocomposite for photocatalytic degradation of bisphenol A (BPA), demonstrating that ZnO-loaded biochar significantly outperformed its non-ZnO counterpart, achieving a peak degradation efficiency of 94.50% under optimal conditions of pH 5, a photocatalyst concentration of 0.2 g L^{-1}, an initial pollutant concentration of 20 ppm, and a contact time of 150 min.[54]

Secondly, the surface of sludge-based materials is adorned with a plethora of functional groups, including carboxyl, hydroxyl, and ketone groups, which play a crucial role in modulating the loading, chemical states, and electron densities of metal monoatoms. However, challenges arise during the preparation process, as the dispersion and stability of metal or other active substances on the sludge-based substrates may be suboptimal, leading to diminished catalytic activity and reduced longevity of the catalysts. To mitigate these challenges, it is essential to optimize the preparation process and parameters, including the control of pyrolysis conditions, pretreatment methods, and loading processes. Such optimizations are crucial for enhancing the dispersion and stability of the catalysts, which in turn boosts their catalytic activity and extends their service life. For instance, Gu *et al.* demonstrated an innovative approach by converting trace redox-responsive transition metals in SS *in situ* into monoatomic species on carbon, nitrogen, sulfur, phosphorus, silicon, and aluminum. This method effectively creates active anchor sites and selective chemical bonds, resulting in SS-derived single-atom catalysts (SSACs) that exhibit remarkable reactivity, stability, and selectivity in the Fenton-like degradation of various pollutants. This performance enhancement is supported by combined structural analysis and density-functional theory (DFT) calculations, which identify co-coordinated iron monoatoms as the primary reactive sites within these catalysts.[55]

Due to their distinctive pore structure, sludge-based materials exhibit superior adsorption capabilities, making them suitable for direct use as catalysts or catalyst carriers. The catalytic potential of these materials can be enhanced by loading them with non-precious metal compounds such as Fe, Ni, Co, Cu, and Mo through a process known as load modification, which utilizes the high specific surface area of the sludge-based catalyst matrix to increase active sites, and further improved by modifying the surface of sludge-based catalyst with various chemical methods to adjust acidic, neutral, and basic functional groups, thus meeting specific catalytic activity requirements and enhancing catalytic efficiency. Depending on the substances used for loading, modifications can be categorized into several types: metal-loaded, metal oxide-loaded, natural mineral-loaded, and heteroatom-loaded modifications. For instance, He *et al.* developed a novel type of sludge-based biochar loaded with ferromanganese oxides *via* the co-precipitation method to activate periodate for the effective removal of thiamethoxam in aqueous environments, demonstrating removal rates exceeding 80% in natural aqueous matrices and surpassing 92% across a broad pH range of 3 to 11.[56]

To enhance the comprehension of the catalytic mechanisms of sludge-based catalysts, it is essential to investigate the pathways, rates, and key intermediates involved in the catalytic reactions. Employing *in situ* spectroscopic methods, such as Fourier transform infrared spectroscopy, alongside isotope tracer techniques and additional methodologies for monitoring structural changes, facilitates the elucidation of the kinetic mechanisms underlying substrate transformation in these catalysts. Additionally, a variety of research tools have been employed to examine the correlation between the formation of sludge-based materials and the chemical states of ash, carbon carriers, and active components in SS. This exploration also extends to identifying factors that influence the degradation efficiency of pollutants in water. Analyzing the functional groups, pore structures, metal elements, external modifiers, and catalytic reaction pathways in sludge-based catalysts deepens our understanding of their catalytic processes.

The keywords of Cluster III are "adsorption", "adsorbent", "kinetics", and "modification", which mainly focus on the application of sludge-based adsorbents in environmental remediation. Research has shown that the production of porous carbon-based adsorbents from sludge through pyrolysis and related methods significantly reduces sludge volume, yields cost-effective, high-value adsorbents that could replace traditional activated carbon, and effectively immobilizes HMs during the pyrolysis process.[57] Due to its unique properties such as a large specific surface area, abundant functional groups, mineral composition, and porous structure, sludge-based adsorbent effectively removes a wide range of pollutants from wastewater, such as dyes,[58] antibiotics,[59] metal ions,[60] phosphate,[61] phenol,[62] and other pollutants, and the sludge-based adsorbent has good adsorption performance for gaseous pollutants, such as volatile organic compounds (VOCs),[63] and malodor gases,[64] *etc.*

Sludge-based adsorbents are prepared using four principal methods, including direct pyrolysis carbonization, physical activation, chemical activation, and a combined approach of physical and chemical activation. Direct pyrolysis carbonization is the most frequently utilized technique for preparing sludge-based adsorbents, with the pyrolysis temperature playing a critical role in shaping the characteristics of the resulting materials. The combination of factors such as pyrolysis temperature, duration of final temperature residence, and heating rate during the preparation process significantly impacts the physicochemical properties of the adsorbent, including carbon content, surface acidity and alkalinity, surface morphology, and pore structure, which in turn determine the efficiency of pollutant removal. For instance, Liang *et al.* observed that as the pyrolysis temperature increased, the adsorption capacity of SS-drived biochar for phosphoric acid also increased, which can be attributed to a reduction in aliphatic functional groups and an enhancement in aromatic structures, with the maximum adsorption capacity reaching 5.93 mg g^{-1} at 700 °C.[65] Lu *et al.* observed that the specific surface area of the sludge-based adsorbent increased from 5.3 m^2 g^{-1} to 21.4 m^2 g^{-1} as the pyrolysis temperature rose from 300 °C to 500 °C, but further increasing the temperature to 600 °C led to a reduction in surface area to 10.6 m^2 g^{-1}, attributable to mass loss from thermal decomposition and the evolution of volatiles during carbonization, which increased the porosity of the adsorbent.[66] Moreover, the higher carbon content in sludge enhances the development of well-structured pores in sludge-based adsorbents, suggesting that blending sludge with other carbon-rich materials before undergoing pyrolysis treatment can increase the porosity of the resultant adsorbent samples. For instance, Yin *et al.* demonstrated that co-pyrolyzing SS with walnut shells to produce biochar not only facilitated the formation of a porous structure but also significantly improved the adsorption capacities. Specifically, when the mixing ratio of sludge to walnut shells was set at 3 : 1, the maximum adsorption capacities for NH_4^+ and PO_4^{3-} were recorded at 22.85 mg g^{-1} and 303.49 mg g^{-1}, respectively.[67] Controlling the temperature and duration of the pyrolysis process is crucial for influencing the pore structure, specific surface area, and adsorption properties of carbonized products. Future research should delve deeper into the thermal decomposition mechanisms during the carbonization process to acquire a comprehensive understanding of how various factors, such as temperature, time, and the pyrolysis environment, affect the performance of sludge-based adsorbents.

The adsorption performance and selectivity of sludge-based adsorbents are generally inferior to those of commercial activated carbon and other materials. However, these characteristics can be significantly improved through various modification methods, including acid washing, alkali treatment, phosphoric acid activation, doping modification, surface oxidation, and composite modification.[68] For instance, treating sludge-based materials with acids such as hydrochloric acid, sulfuric acid, or nitric acid can eliminate impurities, enhance pore structure, and increase surface activity. Nevertheless, it is crucial to meticulously control parameters such as acid concentration and treatment duration during the acid washing process to prevent detrimental impacts on the adsorbent's structure. Wu *et al.* demonstrated that modifying sludge-based activated carbon with chemical agents such as HCl, HNO_3, and NaOH significantly enhanced its adsorption capacity for humic acid and aromatic proteins, with NaOH-modified and HCl-modified versions showing superior removal of various types of aquatic macro-molecular weight dissolved organic matter from wastewater, although HNO_3 modification resulted in a reduction of macropore content.[69] In addition to employing acid wash as an activation method, various other chemical activation techniques such as alkali activation, oxidant activation, and carbonaceous material activation are primarily aimed at augmenting the surface area or introducing oxygen-containing functional groups. Moreover, sludge-based materials are engineered into composite structures with other functional materials, such as magnetic nanomaterials and metal–organic frameworks, to enhance the performance of adsorbents. These composite materials not only improve the efficiency of contaminant removal but also facilitate the simplification of the recovery and regeneration processes of the adsorbents. For instance, Cheng *et al.* observed that the removal of Cr^{6+} was more effective using Fe ion-modified porous carbon compared to porous carbon prepared through the co-pyrolysis of sludge and hybridized *Liriodendron* leaves. The incorporation of the Fe element not only enhanced the material's capacity for the oxidative reduction of Cr^{6+} but also endowed the porous carbon with magnetic properties, thereby improving its reusability.[70] Although modification methods have enhanced the adsorption performance of sludge-based adsorbents, their selectivity for specific pollutants remains suboptimal. Future research should focus on developing simple, cost-effective, and efficient modification techniques that minimize operational challenges and costs associated with modifying sludge-based adsorbents. Such developments are essential for maintaining robust adsorption performance and for devising modification strategies tailored to the types of target pollutants and specific treatment requirements.

The adsorption mechanism of sludge-based adsorbents is notably complex, influenced significantly by the structure of various sludge biomass components and surface functional groups, which greatly impact pollutant adsorption. The adsorption of OPs primarily occurs through electrostatic attraction, hydrogen bonding, and π–π interactions, while the adsorption of HM ions is predominantly facilitated by physical adsorption, electrostatic interactions, ion exchange, surface complexation, and precipitation.[71] The adsorption efficacy of sludge-based materials is influenced by a range of factors, including specific surface area, porosity, pore size distribution, and the composition of surface functional groups. However, research into the adsorption mechanisms for composite or specific pollutants remains superficial and incomplete, with the synergistic effects of various adsorption mechanisms still largely unexplored. Future research should focus on enhancing understanding of the adsorption, desorption, and transformation mechanisms of different types of sludge-based materials across various environmental remediation processes. Additionally, investigating how these adsorbents can synergistically address multiple composite pollutants and examining the interactions and synergistic effects among diverse adsorption mechanisms is crucial, as this will not only improve the application effectiveness and regeneration utilization of these materials but also advance their development. Furthermore, the interrelationship between the adsorption performance of these materials and environmental conditions can be modeled through computer simulations. These simulations offer predictions that can be experimentally validated, thereby deepening our understanding of the underlying mechanisms, providing a foundation for enhancing adsorbent design, and anticipating the practical remediation capabilities of sludge-based materials, effectively bridging the gap between theoretical studies and real-world applications.

Currently, the application of sludge-based adsorbents in wastewater treatment predominantly focuses on the adsorption and removal of single pollutants from aqueous environments, and in the future, it is essential to explore the synergistic mechanisms of these materials in addressing multiple environmental pollutants. Furthermore, it is imperative to enhance research on the regeneration and recycling technologies for sludge-based adsorbents, investigating more efficient and cost-effective methods such as pyrolysis, solvent washing, and chemical oxidation to improve the number of regeneration cycles and the effectiveness of recycling, thereby reducing treatment costs and enhancing resource utilization efficiency. Additionally, the quality of sludge varies significantly based on factors such as the source and volume of water treated, the treatment processes employed, and seasonal changes that affect the content of organic matter and sediments. Consequently, it is vital to conduct more comprehensive studies on the impact of different sludge sources such as municipal, papermaking, and textile industries, and various treatment processes including anaerobic digestion, aerobic digestion, and dewatered sludge. These studies should focus on how factors such as different sludge sources and treatment processes affect the constituent elements, structure, and adsorption catalytic performance of the products of sludge carbonization, which is crucial for advancing the development of sludge-based adsorbents and enhancing their practical applications in environmental management.

3.5.3 Keyword burst analysis. Keyword burst analysis serves as a technique to clarify changing trends and emerging directions within a given discipline while providing a quantitative description of research characteristics and their evolution over time.[72] By tracking hotspots through word frequency thresholds, lexical emergence captures the temporal evolution of a field and indicates future research directions through themes represented by mutated keywords. A total of 25 keywords are obtained by calculating keyword burst strength (Fig. 8). Sorting keywords by their year of appearance, the application of sludge-based materials for environmental pollution remediation exhibits a trend similar to that presented in Section 3.1 and can be categorized into three research stages.

From 2004 to 2010, the keywords "H_2S adsorption/oxidation" and "hydrogen sulfide" demonstrate high burst strength, suggesting that research hotspots predominantly revolved around the adsorption and oxidation of H_2S by sludge-based materials during this stage. During 2011–2018, the keywords "dyes", "equilibrium", "adsorbents", "methylene blue", and "phenol" exhibited higher burst strength, indicating a shift in research hotspots to the adsorption performance and mechanism of sludge-based adsorbents on pollutants such as dyes, methylene blue, and phenol. From 2019 to 2024, the frequent occurrence of keywords such as "sludge-derived biochar," "hydrothermal

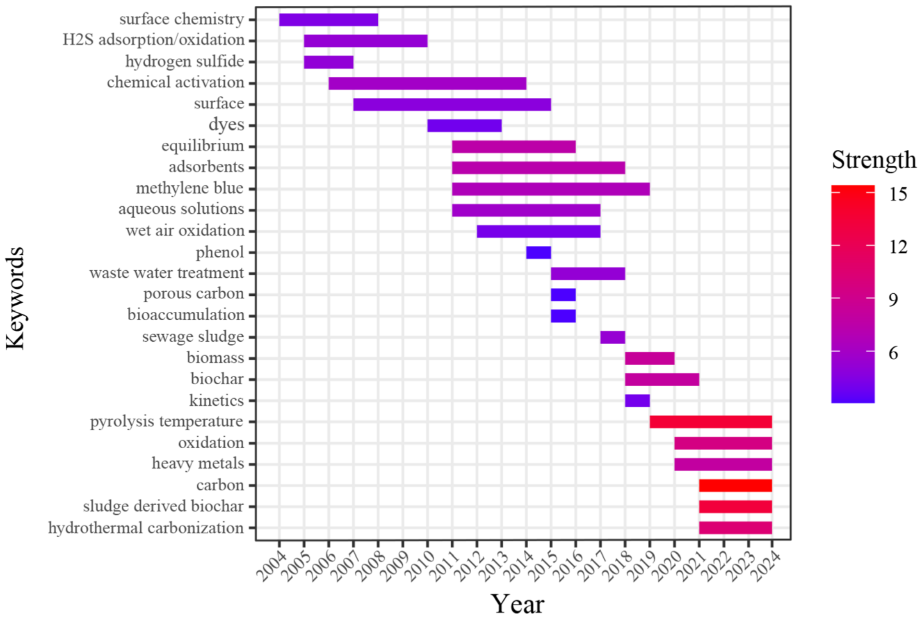

Fig. 8 Top 25 keywords with the highest burst strength from 2014 to 2024.

carbonization," and "pyrolysis temperature" highlights the prevailing focus on the technology for preparing sludge-derived biochar and the critical influence of temperature on this process. Additionally, the keywords "heavy metals" and "oxidation" suggest that the primary research interests during this stage have centered on the application of sludge-based materials for HMs adsorption and as catalysts in environmental pollution remediation. Despite these advancements, there has been comparatively less attention on emerging contaminants (ECs), including brominated flame retardants (BFRs), perfluorinated compounds (PFCs), microplastics, antibiotics resistance gene (ARGs), and nanomaterials. Future research should explore the potential of sludge-based materials to serve as adsorbents and catalysts for ECs, thus addressing critical gaps in current studies.

4. Future perspectives and challenges

4.1 Development of emerging sludge-based materials

The efficacy of sludge-based materials in adsorption and catalysis is significantly influenced by their preparation and modification methods. Frequently, a single method proves insufficient to fulfill the varied specific requirements of different application conditions. Consequently, the development of high-performance sludge-based materials necessitates the integrated application of various preparation and modification techniques tailored to different environmental applications to enhance resource utilization, environmental protection, and the efficiency of adsorption and catalysis. For instance, combining gasification and pyrolysis can effectively increase both the carbon content and the calorific value of biochar. Additionally, blending different types of raw materials, such as waste rubber and plastics, not only reduces production costs but also enhances biochar performance. Furthermore, the adsorptive or catalytic properties of composite biochar can be augmented by modifying its surface with nano-materials.

Numerous carbon-based materials including graphite particles, granular activated carbon, carbon nanotubes, carbon black, and graphene, are commonly utilized as electrode materials in various applications. However, the relatively high cost of these materials often restricts their broader application, making the development of cost-effective electrode materials from readily available sources such as sludge-derived peat a viable alternative. The preparation of low-cost electrode materials from sludge carbon seems to be a effective method. For instance, Zhang *et al.* explored the fabrication of sludge-based biochar electrodes at varying pyrolysis temperatures (400 °C, 500 °C, 600 °C, 700 °C, 800 °C), which were subsequently utilized to create a series of composite biochar electrodes on glassy carbon substrates, designated as GC400, GC500, GC600, GC700, and GC800. Assessed through cyclic voltammetry and electrochemical impedance spectroscopy, the electrodes prepared at temperatures above 600 °C showed enhanced electrocatalytic activity and stability, with superior oxygen evolution potentials that improved electrocatalytic efficiency compared to the control. During the electrocatalytic oxidation of methyl orange, the GC800 electrode displayed the highest removal efficiency, achieving a 94.49% reduction within 240 minutes. The performance of other electrodes followed a descending order with GC700 achieving a 90.61% reduction, GC600 at 86.96%, and GC500 at 80.32%.[73] However, the inherent complexity of sludge sources poses significant challenges in maintaining consistent performance of electrode materials, often rendering them insufficiently active for specific remediation processes. To address this issue, surface modification techniques such as adding functional groups and incorporating metal ions are used to enhance sludge-based electrode materials and improve their selective adsorption and removal capabilities for specific environmental pollutants. Alternatively, sludge-based electrode materials may be combined with other remediation agents, such as nanomaterials or activated carbon, to create emerging composite materials that exhibit enhanced remediation capacity, stability, and controllability. For instance, Zhao *et al.*, employed a straightforward pyrolytic curing method to fabricate a highly efficient electrode composed of Pd-doped sludge-derived biochar loaded onto nickel foam (Pd-SAC@Ni). This electrode demonstrated excellent electrocatalytic degradation capabilities for 4-chlorophenol (4-CP), achieving a reduction rate of 98.9% under conditions of a 5 mA cm^{-2} current density, a 4-CP concentration of 0.8 mM, and an initial pH of 7.0. Furthermore, the Pd-SAC@Ni electrode showcased notable reusability, maintaining a 4-CP removal efficiency of approximately 98% across multiple experimental runs.[74]

As the application fields of emerging materials continue to expand, there is a corresponding increase in the demand for technological research and development to meet specific material properties and application requirements. Addressing these needs requires exploring emerging and efficient preparation methods, including the development of novel activators, enhancements to the hydrothermal carbonation process, and advancements in microbial mineralization techniques, all aimed at achieving higher-performance sludge-based materials. Additionally, investigating sludge-based materials at the nanoscale is crucial as it can lead to a higher specific surface area and enhanced environmental remediation performance.

4.2 Soil improvement and environmental effects

Compared to other raw materials, SS is particularly rich in nutrients and minerals such as calcium (Ca), potassium (K), sodium (Na), and phosphorus (P), which are essential for plant growth. Following pre-treatment processes including drying, disinfection, dewatering, and stabilization, SS can be effectively transformed into organic fertilizer or used as a soil amendment to enhance soil structure and improve the ecological environment. For instance, Frišták *et al.* employed a pre-treatment involving Na_2CO_3 on SS and subsequently produced an inorganic phosphorus fertilizer through pyrolysis, a process that increased the total phosphorus and carbon concentrations in rye biomass while presenting a viable alternative to conventional inorganic phosphorus and organic carbon fertilizers.[75] Hossain *et al.* explored the effects of sludge biochar on the growth, yield, and HMs accumulation in cherry tomatoes, finding that it not only enhanced growth and yield but also significantly mitigated HMs accumulation in the fruits.[76] The preparation and application of sludge-based materials introduce potential environmental risks and safety concerns, primarily due to the presence of HMs, OPs, and other hazardous substances in the SS. The land application of sludge-based materials raises significant concerns due to the potential for soil plants to absorb toxic substances, which could accumulate in the food chain and pose threats to ecosystems and human health.[77] When sewage sludge is converted into biochar, its porous structure enhances soil permeability, water retention, and aeration while also stabilizing heavy metals within the biochar. Through pyrolysis, these metals transition from mobile and bioavailable forms to stable, less bioavailable states, significantly reducing leaching and mitigating environmental risks.[78] While the application of sludge-based biochar to soil increases the total concentration of HMs, its rich and dense pore structure and large specific surface area effectively adsorb and immobilize these metals, sequestering most in the residual fraction with low bioavailability and thereby reducing their uptake and accumulation by plants. For instance, Méndez *et al.* conducted a comparative study on the effects of untreated SS and biochar derived from sludge pyrolysis on HM dynamics in Mediterranean agricultural soils. Their findings revealed that sludge pyrolysis, used for biochar production, not only diminished the mobility and leaching risk of HMs contained within the sludge but also resulted in soils treated with biochar exhibiting lower risks of Cu, Ni, and Zn leaching compared to those treated with untreated sludge. Additionally, the biochar application effectively reduced the plant uptake of Ni, Zn, Cd, and Pb.[79]

Before the preparation and application of sludge-based materials, it is imperative to conduct a comprehensive analysis of the raw materials to ensure compliance with established standards for HM content, organic chemicals, and other relevant indicators, while also enhancing the treatment and stabilization of pollutants during these phases. For instance, integrating biochar with chelating agents such as citric acid or deoxynivalenol can mitigate the bioavailability and mobility of HMs, thereby stabilizing them in the soil.[80] Incorporating additives such as bentonite can enhance the soil's adhesion properties, significantly improving water retention and permeability, as well as increasing resistance to erosion. Furthermore, the addition of bio-fertilizers like microbial fungicides and compost can augment the biological activity of the soil, facilitating the release of nutrients and promoting plant growth. The inclusion of organic materials such as crop residues, and animal and plant wastes, can also elevate the organic matter content of the soil, thereby improving soil structure and permeability.

5. Conclusion

In this study, bibliometric analysis was utilized to assess the current research landscape concerning the use of sludge-based materials for environmental pollution remediation. The analysis included comprehensive assessment of the annual distribution of publications, identification of highly productive authors and their affiliations, international collaborations, sources of publication, prevalent keywords, and associated citation rates. This methodology facilitated the identification and exploration of research hotspots and enabled the discernment of emerging trends in the field. The essential conclusions are outlined as follows:

(1) Between 2004 and 2024, a total of 1228 publications were published in the WOSCC database on the topic of sludge-based materials for environmental pollution remediation, indicating

a phase of rapid development in this research field. China emerges as the leading contributor in this field, accounting for 63.19% of the total publications, significantly outpacing other countries. The leading research institutions involved in this field include the Chinese Academy of Sciences, Harbin Institute of Technology, and Tongji University. The journals most prominently featuring publications on this subject include the *Chemical Engineering Journal*, *Journal of Hazardous Materials*, and *Science of the Total Environment*.

(2) Through keyword co-occurrence and burst analysis, it has been determined that research on sludge-based materials for environmental pollution remediation predominantly concentrates on their preparation methods and the investigation of adsorption and catalytic processes. Future research should prioritize the development of advanced preparation and modification techniques, the creation of innovative catalytic and electrode materials, and the enhancement of sludge-based materials' applications in soil remediation. This entails a detailed investigation of their impacts on soil microbial community structures and functions, soil enzyme activities, and biological properties. Additionally, it is essential to quantitatively evaluate the costs, environmental impacts, and energy consumption of sludge-based materials across their entire lifecycle, from preparation to disposal.

(3) Despite the objective nature of bibliometric approaches, inherent biases and selective retrieval can limit the scope of literature, potentially misaligning with the primary research focus. This issue is compounded by the limitations of the WOSCC database, which may not cover all relevant studies, resulting in gaps that affect the generalizability of findings. Moreover, certain areas or journals might be underrepresented, leading to potential oversight of critical aspects or regional contributions. To enhance the depth and breadth of future research, it is essential to expand the range of consulted bibliographic and patent databases, including PubMed, Scopus, Google Scholar, Dimensions, and the Derwent Innovations Index in the future. Additionally, employing advanced technologies like natural language processing and machine learning for keyword extraction and literature screening can significantly improve literature retrieval, ensuring a more comprehensive and representative dataset in the field of sludge-based materials for environmental pollution remediation.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Author contributions

Fangyuan Jin: writing – original draft preparation, visualization; Jinxia Lu: data collection; Fei Sun: conceptualization; Fang Yang: writing – review and editing, software, supervision; Zhonghong Li: writing – review and editing, conceptualization. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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