Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-12
DOI: *10.15244/pjoes/208929* ONLINE PUBLICATION DATE: 2025-09-24

Original Research

Bibliometric Analysis of Mercury Removal from Flue Gas Based on Web of Science

Yu Feng[1], Yizhen Xie[1], Shijun Fu[1], Min Tan[1], Ping Ning[1,2], Kai Li[1,2], Dongdong Zhang[1,2]*, Xiaofeng Huang[1,2], Fei Wang[1,2], Xin Sun[1,2] , Yonghui Li[3]

[1]Faculty of Environmental Science and Engineering, Kunming University of Science and Technology, Kunming 650500, China
[2]National-Regional Engineering Center for Recovery of Waste Gases from Metallurgical and Chemical Industries, Kunming 650500, China
[3]Kunming Econ Technology Co., Ltd., Kunming 650607, China

Received: 16 March 2025
Accepted: 3 August 2025

Abstract

This study utilized HistCite, VOSviewer, and CiteSpace analytical tools to generate visualizations of data retrieved from the Web of Science (WOS) database, aiming to comprehensively understand current research status and frontier trends in flue gas mercury removal. A systematic analysis was conducted on 2,489 publications spanning 1998 to 2024, involving contributions from 4,496 authors at 1,245 institutions across 64 countries, published in 290 journals. The results indicate that the number of publications in the field of flue gas mercury removal has demonstrated an overall upward trend over the past two decades. Currently, China and Huazhong University of Science and Technology are identified as the most productive country and research institution, respectively, in this research domain. *Environmental Science & Technology* emerges as the most influential and authoritative journal in flue gas mercury removal studies. Keyword cluster analysis reveals three predominant research themes: adsorption-based mercury removal technologies utilizing activated carbon and other adsorbent materials, catalytic oxidation mercury removal technologies, and oxidation-based mercury removal technologies. Furthermore, keyword burst detection analysis highlights that the simultaneous removal of SO_2, NO_x, and Hg^0 has become a current research focus in this field.

Keywords: flue gas, Hg^0 removal, web of science, bibliometric analysis

Introduction

Mercury is a global pollutant posing significant threats to humans and the environment. Coal combustion accounts for a major proportion of anthropogenic mercury emissions [1]. As a toxic air pollutant, mercury exhibits characteristics such as persistence, atmospheric mobility, and bioaccumulation in the environment, causing substantial adverse impacts on both ecosystems and human health, which has garnered worldwide attention. Countries have successively implemented policies establishing mercury emission standards for various regions and industries, along with promulgating relevant legislation [2, 3]. In

*e-mail: zddkmust@163.com

September 2011, China's Ministry of Environmental Protection first included mercury as a controlled pollutant from coal-fired power plants, issuing the “Emission Standard of Air Pollutants for Thermal Power Plants (GB13223-2011)”. This standard mandated that total mercury concentrations in flue gas emissions from coal-fired power plants should not exceed 0.03 mg/m^3 after January 1, 2015. Furthermore, in January 2013, the United Nations Environment Programme (UNEP) adopted the Minamata Convention to mitigate global mercury emissions and pollution [4]. China submitted its instrument of ratification to the UN in August 2016, becoming the 30th signatory nation. The Convention officially entered into force in August 2017 [5]. These developments demonstrate China's heightened prioritization of mercury emission control, active international engagement, rigorous legislative actions, and accelerated research initiatives targeting mercury removal from industrial flue gases.

With China's rapid economic and industrial development, energy demand continues to escalate. Fossil fuels dominate China's energy portfolio, with coal constituting a primary component. Pollutants generated from coal combustion exert substantial impacts on ecological systems and public health [6, 7]. Trace mercury from coal is released into the atmosphere with flue gas during combustion, posing persistent ecological and health risks. Mercury in coal-fired flue gas primarily exists in three forms: elemental mercury (Hg^0), divalent oxidized mercury (Hg^{2+}), and particulate-bound mercury (Hg^p) [8]. As gaseous mercury traverses ductwork, its speciation undergoes transformations influenced by coal composition elements and temperature gradients along the flue path. Halogens in coal oxidize portions of Hg^0 to Hg^{2+}, while oxidative components on fly ash surfaces facilitate partial Hg^0 conversion to Hg^{2+}. Conversely, Hg^{2+} may adsorb onto fly ash particles, forming Hg^p [9]. Distinct mercury species require differentiated removal approaches: water-soluble Hg^{2+} can be absorbed via wet flue gas desulfurization (WFGD) systems, and Hg^p is effectively captured by electrostatic precipitators (ESP) and fabric filters (FF) [10, 11]. However, Hg^0 is extremely difficult to capture due to its low water solubility and high volatility at room temperature. Consequently, the removal of elemental mercury (Hg^0) is a crucial aspect of controlling mercury pollution.

Bibliometric analysis, a mathematical-statistical approach utilizing historical publication data to assess field development and predict future trends/hotspots, has gained increasing application due to its objective quantitative advantages [12, 13]. This study employs bibliometric methods with analytical tools including WOS native functions, HistCite citation mapping, and visualization software VOSviewer/CiteSpace to examine Hg^0 removal research from 1998-2024 in the WOS Core Collection. The analysis encompasses annual trends, leading research entities, prominent journals, research hotspots, and frontiers, providing references for future investigations.

Materials and Methods

Data Sources

The data in this paper is selected from the Web of Science (WOS) Core Collection database, which is the most authoritative database for tracking high-quality research. It holds significant academic value across various fields, including natural sciences, engineering technology, social sciences, arts, and humanities. The search terms used were: “TS = (oxidation and mercury and flue gas) OR TS = (adsorption and mercury and flue gas) OR TS = (catalytic and mercury and flue gas) OR TS = (mercury removal and mercury and flue gas)”, with a period from January 1, 1998, to December 31, 2024. The article types selected were “Article” and “Review Article”. The selected papers were exported in “plain text file” format, with the content option set to “Full Record and Cited References”, and then imported into Histcite Pro and CiteSpace software. The papers were also exported in “Tab-delimited file” format, with the content option set to “Full Record”, and imported into VOSviewer software. A total of 2,489 papers were retrieved, involving 4,496 authors, 290 journals, and 46,153 references.

Research Methods

Statistical analysis of literature related to flue gas mercury removal was performed using the WOS database’s built-in analysis tools, Histcite citation analysis software, VOSviewer, CiteSpace literature visualization software, Excel 2019, and Origin 2021. The research outcomes in the field of flue gas mercury removal were summarized, including publication volume and annual trends, major research institutions, leading journals, research hotspots, and frontiers. Citation analysis was conducted using Histcite Pro 2.1 software to gather statistics on publication volume, total citations, and local citations. Total global citation score (TGCS) refers to the total number of citations of articles within different categories in the WOS database, where the citing papers may be unrelated to the original research direction. Local total citation score (TLCS) refers to the number of citations of articles within different categories in a local dataset (i.e., all literature imported into Histcite Pro 2.1 software after entering search terms into the WOS database). Since articles in the local dataset are related to the search terms, TLCS is often used to reflect the influence within the research field. VOSviewer 1.6.20 literature visualization software was used to map author collaboration and keyword co-occurrence networks, reflecting the core academic groups and research hotspots in the field. CiteSpace 6.3.1 was used for scientific mapping analysis of institutional collaborations and research hotspots.

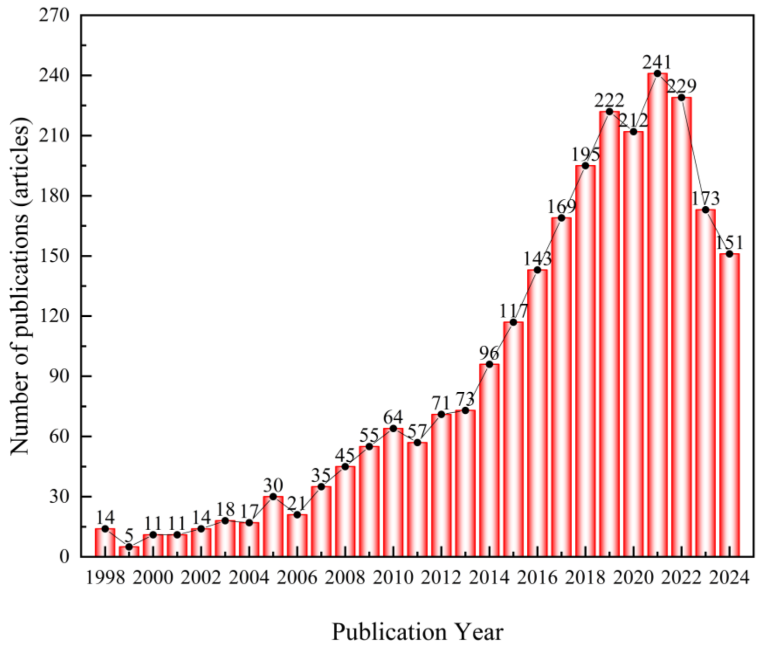

Fig. 1. Trend of published literature on flue gas mercury removal research from 1998 to 2024.

Results and Discussion

Number of Publications and Annual Trends

The publication volume reflects the temporal variation in the number of papers published within a research field, thereby providing readers with insights into the developmental status of the field and enabling predictions of future trends [14]. Analysis of publication volumes over distinct periods in a specific domain can intuitively reveal research dynamics. Analysis of the annual publication volume of flue gas mercury removal research from 1998 to 2024 (Fig. 1) demonstrates an overall increasing trend in publications. The growth trend can be divided into three distinct stages:

(1) 1998-2004: A stage characterized by low publication output and slow growth, with a total of 90 publications and an annual average of approximately 13 papers. It indicates that during this period, research in flue gas purification predominantly focused on conventional pollutants such as sulfur oxides (SO_x) and nitrogen oxides (NO_x), with limited attention to mercury removal.

(2) 2005-2011: A stage marked by accelerated growth, with 307 publications and an annual average of approximately 44 papers. This signifies that mercury removal gradually emerged as a cutting-edge and highly prioritized topic in flue gas purification, attracting global research attention.

(3) 2012-2024: A stage of rapid growth, with 2,092 publications and an annual average of approximately 174 papers. The publication volume peaked at 241 papers in 2021, accounting for 84.05% of the total publications within the statistical period. During this phase, global attention to mercury pollution intensified. In January 2013, the United Nations Environment Programme adopted the Minamata Convention on Mercury to mitigate global mercury emissions and pollution. In China, a series of laws and regulations addressing mercury pollution were enacted starting in 2011. Notably, the Emission Standard of *Air Pollutants for Thermal Power Plants (GB13223-2011)*, implemented on January 1, 2015, for the first time classified mercury as a controlled pollutant in coal-fired power plants and stipulated a stringent emission limit of 0.03 mg/m^3. The enforcement of these conventions, laws, and standards has significantly heightened academic interest in mercury removal research, driven by increased research investments and, consequently, accelerated publication growth.

Analysis of Research Countries

The publication volume in a particular research field serves as an indicator of a nation's academic impact and scientific proficiency within that domain [15]. According to the SCI database in the Web of Science core collection, researchers from 64 countries and regions have conducted studies on mercury removal. Table 1 lists the top 10 countries and regions based on publication volume. China holds the leading position with 1,892 papers, representing 76.01% of the total publications, establishing overwhelming superiority in this field. The United States follows with 374 papers (15.03%). China's dominance is further evidenced by exceptional citation metrics: a Total Local Citation Score (TLCS) of 27,437 and a Total Global Citation Score (TGCS) of 62,964, both substantially higher than those of other nations. This reflects substantial research investment and the presence of numerous research teams in China, resulting in a high

Table 1. Top 10 countries of publications on flue gas mercury removal from 1998 to 2024.

Rank	Country	Records	TLCS	TGCS
1	China	1892	27437	62964
2	USA	374	10261	20424
3	Canada	66	1658	3309
4	South Korea	57	737	1798
5	Japan	51	969	1739
6	Spain	50	227	1433
7	Poland	50	152	1791
7	UK	46	584	1883
9	Australia	44	348	1554
10	Germany	41	367	1391

Table 2. Top 10 institutions of publications on flue gas mercury removal from 1998 to 2024.

Rank	Institution	Records	TLCS	TGCS	TLCSPR
1	Huazhong University of Science and Technology	295	6238	12262	21.15
2	North China Electric Power University	183	1176	4781	6.43
3	Southeast University	150	2080	4378	13.87
4	Jiangsu University	120	2427	5873	20.22
5	Zhejiang University	112	1203	3310	10.74
6	Shanghai Jiao Tong University	110	3171	5597	28.83
7	Shanghai University of Electric Power	110	690	3324	6.27
8	Central South University	104	443	2319	4.26
9	Chinese Academy of Sciences	96	1496	3557	15.58
10	Tsinghua University	87	1551	3864	17.83

volume of scientific output. It also highlights China's strong commitment to mitigating mercury pollution from flue gas. In the United States, scholars have made notable advancements in optimizing Activated Carbon Injection (ACI) technology and elucidating the synergistic mechanisms of mercury removal via SCR catalysts [16, 17]. Canadian researchers have focused on developing low-temperature catalytic systems; notably, the University of Waterloo's CuO/TiO_2 catalyst achieved Hg^0 oxidation rates exceeding 85% at 120 °C [18, 19]. In South Korea, significant progress has been made in novel catalytic materials. The Korea Advanced Institute of Science and Technology (KAIST) developed a Ce-doped MnO_x/TiO_2 catalyst that enables highly efficient oxidation at 100 °C [20]. At the same time, Yonsei University investigated synergistic mercury removal by integrating photocatalysis with wet desulfurization processes [21, 22]. In Spain, the Royal Academy of Sciences reported that ionic liquid scrubbing technology achieved a mercury removal efficiency of 98%, and the Technical University of Madrid developed nitrogen-doped activated carbons with enhanced adsorption capacity [23]. Collectively, these efforts underscore the global nature of research on mercury removal technologies and the diverse contributions made by different countries.

Analysis of Key Research Institutions

According to the SCI database in the Web of Science core collection, a total of 1,245 research institutions have conducted studies on mercury removal. Table 2 reveals that all the top 10 institutions in publication output are Chinese. Huazhong University of Science and Technology leads with 295 publications, followed by North China Electric Power University (183) and Southeast University (150). In citation metrics, Huazhong University of Science and Technology maintains its leadership with a TLCS of 6,238 and a TGCS of 12,262. Shanghai Jiao Tong University achieves the highest TLCSPR (about 29 citations per paper), demonstrating the significant impact of both institutions in this field.

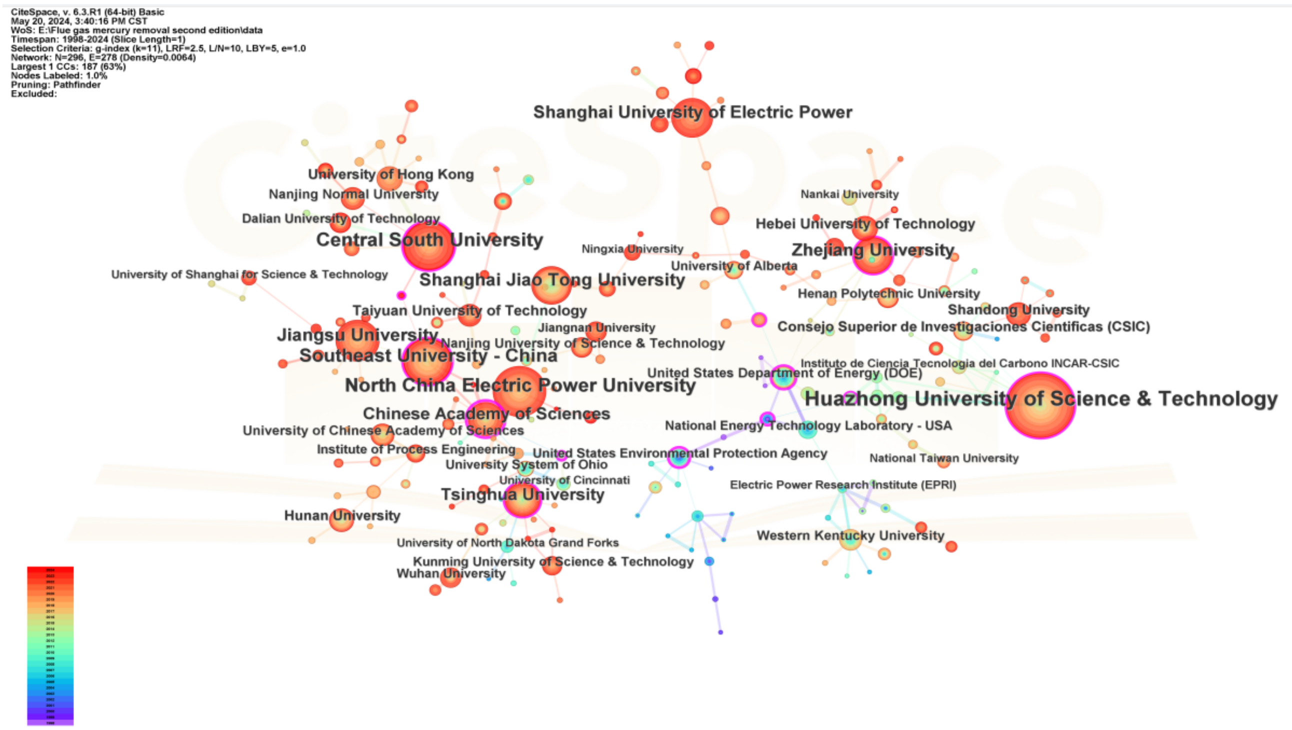

Fig. 2. Co-occurrence network map of publishing organizations.

These findings confirm Chinese research institutions as primary contributors to mercury removal research with remarkable achievements.

This study employed CiteSpace 6.3.1 to construct an institutional co-occurrence network (Fig. 2), visually illustrating publication contributions and collaborative relationships among institutions. Each node represents a research institution, with concentric rings of varying colors denoting publication timelines (inner rings correspond to earlier years). The width of each colored ring reflects annual publication volume, while connecting lines indicate collaborations, with line thickness proportional to collaboration frequency [24]. The analysis yielded a network with N = 296 nodes (institutions) and E = 278 links (collaborations), with a network density of 0.0064. The relatively high number of inter-institutional connections suggests active collaborations among leading contributors in this field. Analysis indicates that research institutions in China are at the forefront of this field, possessing notable developmental advantages and occupying a central role in global research networks. Their publication output and frequency of collaboration considerably exceed those of institutions in other countries. International collaborations are primarily concentrated with entities such as the University of Waterloo in Canada and laboratories affiliated with the U.S. Department of Energy. However, these partnerships remain relatively limited, often taking the form of sporadic, single-institution collaborations—for example, joint research on catalyst mechanisms between Huazhong University of Science and Technology and the U.S. Argonne National Laboratory. Overall, international cooperation in this domain remains insufficient and warrants further strengthening. Looking ahead, it is essential to promote more robust technical exchange through transnational research projects, the establishment of joint laboratories, and other collaborative platforms to accelerate the global development of mercury removal technologies for flue gas treatment.

Main Published Journals

Bibliometric analysis enables researchers to identify core journals within a specific research domain. Analysis using the HistCite Pro 2.1 software revealed a total of 290 journals published research papers on flue gas mercury removal during the statistical period. Table 3 shows the top 10 journals by publication volume, predominantly in energy, environmental, and chemical engineering fields, mainly comprising high-impact journals in their respective fields.

In terms of publication volume, *Fuel* ranked first with 336 publications, demonstrating strong thematic alignment with mercury removal research, as well as indicating its strong appeal to researchers and high submission rates. *Chemical Engineering Journal* and *Energy & Fuels* follow closely with 252 and 236 publications, respectively. Subsequent journals include *Environmental Science & Technology*, *Journal of Hazardous Materials*, and *Fuel Processing Technology*, with publications ranging from 108 to 138. These six journals, each exceeding 100 publications, represent the

Table 3. Top 10 journals of publications on flue gas mercury removal from 1998 to 2024.

Rank	Journal	Records	TLCS	TGCS
1	Fuel	336	4505	11673
2	Chemical Engineering Journal	252	4814	11797
3	Energy & Fuels	236	3793	6343
4	Environmental Science & Technology	138	6543	11570
5	Journal of Hazardous Materials	125	2672	6959
6	Fuel Processing Technology	108	3013	5802
7	Industrial & Engineering Chemistry Research	77	1959	3431
8	Environmental Science and Pollution Research	55	386	991
9	Applied Surface Science	51	568	1619
10	Journal of the Air & Waste Management Association	49	882	1563

most influential platforms for flue gas mercury removal research.

From the perspective of Total Local Citation Score (TLCS), *Environmental Science & Technology* (EST) dominates with 6,543 citations, significantly outperforming other journals. As an authoritative and highly influential journal in environmental sciences, it consistently leads research frontiers and hotspots in this field. *Chemical Engineering Journal* and *Fuel* rank second and third with TLCS values exceeding 4,500 each, followed by *Energy & Fuels* at 3,793 citations. These three top journals in chemical engineering and energy demonstrate broad academic impact.

Regarding the Total Global Citation Score (TGCS), *Environmental Science & Technology*, *Fuel*, and *Chemical Engineering Journal* all surpass 10,000 citations with narrow margins between journals, reflecting their global recognition and exceptional influence in the field. *Journal of Hazardous Materials*, *Energy & Fuels*, and *Fuel Processing Technology* follow with TGCS ranging from 5,802 to 6,959, showing notable gaps compared to the top three.

Synthesizing publication and citation metrics, *Environmental Science & Technology* emerges as the most impactful and guiding journal in flue gas mercury removal. Despite not having the highest publication volume, its TLCS and TGCS demonstrate overwhelming advantages, providing researchers worldwide with cutting-edge breakthroughs and making outstanding contributions to field development. *Chemical Engineering Journal* and *Fuel* also exhibit significant strengths in publication volume, TLCS, and TGCS, playing vital roles in advancing this research area. Close attention to these journals enables researchers to efficiently track global trends and hotspot issues in flue gas mercury removal studies.

Distribution of Authors

Table 4 summarizes the top 10 most prolific authors in the field of flue gas mercury removal research from 1998 to 2024, all of whom are affiliated with Chinese institutions. Notably, some authors belong to the same research teams, further highlighting the significant contributions of Chinese researchers in this field.

In terms of publication output, Duan Yufeng from Southeast University, Wu Jiang from Shanghai University of Electric Power, and Liu Yangxian from Jiangsu University ranked as the top three individual contributors. Among the top 10 authors, Liu Yangxian and Wang Yan from Jiangsu University formed the most productive team, achieving a total of 186 publications. Yang Jianping and Li Hailong from Central South University ranked second with 178 collaborative publications. It demonstrates these researchers' sustained engagement in mercury pollution control from flue gases, reflecting their profound expertise, consistent academic output, and substantial influence in this field.

Regarding citation metrics, Li Hailong attained the highest total local citation score (TLCS) of 3,079, followed closely by Qu Zan (2,869 TLCS) and Zhang Junying (2,799 TLCS). In total global citations (TGCS), Liu Yangxian led with 5,346 citations, followed by Li Hailong (4,894 TGCS) and Qu Zan (4,824 TGCS), with Yan Naiqiang and Zhang Junying both receiving approximately 4,500 TGCS. When considering average local citations per paper (TLCSPR), Zhang Junying, Yan Naiqiang, and Qu Zan (along with Li Hailong) demonstrated particularly high performance. These citation metrics confirm these scholars' substantial influence and recognition in mercury removal research, with Li Hailong, Qu Zan, Yan Naiqiang, and Zhang Junying emerging as representative figures whose work exemplifies China's research capabilities and plays a pioneering role in advancing this field.

Systematic analysis of authors and their collaborative networks facilitates identification of core academic

Table 4. Top 10 authors of flue gas mercury removal studies from 1998 to 2024.

Rank	Author	Records	TLCS	TGCS	TLCSPR
1	Duan Yufeng	104	1556	3072	14.96
2	Wu Jiang	103	713	3141	6.92
3	Liu Yangxian	95	2308	5346	24.29
4	Wang Yan	91	1347	3401	14.80
5	Yang Jianping	90	2270	4282	25.22
6	Liu Jing	90	1529	3749	16.99
7	Li Hailong	88	3079	4894	34.99
8	Qu Zan	81	2869	4824	35.42
9	Zhang Junying	78	2799	4513	35.88
10	Yan Naiqiang	76	2720	4609	35.79

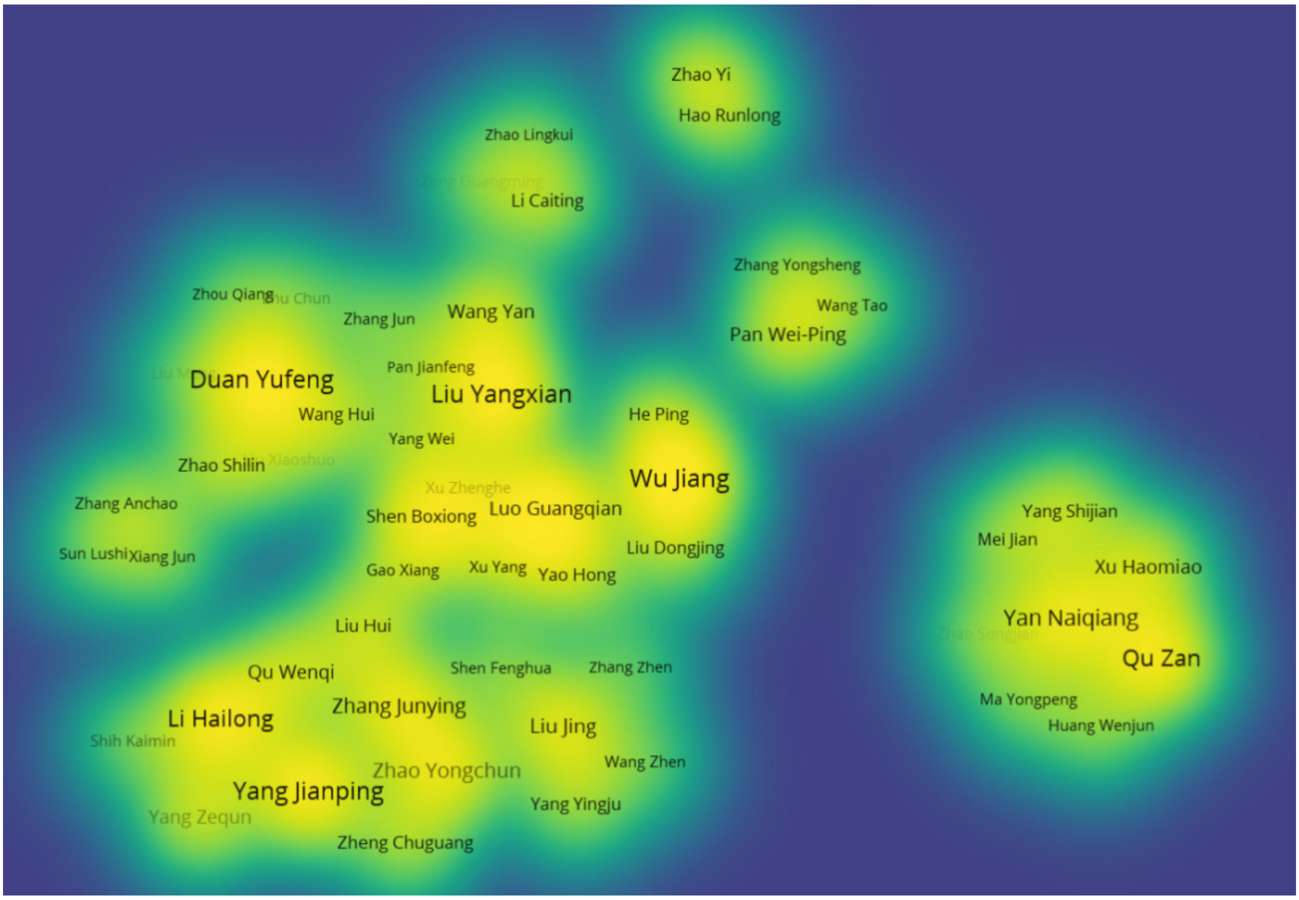

Fig. 3. Author cooperative network density visualization.

groups and prolific contributors in flue gas mercury removal research [25]. Key research teams are led by Liu Yangxian, Duan Yufeng, Li Hailong, Yang Jianping, Wu Jiang, and Qu Zan (Fig. 3). The team led by Liu Yangxian focuses on photocatalytic oxidation and radical-based advanced oxidation methods for multi-pollutant removal [26]. Duan Yufeng's group investigates mercury and heavy metal removal from coal combustion, sustainable renewable adsorbent technologies and equipment for mercury removal in coal-fired power plants, online monitoring systems for mercury in flue gas, and high-efficiency mercury removal technologies and devices [27]. Li Hailong and Yang Jianping's team investigates catalytic oxidation mechanisms of elemental mercury (Hg^0) and adsorption-fixation mechanisms and stability of mercury in coal-fired flue gas [28]. Wu Jiang's group explores combustion and pollutant control, solar photovoltaic/thermal/photochemical applications, and novel catalytic/energy storage materials, achieving breakthroughs in emerging advanced oxidation technologies and photocatalytic removal of heavy metals from flue gas [29]. Qu Zan's team pioneers innovative methods and theories for mercury pollution control, with notable advancements in Hg^0 speciation regulation, interfacial reaction mechanisms, and functional materials development [30].

Cluster Analysis of Research Hotspots

“Keywords” refer to the high-level generalization and refinement of an author’s academic ideas, research themes, and research content within a particular field [31]. By analyzing the keywords and their frequency within a specific field, one can grasp the current research hotspots and assess the pace of updates in the field’s research and the vitality of the discipline [32].

Keyword analysis was performed on the literature retrieved for this study using VOSviewer 1.6.20 software, generating a keyword clustering analysis map (Fig. 4). The map uses different colors to represent distinct clusters, and the size of the circles indicates the frequency of keyword occurrences. The keyword co-occurrence network is divided into three clusters: Cluster A focuses on elemental mercury in coal-fired flue gas, addressing mercury forms, emissions, removal, and removal efficiency, primarily via oxidation, catalytic oxidation, adsorption, and other methods for removing elemental mercury. It includes research on adsorbents, catalysts, oxidants, photocatalysis, and selective catalytic reduction. Cluster B centers on the removal of elemental mercury, focusing on low-temperature removal, photocatalytic oxidation of elemental mercury, reaction mechanisms, and reaction kinetics. Cluster C focuses on the simultaneous removal of SO_2, NO_x, and Hg^0 from flue gas.

Clusters A and B indicate that over the past few decades, many techniques for controlling elemental mercury have been developed, including adsorption removal, catalytic oxidation, advanced oxidation, and traditional chemical oxidation [33-36]. Adsorption removal technology can firstly convert Hg^0 into Hg^p, which is then captured by electrostatic precipitators (ESP) or bag filters, effectively removing Hg^0 from flue gas. The main adsorbents used for removing Hg^0 from flue gas include activated carbon, fly ash, and other carbon-based adsorbents, calcium-based adsorbents, metal oxides, and natural mineral materials [37, 38]. Currently, exploring and developing high-performance and low-cost adsorbents is a key research focus and direction in this field. In recent years, catalytic oxidation removal technology for Hg^0 in flue gas has also gained widespread attention because it can fully utilize selective catalytic reduction (SCR) denitrification catalysts to oxidize Hg^0 to Hg^{2+} in a simplified and low-cost process [39, 40]. Currently, the focus in this field is on developing cost-effective and highly reliable catalysts. Both adsorption and catalytic oxidation technologies show promising results in laboratory studies, but still require further improvement for industrial applications due to their low stability, reliability, lack of effective regeneration methods, and high costs. Additionally, traditional chemical oxidation methods, such as $KMnO_4$, $NaClO_2$, H_2O_2, O_3, ClO_2, KClO, and ferrates, have been used in various reactor types, employing ionic liquids, air, halides, and membrane separation for the removal of gaseous Hg^0 [41-44]. However, these technologies remain commercially unviable due to their high costs, secondary pollution, and low removal efficiency. Therefore, more research is needed to develop more cost-effective flue gas mercury removal technologies for large-scale applications. Advanced oxidation technology refers to methods that generate hydroxyl radicals (·OH) through various physical or chemical processes. ·OH is a highly potent oxidant in nature, enabling nearly complete oxidation of most environmental pollutants. Additionally, ·OH-induced oxidation reactions produce almost no secondary pollutants, as the final decomposition products are O_2 and H_2O [45]. Currently, there are four major types of advanced oxidation technologies with great potential for removing Hg^0 from flue gas: (1) plasma advanced oxidation technology; (2) TiO_2 photocatalytic advanced oxidation technology; (3) photochemical advanced oxidation technology; and (4) active oxidant advanced oxidation technology [46-49].

Cluster C focuses on research related to the simultaneous removal of SO_2, NO_x, and Hg^0, with the most mature technologies for removing SO_2, NO_x, and Hg^0 from flue gas being selective catalytic reduction (SCR) [50], wet flue gas desulfurization (WFGD) [51], and activated carbon injection (ACI) [52]. Although this multi-stage treatment strategy can achieve deep removal of SO_2, NO_x, and Hg^0, it still faces drawbacks such as high construction and operating costs, large land requirements, complexity, and low stability. Therefore, developing an economical, efficient, and integrated method for the simultaneous removal of SO_2, NO_x, and Hg^0 is one of the main research directions in atmospheric pollution control. Efficient and rapid removal of NO and Hg^0 is the key step in the simultaneous removal of SO_2, NO_x, and Hg^0 [53]. Traditional adsorption techniques exhibit limited efficacy in the removal of nitric oxide (NO) and elemental mercury (Hg^0). Catalytic oxidation has emerged as a superior approach for synergistic control of multiple flue gas contaminants, notably sulfur dioxide (SO_2), nitrogen oxides (NO_x), and Hg^0. This methodology enhances subsequent capture processes as oxidized species (including NO_2, NO_3, N_2O_5, and Hg^{2+}) demonstrate significantly improved solubility, enabling efficient removal through downstream pollution control devices such as wet flue gas desulfurization systems or electrostatic precipitation units. These simultaneous removal methods are classified based on the reaction medium as solid-gas phase, liquid-phase oxidation, gas-phase oxidation, and combined-phase oxidation [54-

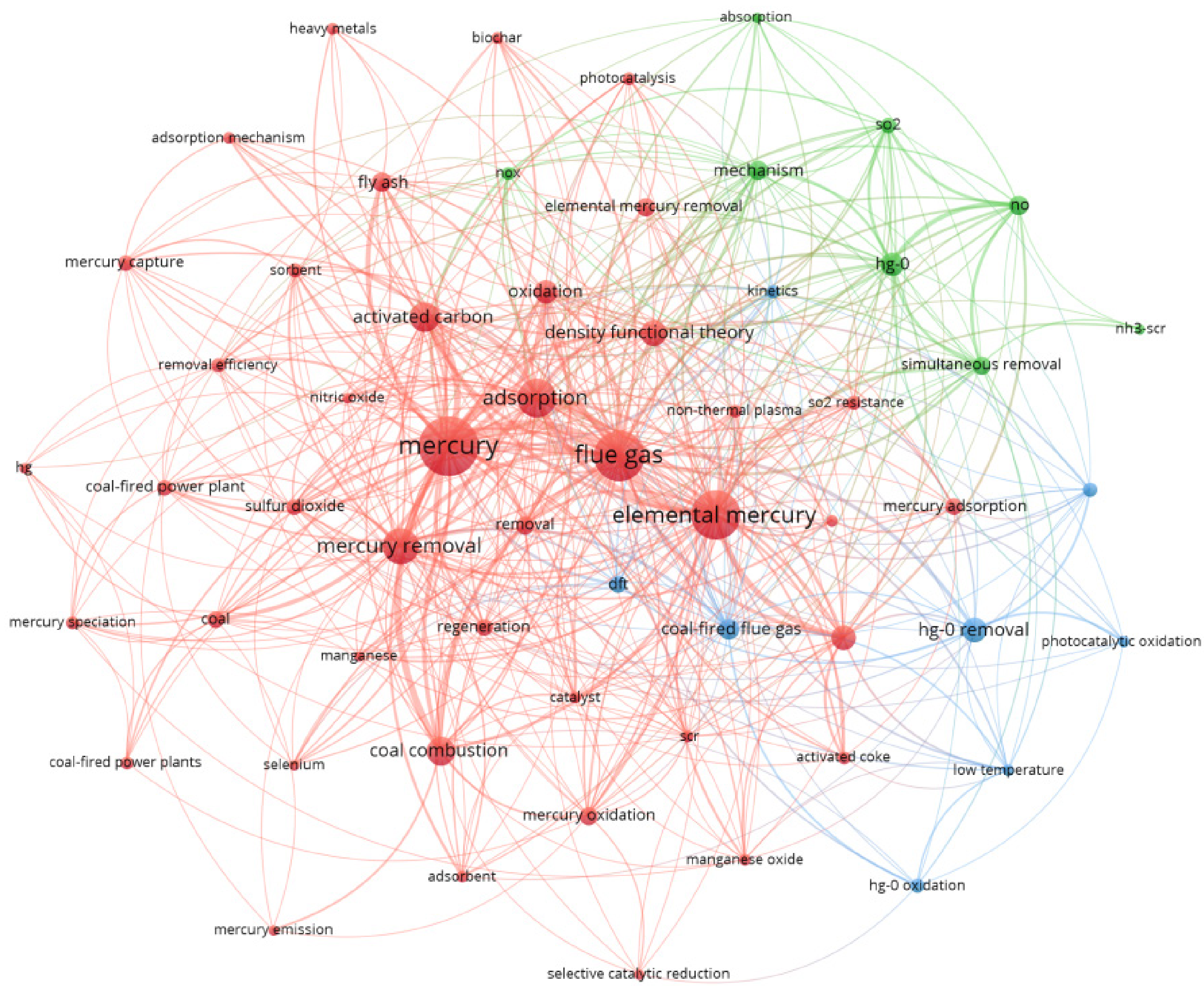

Fig. 4. Keyword co-occurrence cluster visualization.

57]. Another technological approach is to develop more efficient SCR catalysts that can oxidize Hg^0 to Hg^{2+} efficiently without reducing the NO reduction rate [58].

Keyword Emergence Analysis

Emergent keywords refer to terms that suddenly appear and have high citation frequencies, which, to some extent, represent the research hotspots and the spatiotemporal evolution patterns of a research field [59]. In terms of time, frontier keywords evolve continuously, showing a phased development pattern. This paper uses CiteSpace 6.3.1 software to extract the top 25 keywords with the strongest emergence intensity in the field of flue gas mercury removal from 1998 to 2024 (Fig. 5). These keywords were chronologically arranged based on their initial burst years for burst analysis. As shown in Fig. 5, 1998-2006 marked the early stage, featuring keywords with the strongest emergence intensity, including "sorption (18.88)", "sorbents (16.79)", "fired power plants (21.23)", and "activated carbon (12.67)". Initial research primarily focused on Hg^0 removal through adsorption methods, particularly using activated carbon as a sorbent. The intermediate stage (2007-2015) was characterized by prominent keywords such as "combustion flue gas (20.35)", "emissions (16.99)", "low temperature (12.57)", and "catalysts (11.23)". Research during this period emphasized mercury emission issues in coal-fired flue gas and employed catalytic oxidation/photocatalytic methods for elemental mercury removal. Recent developments (2016-2023) featured high-emergence keywords including "efficient removal (11.39)", "simultaneous absorption (9.75)", and "integrative process (9.56)". Current research hotspots focus on synergistic removal of multiple pollutants to enhance mercury elimination efficiency through integrated approaches. In summary, existing mercury removal technologies still face challenges, including high investment and operational costs, low removal efficiency, and secondary pollution risks. Therefore, developing more efficient and cost-effective mercury removal technologies and equipment remains crucial and represents the primary direction for future research.

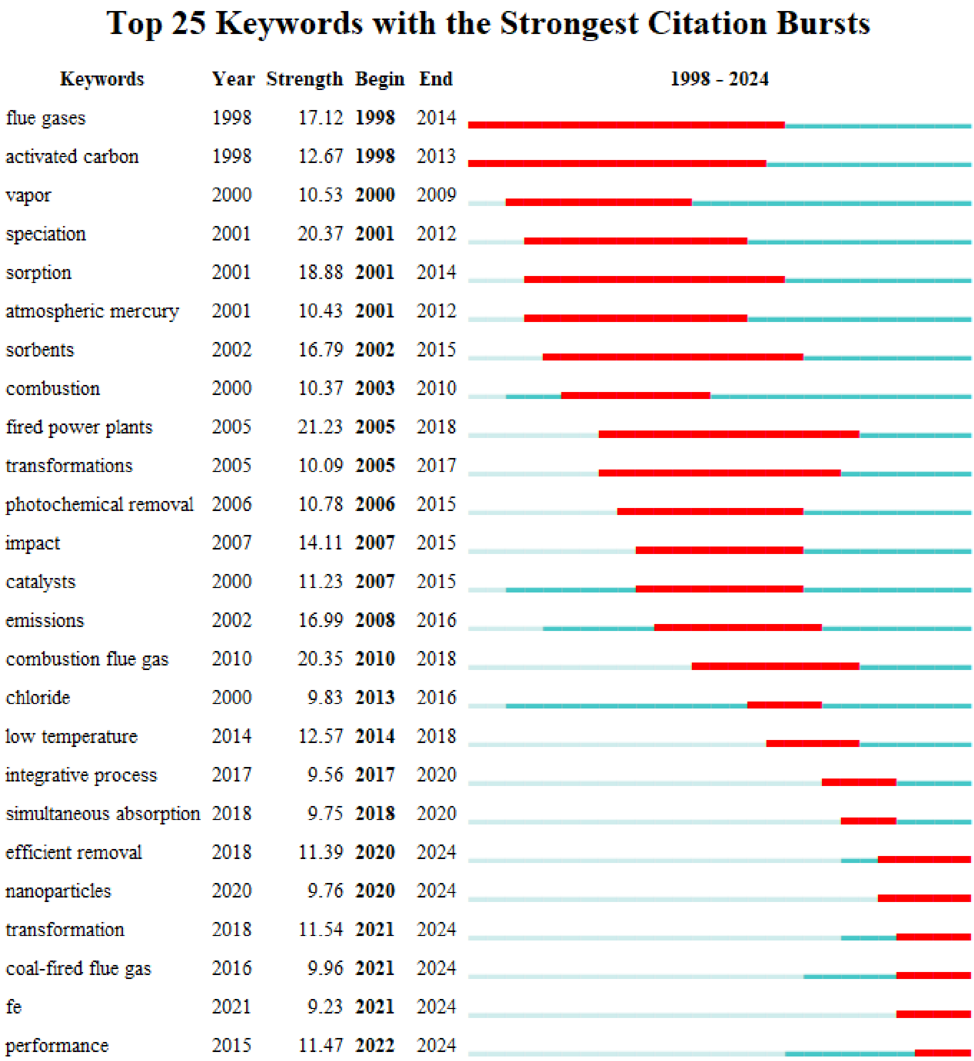

Fig. 5. Keyword emergence analysis.

Summary and Outlook

The findings demonstrate that research on flue gas mercury removal has garnered increasing attention in recent years, with a consistent annual growth in publications. China exhibits the highest research engagement, leading in both publication quantity and citation metrics (TLCS and TGCS), significantly surpassing other nations. Huazhong University of Science and Technology and Shanghai Jiao Tong University hold substantial influence in this research domain. The primary journals publishing mercury removal research include *Fuel*, *Chemical Engineering Journal*, *Energy & Fuels*, *Environmental Science & Technology*, and *Journal of Hazardous Materials*. Scholars Li Hailong, Qu Zan, Yan Naiqiang, and Zhang Junying represent China's research leadership in this field, demonstrating significant academic influence. High-frequency keyword analysis and keyword co-occurrence network mapping reveal that current research focuses on Hg^0 removal through adsorption, catalytic oxidation, and oxidation methods. Emerging technologies such as photocatalytic oxidation, non-thermal plasma, and photochemical removal are also gaining traction. A prominent research frontier involves synergistic pollutant removal to enhance mercury elimination efficiency. The simultaneous removal of SO_2, NO_x, and Hg^0 has emerged as a promising strategy for cost-effective multi-pollutant control in flue gas, representing a significant development direction in air pollution control technologies.

Acknowledgments

This work was funded by the Natural Science Foundation of China (21966017), Yunnan Key Laboratory of Phosphogypsum Recycling and Ecological Utilization (202449CE340028), and Yunnan International Joint R&D Center for Waste Resource Recovery in Metallurgical and Chemical Industries (202403AP140008).

Conflict of Interest

The authors declare that they have all consented to be identified as the authors of the work submitted, there is no conflict or dispute between them in respect of their contributions to the work, the work does not violate third parties' rights, and there is no conflict of interest whatsoever in connection with the work submitted.

References

1. MA Y.P., WANG J.D., GU W.T., ZHANG X.J., XU H.M., HUANG W.J., GUO Y.H., WANG S.B. New insights into elemental mercury removal from flue gas by a MoS_2 heterogeneous system. Chemical Engineering Journal, **433**, 8, **2022**.
2. WEI Z., TANG M., HUANG Z., JIAO H. Mercury removal from flue gas using nitrate as an electron acceptor in a membrane biofilm reactor. Frontiers of Environmental Science & Engineering, **16** (2), 20, **2022**.
3. ZHAO B., WANG S., HAO J. Challenges and perspectives of air pollution control in China. Frontiers of Environmental Science & Engineering, **18** (6), 68, **2024**.
4. WANG Z., PAN L., LI Y., XU W., NIE T., SUN Z. Effect of emission standard of air pollutants for thermal power plants on regional acid deposition: a numerical simulation. China Environmental Science, **34** (9), 2420, **2014**.
5. ZHAO Z., YANG J., ZHAO M., ZHU J. Mercury waste management in China: implications on the implementation of the Minamata Convention on Mercury. Journal of Material Cycles and Waste Management, **25** (5), 2584, **2023**.
6. LI S., GAO L., HE S., YANG D., WANG C., ZHENG Y. Carbon capture in power sector of China towards carbon neutrality and its comparison to renewable power. Fundamental Research, **4** (4), 916, **2024**.
7. YUAN P., MA H., SHEN B., JI Z. Abatement of $NO/SO_2/Hg^0$ from flue gas by advanced oxidation processes (AOPs): Tech-category, status quo and prospects. Science of the Total Environment, **806**, 150958, **2022**.
8. AO R., MA L., DAI Q., GUO Z., LIU H., LI W. Promotional effect of acetic acid on simultaneous NO and Hg^0 oxidation over $LaCoO_3$ perovskite. International Journal of Hydrogen Energy, **47** (6), 3741, **2022**.
9. LIU Y., SHI S., WANG Y. Removal of pollutants from gas streams using Fenton (-like)-based oxidation systems: A review. Journal of Hazardous Materials, **416**, 125927, **2021**.
10. GEORGE A., SHEN B., KANG D., YANG J., LUO J. Emission control strategies of hazardous trace elements from coal-fired power plants in China. Journal of Environmental Sciences, **93**, 66, **2020**.
11. WAN Q., YAO Q., DUAN L., LI X., ZHANG L., HAO J. Comparison of Elemental Mercury Oxidation Across Vanadium and Cerium Based Catalysts in Coal Combustion Flue Gas: Catalytic Performances and Particulate Matter Effects. Environmental Science & Technology, **52** (5), 2981, **2018**.
12. HARDYANTI N., SUSANTO H., KUSUMA F.A., BUDIHARDJO M.A. A Bibliometric Review of Adsorption Treatment with an Adsorbent for Wastewater. Polish Journal of Environmental Studies, **32** (2), 981, **2023**.
13. PAULINO J., SILVA A., SANTOS D., NAGLIATE P., MEILI L. Hotspots and Trends of Layered Double Hydroxide-based Adsorbents for Polluted Water Treatment: Insights from Bibliometric Analysis. Environmental Management, **71** (5), 1098, **2023**.
14. GAO J., HUANG X., ZHANG L. Comparative Analysis between International Research Hotspots and National-Level Policy Keywords on Artificial Intelligence in China from 2009 to 2018. Sustainability, **11** (23), 6574, **2019**.
15. KAO X., WANG W., KAO Q., ZHANG J. Visualization of energy-environment-economy system research characteristics and hotspots evolution trends based on CiteSpace. Environmental Research Communications, **4** (5), 055004, **2022**.
16. GRUSS A.F. Mercury removal from simulated coal-fired power plant flue gas using UV irradiation and silica-titania composites, **2011**.
17. LIU Z. Heterogeneous Catalytic Elemental Mercury Oxidation in Coal Combustion Flue Gas, **2017**.
18. BISSON T.M., XU Z., GUPTA R., MAHAM Y., LIU Y., YANG H., CLARK I., PATEL M. Chemical-mechanical bromination of biomass ash for mercury removal from flue gases. Fuel, **108**, 54, **2013**.
19. PUDASAINEE D., SEO Y.C., SUNG J.H., JANG H.N., GUPTA R. Mercury co-beneficial capture in air pollution control devices of coal-fired power plants. International Journal of Coal Geology, **170**, 48, **2017**.
20. LEE W., BAE G.N. Removal of Elemental Mercury (Hg(O)) by Nanosized V_2O_5/TiO_2 Catalysts. Environmental Science & Technology, **43** (5), 1522, **2009**.
21. PUDASAINEE D., KIM J.H., YOON Y.S., SEO Y.C. Oxidation, reemission and mass distribution of mercury in bituminous coal-fired power plants with SCR, CS-ESP and wet FGD. Fuel, **93** (1), 312, **2012**.
22. PUDASAINEE D., LEE S.J., LEE S.-H., KIM J.H., JANG H.N., CHO S.J., SEO Y.C. Effect of selective catalytic reactor on oxidation and enhanced removal of mercury in coal-fired power plants. Fuel, **89** (4), 804, **2010**.
23. BARNEA Z., SACHS T., CHIDAMBARAM M., SASSON Y. A novel oxidative method for the absorption of Hg^0 from flue gas of coal fired power plants using task specific ionic liquid scrubber. Journal of Hazardous Materials, **244**, 495, **2013**.
24. ZHANG Y., YOU X., HUANG S., WANG M., DONG J. Knowledge Atlas on the Relationship between Water Management and Constructed Wetlands-A Bibliometric Analysis Based on CiteSpace. Sustainability, **14** (14), 8288, **2022**.
25. MELAKU A., IVARS J.P., SAHLE M. The state-of-the-art and future research directions on sacred forests and ecosystem services. Environmental Management, **71** (6), 1255, **2023**.
26. XU W., HUSSAIN A., LIU Y. A review on modification methods of adsorbents for elemental mercury from flue gas. Chemical Engineering Journal, **346**, 692, **2018**.
27. ZHOU Q., DUAN Y.F., HONG Y.G., ZHU C., SHE M., ZHANG J., WEI H.Q. Experimental and kinetic studies of gas-phase mercury adsorption by raw and bromine modified activated carbon. Fuel Processing Technology, **134**, 325, **2015**.
28. LIU X., JIANG S., LI H., YANG J., YANG Z., ZHAO J., PENG H., SHIH K. Elemental mercury oxidation over manganese oxide octahedral molecular sieve catalyst at low flue gas temperature. Chemical Engineering Journal, **356**, 142, **2019**.
29. GUAN Y., LIU Y., LV Q., WU J. Bismuth-based photocatalyst for photocatalytic oxidation of flue gas

mercury removal: A review. Journal of Hazardous Materials, **418**, 126280, **2021**.
30. MA Y., MU B., ZHANG X., YUAN D., MA C., XU H., QU Z., FANG S. Graphene enhanced Mn-Ce binary metal oxides for catalytic oxidation and adsorption of elemental mercury from coal-fired flue gas. Chemical Engineering Journal, **358**, 1499, **2019**.
31. LIU K., LIANG J., ZHANG N., LI G., XUE J., ZHAO K., LI Y., YU F. Global perspectives for biochar application in the remediation of heavy metal-contaminated soil: a bibliometric analysis over the past three decades. International Journal of Phytoremediation, **25** (8), 1052, **2023**.
32. OUYANG W., WANG Y., LIN C., HE M., HAO F., LIU H., ZHU W. Heavy metal loss from agricultural watershed to aquatic system: A scientometrics review. Science of the Total Environment, **637**, 208, **2018**.
33. DOU Z., WANG Y., LIU Y., ZHAO Y., HUANG R. Enhanced adsorption of gaseous mercury on activated carbon by a novel clean modification method. Separation and Purification Technology, **308,** 122885, **2023**.
34. LIU Y., WANG Q. Removal of Elemental Mercury from Flue Gas by Thermally Activated Ammonium Persulfate in A Bubble Column Reactor. Environmental Science & Technology, **48** (20), 12181, **2014**.
35. ZHENG J.R., YUAN C.S., IE I.R., SHEN H. S-scheme heterojunction CeO_2/TiO_2 modified by reduced graphene oxide (rGO) as charge transfer route for integrated photothermal catalytic oxidation of Hg^0. Fuel, **343**, 127973, **2023**.
36. ZHOU C., SONG Z., YANG H., WU H., WANG B., YU J., SUN L. Insight into elemental mercury (Hg^0) removal from flue gas using UV/H_2O_2 advanced oxidation processes. Environmental Science and Pollution Research, **25** (21), 21097, **2018**.
37. OCHEDI F.O., LIU Y., HUSSAIN A. A review on coal fly ash based adsorbents for mercury and arsenic removal. Journal of Cleaner Production, **267**, 122143, **2020**.
38. LI C., DUAN Y., TANG H., ZHU C., ZHENG Y., HUANG T. Mercury emissions monitoring in a coal-fired power plant by using the EPA method 30B based on a calcium-based sorbent trap. Fuel, **221**, 171, **2018**.
39. ZHANG S., ZHANG Q., ZHAO Y., YANG J., XU Y., ZHANG J. Enhancement of CeO_2 modified commercial SCR catalyst for synergistic mercury removal from coal combustion flue gas. Rsc Advances, **10** (42), 25325, **2020**.
40. MA Y., WANG J., ZHANG X., ZHANG X., MU B., ZHANG H. Enhancement of Hg^0 oxidation removal in chloride-free flue gas over FeOCl-modified commercial selective catalytic reduction catalyst. Colloid and Interface Science Communications, **44**, 100472, **2021**.
41. BARNEA Z., SACHS T., CHIDAMBARAM M., SASSON Y. A novel oxidative method for the absorption of Hg^0 from flue gas of coal fired power plants using task specific ionic liquid scrubber. Journal of Hazardous Materials, **244**, 495, **2013**.
42. BYUN Y., KIM J., SHIN D. Reaction of SO_2 with sodium chlorate powder triggering oxidation of NO and Hg^0. Chemical Engineering Journal, **189,** 5, **2012**.
43. FANG P., CEN C.P., TANG Z.J. Experimental study on the oxidative absorption of Hg^0 by $KMnO_4$ solution. Chemical Engineering Journal, **198**, 95, **2012**.
44. ZHAO S., QU Z., YAN N., LI Z., ZHU W., PAN J., XU J., LI M. Ag-modified AgI-TiO_2 as an excellent and durable catalyst for catalytic oxidation of elemental mercury. Rsc Advances, **5** (39), 30841, **2015**.
45. FENG L., VAN HULLEBUSCH E.D., RODRIGO M.A., ESPOSITO G., OTURAN M.A. Removal of residual anti-inflammatory and analgesic pharmaceuticals from aqueous systems by electrochemical advanced oxidation processes. A review. Chemical Engineering Journal, **228**, 944, **2013**.
46. LIU Y., ZHOU J., ZHANG Y., PAN J., WANG Q., ZHANG J. Removal of Hg^0 and simultaneous removal of $Hg^0/SO_2/NO$ in flue gas using two Fenton-like reagents in a spray reactor. Fuel, **145**, 180, **2015**.
47. WANG Z.H., JIANG S.D., ZHU Y.Q., ZHOU J.S., ZHOU J.H., LI Z.S., CEN K.F. Investigation on elemental mercury oxidation mechanism by non-thermal plasma treatment. Fuel Processing Technology, **91** (11), 1395, **2010**.
48. WU J., LI C., CHEN X., ZHANG J., ZHAO L., HUANG T., HU T., ZHANG C., NI B., ZHOU X., LIANG P., ZHANG W. Photocatalytic oxidation of gas-phase Hg^0 by carbon spheres supported visible-light-driven CuO-TiO_2. Journal of Industrial and Engineering Chemistry, **46**, 416, **2017**.
49. ZHAO Y., MA X., XU P., WANG H., LIU Y., HE A. Elemental mercury removal from flue gas by $CoFe_2O_4$ catalyzed peroxymonosulfate. Journal of Hazardous Materials, **341**, 228, **2018**.
50. JI M., LI H., HU K., HU J. Effects of Chlorine Addition on Nitrogen Oxide Reduction and Mercury Oxidation over Selective Catalytic Reduction Catalysts. Acs Omega, **7** (14), 12098, **2022**.
51. ZHAO S., PUDASAINEE D., DUAN Y., GUPTA R., LIU M., LU J. A review on mercury in coal combustion process: Content and occurrence forms in coal, transformation, sampling methods, emission and control technologies. Progress in Energy and Combustion Science, **73**, 26, **2019**.
52. LUO J., NIU Q., XIA Y., CAO Y., DU R., SUN S., LU C. Investigation of Gaseous Elemental Mercury Oxidation by Non-thermal Plasma Injection Method. Energy & Fuels, **31** (10), 11013, **2017**.
53. LIU Y., ADEWUYI Y.G. A review on removal of elemental mercury from flue gas using advanced oxidation process: Chemistry and process. Chemical Engineering Research & Design, **112**, 199, **2016**.
54. LIU Z., SRIRAM V., LEE J.-Y. Heterogeneous oxidation of elemental mercury vapor over RuO_2/rutile TiO_2 catalyst for mercury emissions control. Applied Catalysis B-Environmental, **207**, 143, **2017**.
55. DONG S., WANG J., LI C., LIU H., GAO Z., WU C., YANG W. Simultaneous catalytic oxidation mechanism of NO and Hg^0 over single-atom iron catalyst. Applied Surface Science, **609**, 155298, **2023**.
56. MA Y., WANG J., ZHANG X., GU W., HAN L., LI Y. Mercury removal from flue gas by a MoS_2/H_2O heterogeneous system based on its absorption kinetics. Environmental Science and Pollution Research, **30** (11), 29043, **2023**.
57. ZHAO Y., HAO R., QI M. Integrative process of preoxidation and absorption for simultaneous removal of SO_2, NO and Hg^0. Chemical Engineering Journal, **269**, 159, **2015**.
58. SHEN B., ZHU S., ZHANG X., CHI G., PATEL D., SI M., WU C. Simultaneous removal of NO and Hg^0 using Fe and Co co-doped Mn-Ce/TiO_2 catalysts. Fuel, **224**, 241, **2018**.
59. JU F. Mapping the Knowledge Structure of Image Recognition in Cultural Heritage: A Scientometric Analysis Using CiteSpace, VOSviewer, and Bibliometrix. Journal of Imaging, **10** (11), 272, **2024**.