Global analysis of the environmental management of hazardous industrial wastes: systematic and bibliometric review

Análisis global de la gestión ambiental de los residuos industriales peligrosos: revisión sistemática y bibliométrica

Análise global da gestão ambiental de resíduos industriais perigosos: uma revisão sistemática e bibliométrica

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Received: January 20th, 2025
Accepted: March 25th, 2025
Available: May 5th, 2025

How to cite this article:
F.J. Bedoya-Rodríguez, A. Hurado-Sánchez, and A.F. Ibagón-Bravo, "Global Analysis of the Environmental Management of Hazardous Industrial Wastes: Systematic and Bibliometric Review," *Revista Ingeniería Solidaria*, vol. 21, no. 2, 2025.
doi: https://doi.org/10.16925/2357-6014.2025.02.02

Research article. https://doi.org/10.16925/2357-6014.2025.02.02

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Abstract

Introduction: This article presents research on the sustainable management of hazardous industrial waste, based on a systematic and global bibliometric review conducted at Fundación Universitaria de Popayán in 2024.

Problem: Inadequate management of hazardous industrial waste poses significant risks to both health and the environment, highlighting the urgent need to integrate sustainable practices and circular economy principles into waste management strategies.

Objective: The study aims to perform a systematic review and bibliometric analysis of global research on hazardous industrial waste management, identifying key trends and innovative technologies.

Methodology: Following the PRISMA guidelines to ensure transparency, the review is complemented by bibliometric analysis using Vosviewer software.

Results: The literature on hazardous industrial waste management has grown, with particular focus on the metallurgical industry and sustainable approaches. China and India are leading contributors, although publication rates declined between 2016 and 2019 due to shifts in research priorities.

Conclusion: The study emphasizes the critical role of adopting circular economy practices in hazardous waste management and the need to strengthen international collaboration to effectively address environmental challenges.

Originality: This systematic review offers a comprehensive knowledge matrix on hazardous industrial waste management, underscoring emerging trends toward circular economy adoption and sustainable practices.

Limitations: Limitations include the scope of the review, which could be expanded in future research by including additional databases such as Web of Science alongside Scopus and Google Scholar for a more exhaustive analysis.

Keywords: hazardous industrial waste, waste management, waste disposal, circular economy, bibliometric study.

Resumen

Introducción: El artículo es producto de una investigación sobre la gestión sostenible de residuos peligrosos en la industria, a partir de una revisión bibliométrica sistemática y global, desarrollada en la Fundación Universitaria de Popayán en 2024.

Problema: La gestión inadecuada de residuos industriales peligrosos representa un riesgo significativo para la salud y el medio ambiente, lo que subraya la necesidad de integrar prácticas sostenibles y la economía circular en su gestión.

Objetivo: El objetivo del estudio es realizar una revisión sistemática y un análisis bibliométrico sobre la gestión de residuos industriales peligrosos a nivel mundial, identificando tendencias y tecnologías innovadoras.

Metodología: La metodología se basa en la declaración PRISMA para garantizar una revisión transparente, complementada con un análisis bibliométrico mediante Vosviewer.

Resultados: Existe un aumento en la literatura sobre la gestión de residuos industriales peligrosos, con especial atención a la industria metalúrgica y a los métodos sostenibles, con China e India a la cabeza en publicaciones, aunque se observó una disminución entre 2016 y 2019 debido a cambios en las prioridades de investigación.

Conclusión: El estudio destaca la importancia de adoptar prácticas circulares en la gestión de residuos industriales peligrosos y fortalecer las alianzas internacionales para abordar los desafíos ambientales.

Originalidad: La revisión sistemática proporciona una matriz de conocimiento sobre la gestión de residuos industriales peligrosos, destacando las tendencias hacia la economía circular y el interés en prácticas sostenibles.

Limitaciones: La revisión presenta algunas limitaciones que podrían abordarse en otras investigaciones, como realizar una revisión más exhaustiva del tema de estudio e incluir en la revisión no solo Scopus y Google Académico, sino también Web of Science y otras fuentes.

Palabras clave: residuos industriales peligrosos, gestión de residuos, eliminación de residuos, economía circular, estudio bibliométrico.

Resumo

Introdução: Este artigo é o produto de uma pesquisa sobre a gestão sustentável de resíduos perigosos na indústria, baseada em uma revisão bibliométrica sistemática e global, conduzida na Fundação Universitária Popayán em 2024.

Problema: A gestão inadequada de resíduos industriais perigosos representa um risco significativo à saúde e ao meio ambiente, reforçando a necessidade de integrar práticas sustentáveis e a economia circular em sua gestão.

Objetivo: O objetivo do estudo é realizar uma revisão sistemática e análise bibliométrica sobre a gestão de resíduos industriais perigosos em todo o mundo, identificando tendências e tecnologias inovadoras.

Metodologia: A metodologia baseia-se na declaração PRISMA para garantir uma revisão transparente, complementada por uma análise bibliométrica utilizando o Vosviewer.

Resultados: Há um aumento na literatura sobre gestão de resíduos industriais perigosos, com foco particular na indústria metalúrgica e métodos sustentáveis, com China e Índia liderando as publicações. No entanto, observou-se uma diminuição entre 2016 e 2019 devido a mudanças nas prioridades de pesquisa. Conclusão: O estudo destaca a importância da adoção de práticas circulares na gestão de resíduos industriais perigosos e do fortalecimento de parcerias internacionais para enfrentar os desafios ambientais.

Originalidade: A revisão sistemática fornece uma matriz de conhecimento sobre a gestão de resíduos industriais perigosos, destacando tendências em direção à economia circular e o interesse em práticas sustentáveis.

Limitações: A revisão apresenta algumas limitações que poderiam ser abordadas em outras pesquisas, como a realização de uma revisão mais abrangente do tema em estudo e a inclusão não apenas do Scopus e do Google Acadêmico, mas também da Web of Science e de outras fontes.

Palavras-chave: resíduos industriais perigosos, gestão de resíduos, descarte de resíduos, economia circular, estudo bibliométrico.

1. INTRODUCTION

The sustainable management of hazardous industrial waste (HIW) is of critical global importance, particularly when integrated with the circular economy (CE) and environmental regulations, as it helps mitigate adverse effects on human health and ecosystems. Effective HIW management encompasses prevention, recovery, recycling, energy recovery, and treatment processes aimed at reducing the toxic load of waste [1]. The field of industrial waste (IW) management reflects diverse economic and cultural contexts, as well as varying government fiscal policies. For instance, Bamatov et al. [2] analyze and propose the implementation of innovative technologies to minimize waste generation in industrial production while promoting CE principles. Similarly, Naqvi et al. [3] focus on CE drivers that facilitate proper IW management, enhancing waste utilization within material flow cycles. Additionally, Suksanguan et al. [4] highlight the cement industry's preference for CE-based waste treatment approaches, particularly the conversion of IW into renewable fuels.

Industries produce significant quantities of HIW that can negatively impact the environment and human health, underscoring the need for clean technologies that balance economic and environmental considerations. Relevant industrial sectors include agribusiness, mining, fishing, food and beverages, textiles, wood and paper, printing, petroleum, chemicals, plastics, basic metals, metal products, electricity, and construction, among others [5, 6]. From both organizational and environmental perspectives, the adoption of intelligent technologies is recommended to optimize raw material management and safeguard environmental quality [7]. For example, Jjagwe et al. [8] demonstrate the efficacy of iron oxide nanoparticles in wastewater treatment through adsorption and photocatalysis, effectively capturing heavy metals. Other research focuses on e-waste management by designing innovative algorithms and standardized protocols to enhance the refurbishment and recovery processes of waste electrical and electronic equipment [9].

Final disposal of IW extends beyond landfilling and thermal or physicochemical treatments; post-treatment waste application to soils can be beneficial if the physicochemical properties are properly managed to avoid harmful environmental or health impacts. Consequently, source control and CE-based waste reduction techniques are essential in industrial settings [10]. For highly hazardous wastes such as mercury, recycling is preferred over landfilling due to its toxic and carcinogenic nature [11]. Yan et al. [12] emphasize the role of thermal treatments—incineration, gasification, and pyrolysis—in modern IW management, highlighting their potential to reduce waste volume and toxicity. Krishnan et al. [13] review current HIW treatment technologies with a focus on recovering precious metals, noting the effectiveness of hydrometallurgical processes combining dissolution and leaching for extracting metals from industrial effluents. Other studies demonstrate the valorization of food industry wastes for biofuel production through microbial bioconversion [14].

Bibliometric analyses related to HIW management cover diverse topics such as mineral carbonation for carbon capture and emission reduction [15], agro-industrial wastes like bacterial nanocellulose in crop production alternatives [16], and hazardous waste treatment technologies including adsorption and co-processing within CE frameworks [17]. Additional reviews explore the use of steel slag in concrete production [18], membrane technologies for critical metal recovery [19], industrial wastewater treatment [20, 21], microalgae applications for heavy metal biosorption [22], and bioenergy recovery from citrus industry by-products [23].

In this context, the present article provides a systematic review and bibliometric analysis of global research focused on the environmental management of hazardous industrial waste. It offers a comprehensive overview of industrial sectors, the types of waste they generate, and associated treatment technologies. The findings aim to serve as a reference for future investigations, addressing existing gaps and supporting the advancement of effective HIW management strategies.

1.1 Literature review

In China, industrial waste (IW) management faces significant challenges that impact both industrial safety and environmental protection. Yang et al. [24] analyzed these risks, emphasizing the frequent occurrence of accidents due to the inadequate separation of waste, which is often mixed with municipal solid waste and disposed of in landfills. Research conducted in Zhejiang Province by Zhang et al. [25] examined five landfills and found contamination of groundwater from wastes generated by industries such as rubber, leather, plastic, machinery, and pharmaceuticals. Physicochemical analyses revealed elevated levels of harmful substances. To address part of this problem, chemical hydrogenation treatment of red sludge, a by-product of the aluminum industry, has proven effective in removing heavy metals such as chromium and others [26]. Moreover, Kanwal et al. [27] propose integrating red muds and gold-related wastes into a circular economy (CE) model, which could mitigate environmental impacts and enhance the sustainability of industrial residue (IR) management in China.

India has implemented various IW management and recovery strategies, notably the electrocoagulation process for treating textile industry wastewater [28]. Additionally, fly ash from coal combustion and ceramic tile waste have been incorporated into concrete manufacturing, improving its strength and durability [29, 30]. A study in a southern industrial zone demonstrated the management of non-hazardous waste through sorting and recovery in alignment with CE principles [31]. Research in the construction sector indicates that concrete's compressive strength improves when mixed with cementitious waste, aluminum oxide nanoparticles, and plastic and electronic wastes, which also enhance tensile and flexural strength [32]. Nevertheless, challenges remain due to insufficient waste management policies and high landfill costs in the construction industry [33]. In hazardous waste management, some industries utilize these wastes as alternative fuels and raw materials in cement production, reflecting an interest in efficient hazardous waste recirculation [34]. Furthermore, pickling sludge and copper tailings have been explored as fertilizers for floriculture, showing promising reductions in barium soil contamination [35]. The citrus industry has also begun converting its waste into bioethanol [36], while Srikanth et al. [37] investigate bioelectrochemical systems for converting oil industry waste into energy, thus enhancing waste treatment efficiency.

In South Korea, the increasing generation of HIW is attributed primarily to industrial production and the high consumption and export levels in the chemical, electrical, electronics, and metals sectors. In response, the country has focused on improving HIW management by implementing CE strategies, adopting clean technologies, and projecting stricter environmental policies [38, 39, 40]. Lee et al. [40] highlight the necessity of considering technological advances and consumption patterns to formulate effective environmental policies for HIW management.

Pakistan, a developing country, faces serious challenges in industrial wastewater treatment, with polluted effluents frequently discharged into water bodies, impacting groundwater quality [41]. The phosphate fertilizer industry generates hazardous wastes, including toxic and radioactive dihydrogen phosphates and emissions rich in fluorides and sulfur dioxide, which pose significant health and environmental risks; thus, these industries require stringent supervision and adaptive IW management [42].

In Thailand, the petrochemical industry stands out for adopting the 3R (reduce, reuse, recycle) approach in managing its HIW, such as activated carbon, caustic, and yellow oil wastes, which has reduced waste volume and disposal costs [43]. However, increasing concern about IW has prompted the development of company-level management models incorporating professional ethics and the impact of technological innovation [44]. Despite these advances, some cases of improper IW disposal through illegal methods have been reported [45].

In Iran, Farzadkia et al. [46] and Shayesteh et al. [47] analyzed IW management in the Brujen and Savojbolagh industrial zones, identifying pyrolysis, incineration, recycling, and landfill as the most sustainable treatment options to minimize environmental impacts. Singapore's metallurgical industry has implemented immobilization processes for zinc and measures to reduce ladle slag dumping, alongside CO2 capture through stabilization, solidification, chemical fixation, and physical encapsulation treatments, contributing to reduced environmental pollution [48]. Taiwan's environmental policies prioritize HIW management, emphasizing recycling and CE processes targeting acid and pickling liquid wastes generated by the electronics manufacturing sector [49].

In Africa, the textile industry generates substantial wastewater, sometimes discharged untreated into natural water bodies. For example, some Ethiopian textile factories possess wastewater treatment plants (WTPs), but their inadequate operation leads to effluents exceeding regulatory limits for parameters such as chemical oxygen demand (COD), nitrates, nitrites, and metals [50]. In Egypt, hazardous textile wastes are often landfilled or incinerated, resulting in adverse health and environmental impacts due to their ecotoxic and carcinogenic properties [51]. Bassyouni et al. [52] demonstrate that electrocoagulation is an effective method to remove cyanide from wastewater in the electroplating industry. In Algeria, improper storage of HIW—such as used batteries and oils—has been linked to contamination and risks to human and environmental health [53]. Meanwhile, Schoeman et al. [54] explore CE applications in managing IW within South Africa's iron and steel industry, highlighting their potential to reduce environmental impacts.

In the UK, the agribusiness sector reflects a growing trend toward sustainability and CE innovation. For instance, tomato production in greenhouses employs IW recycling processes that capture up to 50,000 kg/year of CO2 from crop biomass, preventing its release into the atmosphere [55]. Advances in wastewater treatment within the metallurgical industry have also been noted, with Chalaris et al. [56] identifying advanced oxidation processes as highly effective for pollutant removal in Greece. Spain has reported beneficial results from thermochemical IW treatments, such as hydrothermal liquefaction of surfactant-containing wastewater, capable of producing fuels including crude oil and coal derivatives [57].

Case studies in Ecuador illustrate the feasibility of converting agro-industrial wastes like banana, plantain, and corn residues into bioplastics via physicochemical and biotechnological processes [58], reflecting broader South American trends. Chile ranks as the second largest producer of industrial solid waste in the region [59]. In Colombia, CE initiatives promote the recovery and transformation of aluminum dross—an HIW contaminating water with heavy metals [60]—as well as biogas generation from sugarcane and other agricultural residues with positive environmental outcomes [61]. The Colombian brewing industry valorizes malt bagasse through pyrolysis to produce biochar and pyrolytic oil, the latter useful for biodiesel production [62]. Additionally, co-pelletization of wood sector wastes with boiler ash and wood chips has demonstrated efficiency in thermal power generation with low emissions [63].

2. MATERIALS AND METHODS

An exhaustive investigation was conducted to analyze recent developments in hazardous industrial waste (HIW) management and to provide a global perspective on scholarly output and collaboration patterns among countries and authors within this thematic field.

2.1 Search strategy

The systematic review methodology followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [64], which provide a transparent framework covering the identification, eligibility, selection, and inclusion of relevant literature. Complementing this, bibliometric analyses were performed using Vosviewer software [65, 66, 67] to identify current trends and research dynamics in HIW management. The database search was conducted on March 16, 2024, using Scopus as the primary source due to its extensive multidisciplinary coverage and high-quality metadata, essential for rigorous bibliometric analysis, as noted by Pranckutė [68]. The search query combined key terms with Boolean operators as follows: (“industrial hazardous waste” OR “industrial waste”) AND (“waste management” OR “waste disposal”).

2.2 Eligibility Criteria

Following PRISMA recommendations and to ensure scientific relevance, publications from the last ten years (2014–2023) were considered to capture recent trends comprehensively. The review included full-text manuscripts at the final publication stage, encompassing articles, reviews, and book chapters published in English and focused on environmental sciences and engineering. Publications unrelated to the study topic were excluded.

2.3 Data selection and debugging

The initial search retrieved 18,947 records from Scopus. Applying the eligibility criteria resulted in a final selection of 65 publications for the systematic review and 4,135 records for bibliometric analysis (see Figure 1). The dataset was imported into Excel for preliminary handling, followed by qualitative data extraction using ATLAS.ti 8 to facilitate detailed country-level reporting on HIW management. Duplicate records were removed prior to bibliometric processing with Vosviewer (version 1.6.19).

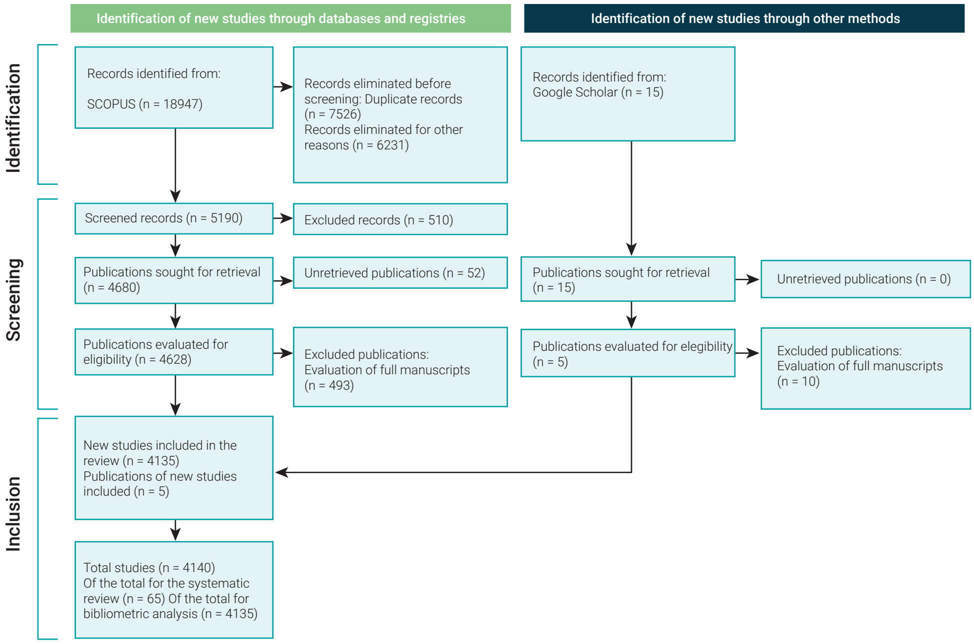

Figure 1. Systematic and bibliometric review flowchart based on the PRISMA statement. Prepared by the authors based on Page et al. [64].

2.4 Data analysis

The qualitative data extracted from ATLAS.ti were systematically recorded in a summary table categorizing information by industry type, type of industrial waste, treatment or final disposal method, general treatment classification, and country of publication. This approach enabled a descriptive identification of the most prevalent hazardous industrial waste (HIW) treatments investigated across different countries worldwide. Bibliometric metadata were retrieved from Scopus in RIS and CSV formats. The bibliometric analysis comprised three main components: performance measurement, which assessed publication and citation metrics; scientific mapping, which identified the significance and impact of co-authorships and keyword co-occurrences among authors, countries, and topics; and network analysis, which complemented the mapping through grouped visualizations of collaborative relationships [65].

3. RESULTS

The results of the systematic review following PRISMA guidelines, together with the bibliometric analysis performed using Vosviewer, are presented below. Initially, descriptive characteristics of the studies are detailed, focusing on industry types and

HIW management practices. This is followed by bibliometric performance analysis highlighting research trends, productivity, and geographic distribution, including total link strength (TLS) as a measure of international collaboration and cooperation.

3.1 Analysis of aspects of the systematic review

Data from the 65 selected publications in the systematic review are summarized in Table 1. This table outlines key study characteristics such as industry sector, type of industrial waste, applied treatment or disposal method, treatment classification, and country of publication to provide a comprehensive global overview of HIW management research. The metallurgical industry is the most frequently studied sector (36%), largely due to the presence of heavy metals in its waste streams. China and India emerge as leaders in chemical treatment and recycling of industrial waste. Meanwhile, countries like Pakistan, Singapore, and Thailand employ a diverse range of management methods including landfill disposal and incineration. Notably, Colombia shows a preference for electrocoagulation (EC) in its HIW management strategies.

Table 1. Environmental management of hazardous industrial waste by type of industry in the systematic review.

Industry type	Industrial waste type	Treatment or final disposal	General classification of treatment	Country of publication	Citation
Steel industry	Wastewater containing heavy metals	Adsorption and photocatalysis using iron oxide nanoparticles	Physicochemical treatment	East Africa	Jjagwe et al. [8]
Electrical and Electronics Industry	Waste electrical and electronic equipment	Reduction, reuse and recycling	Chemical treatment	China	Resmi and Fasila [9]
Aluminum Industry	Solid red sludge (aluminum oxide, iron oxide and other metal oxides)	Hydrogenation, catalytic ozonation	Chemical treatment	China	Yan et al. [12]
Metallurgical Industry	Heavy metal wastes	Hydrometallurgical method (dissolution and leaching), Pyrometallurgical method	Circular Economy	Malaysia	Krishnan et al. [13]

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e-ISSN 2357-6014 / Vol. 21, no. 2 / may-august 2025 / Bogotá D.C., Colombia
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Industry type	Industrial waste type	Treatment or final disposal	General classification of treatment	Country of publication	Citation
Textile Industry	Textile wastewater (heavy metals, oils, suspended solids, etc.)	Electrocoagulation, Activated carbon adsorption processes	Construction process	India	Gowthaman and Selvaraju [28]
Construction industry	Fly ash and ceramic tile wastes	Concrete Manufacturing	Circular Economy	India	Gupta y Chaudhary [29] Packrisamy and Jayakumar [30]
Construction industry	Nanoparticles, Plastic wastes, electronic wastes	Mixing to improve the compressive, tensile and flexural strength of concrete	Construction process	India	Rani and Senthil [32]
Metallurgical Industry	Inorganic wastes with heavy metals, Pickling sludge, Tailing wastes	Recovery for use as fertilizer	Physicochemical treatment	India	Verma et al. [35]
Citrus Industry	Cellulose and oil wastes	Conversion to bioethanol	Circular Economy	India	Kaur [36]
Petroleum Industry	Oily sludges, Wastewater, Volatile organic compounds, Residual catalysts, Heavy metals	Bioelectrochemical system, energetic valorization	Circular Economy	India	Srikanth et al. [37]
Phosphate Fertilizer Industry	Dihydrogen phosphate, Toxic elements (heavy metals), Radioactive substances	Disposal as sludge in storage ponds	Metallurgical treatment	Pakistan	Ahmad et al. [42]
Petrochemical industry	Activated carbon, caustic oil and yellow oil	Reduction, reuse and recycling	Circular Economy	Thailand	Usapein and Chavalparit [43]
Metallurgical Industry	Zinc, Slag, CO_2	Stabilization and solidification, chemical fixation and physical encapsulation	Waste disposal	Singapore	Xu et al. [48]
Electrical and Electronics Industry	Spent acid and pickling liquid, liquid containing spent dimethylformamide	Recycling	Circular Economy	Taiwan	Tsai et al. [49]
Textile Industry	Wastewater (metals, nitrates, nitrites, COD, etc.)	WTP (activated sludge)	Circular Economy	Ethiopia	Wondim et al. [50]
Textile Industry	Acrylic fibers, pigment wastes	Landfill and incineration	Waste disposal	Egypt	Yacout and Hassouna [51]

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Industry type	Industrial waste type	Treatment or final disposal	General classification of treatment	Country of publication	Citation
Electroplating Industry	Cyanide from industrial waste solutions	Electrocoagulation (oxidation, hydrolysis, coagulation, flocculation, sweep-off coagulation, sedimentation and filtration)	Physicochemical treatment	Egypt	Bassyouni et al. [52]
Iron and Steel Industry (Iron and Steel)	Crude steel	Conversion to bioenergy	Circular Economy	South Africa	Schoeman et al. [54]
Agroindustry	CO_2 from organic matter	Recycling or recovery	Circular Economy	United Kingdom	McDonald et al. [55]
Metallurgical Industry	Metallurgical wastewater (heavy metals)	Advanced oxidation	Chemical treatment	Greece	Chalaris et al. [56]
Tensiochemical Industry	Wastewater with liquid surfactants	Hydrothermal liquefaction	Thermochemical treatment	Spain	Mascarell et al. [57]
Agroindustry	Agro-industrial waste (banana, plantain and corn waste)	Physicochemical and biotechnological treatments for the manufacture of bioplastics	Circular Economy	Ecuador	Riera et al. [58]
Metal and Construction Industry	Aluminum slag (heavy metals)	Recovery and transformation	Circular Economy	Colombia	Muñoz-Vélez et al. [60]
Agroindustry	Agricultural crop and sugar cane wastes	Anaerobic co-digestion	Circular Economy	Colombia	Mendieta et al. [61]
Wood and Paper Industry	Primary sludge, coal boiler ashes, wood waste wood chips	Co-pelletization, Thermal co-processing	Circular Economy	Colombia	Valdés et al. [63]

It was also evident that electrocoagulation (EC) is the predominant treatment method for hazardous industrial waste, accounting for 52% of the cases analyzed (Table 1, Figure 2). Chemical and physicochemical treatments each represent 12%, sharing the second most common position. Additionally, several processes emphasize not only the elimination of HIW but also its reuse and recovery, aligning with circular economy principles.

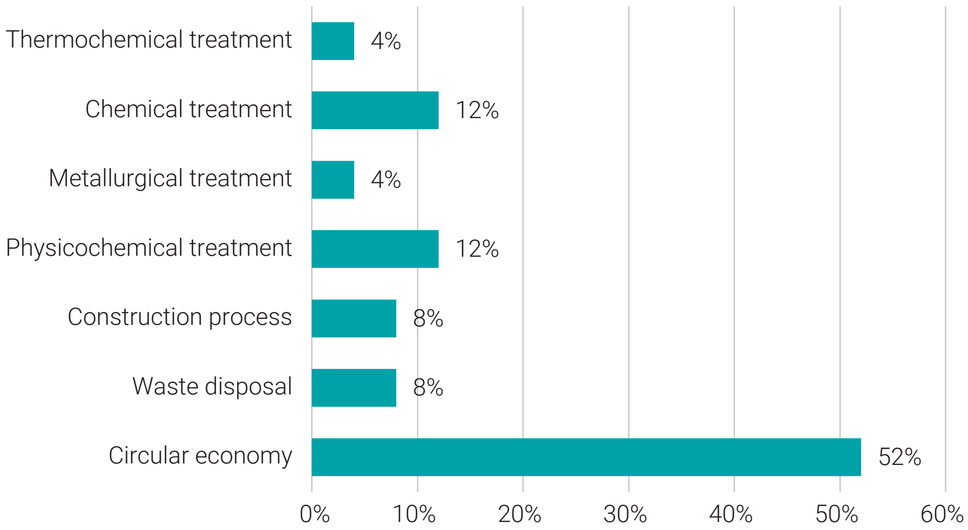

Figure 2. General classification of HIW treatment

3.2 Descriptive analysis

The bibliometric data on literary production related to hazardous industrial waste management from 2014 to 2023 reveals a fluctuating trend. The period began in 2014 with 407 publications, reaching its highest peak in 2016 with 522 papers. This was followed by a decline, culminating in 2019 with 351 publications—a decrease of 32.8% from the peak. Since then, the number of publications has gradually recovered, albeit with some fluctuations, reaching 418 publications in 2023 (Figure 3).

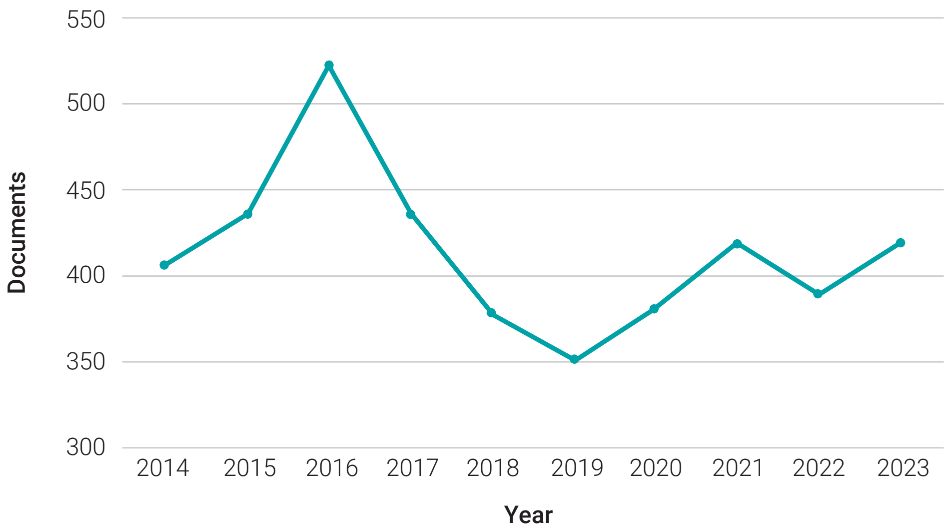

Figure 3. Annual trend of bibliometric document publications from 2014 to 2023.

3.3 Co-authorship analysis

Table 2 presents the five most prolific authors in the field of hazardous industrial waste management. Li J., affiliated with Tsinghua University in Beijing, China, leads with 55 publications (Total Link Strength, TLS = 168). However, Zhang Y., who ranks second with 49 publications, demonstrates a higher degree of collaboration, reflected by a slightly greater TLS of 170. Figure 4 illustrates the author collaboration networks generated by Vosviewer, revealing 25 distinct author clusters, with Zhang Y. showing a particularly strong collaborative presence.

Table 2. Main authors and their collaborative strength

Author	Documents	Total link strength
Li, J.	55	168
Zhang, Y.	49	170
Wang, Y.	39	134
Liu, Y.	38	137
Li, Y.	35	142

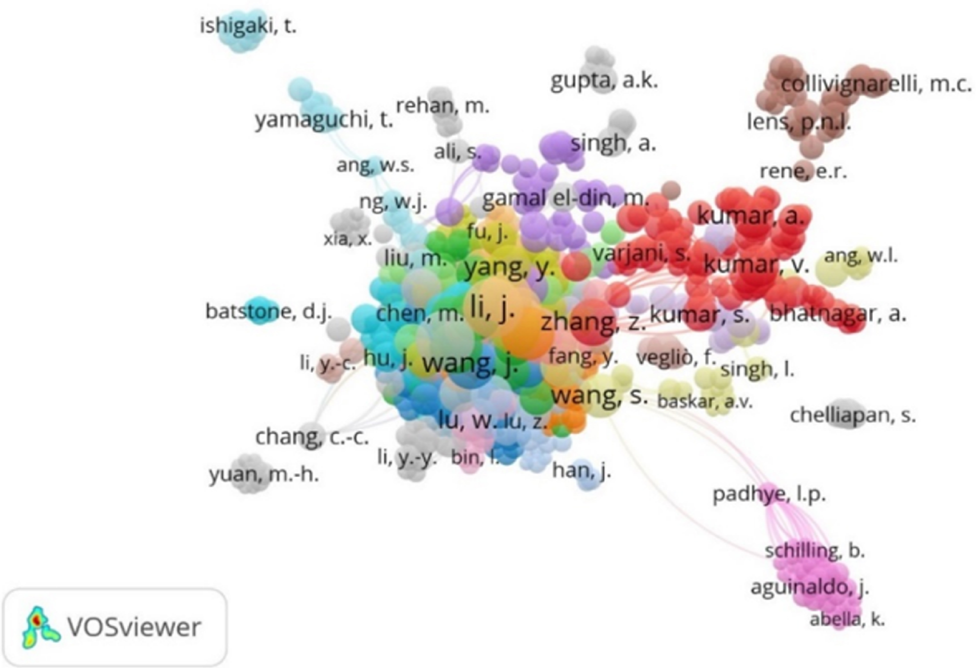

Figure 4. Visualization of co-authored author networks

3.4 Keyword co-occurrence analysis

Four network visualization clusters were formed for the keywords evidencing their occurrences (*Oc*) (Figure 5). The top five keywords used in the HIW management research were industrial waste (*Oc* = 3224), waste management (*Oc* = 1685), Wastewater (*Oc* = 1429), waste disposal (*Oc* = 1112), and wastewater treatment (*Oc* = 965). In addition, the strongest linkage strength with other concepts was identified for the keywords: industrial waste (*TLS* = 86041) and wastewater (*TLS* = 47809).

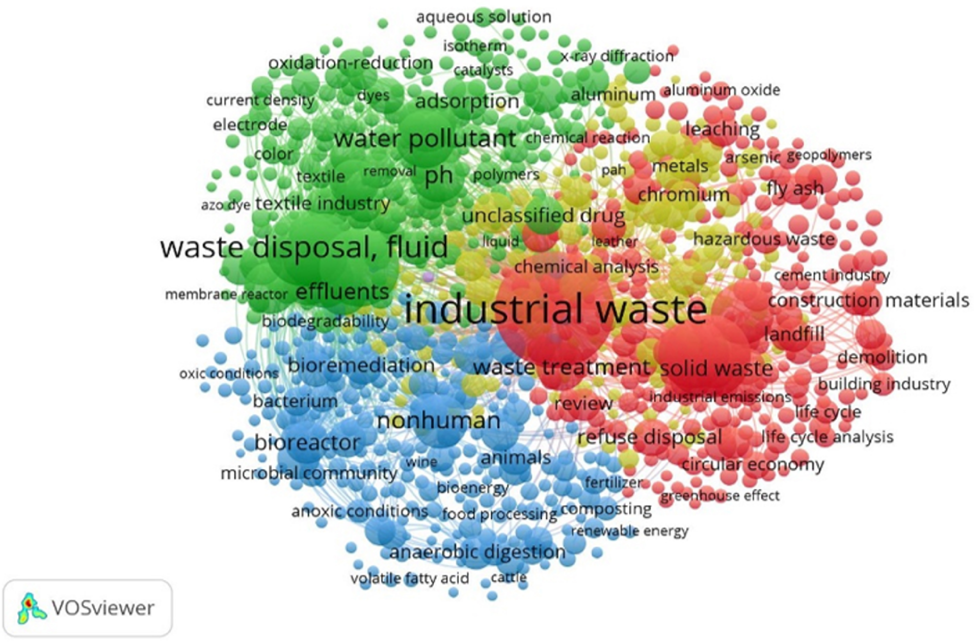

Figure 5. Keyword network representation

3.5 Analysis of geographic distribution and country co-authorship

Geographically, China leads the number of publications, contributing 815 documents, which account for 26.37% of the total publications among the top 10 countries (Table 3). India follows with 20.9%, and the United States with 9.1%. Brazil and Spain share fourth place, each with 248 publications; however, Spain surpasses Brazil in citations, with 10,062 citations, as well as in connectivity and collaboration within the scientific community, indicated by a higher Total Link Strength (TLS = 135). Notably, Italy, despite having fewer publications, has accumulated 11,170 citations, exceeding those of Brazil, Spain, and the United States.

Table 3. Top 10 countries with the highest number of publications

Country	Documents	Citation	Total link strength
China	815	34787	458
India	646	19071	291
United States	281	10276	254
Brazil	248	6264	83
Spain	248	10062	135
Italy	192	11170	120
Australia	187	8351	202
United Kingdom	171	7331	219
Turkey	159	4280	66
Malaysia	144	5771	145

Additionally, the country co-authorship analysis using Vosviewer identified more than five key research collaboration clusters. In descending order of relevance, these are China (TLS = 458), India (TLS = 291), the United States (TLS = 254), the United Kingdom (TLS = 219), and Australia (TLS = 202). China's collaborations notably include partnerships with Italy, the United States, the United Kingdom, Spain, and other countries (Table 3, Figure 6).

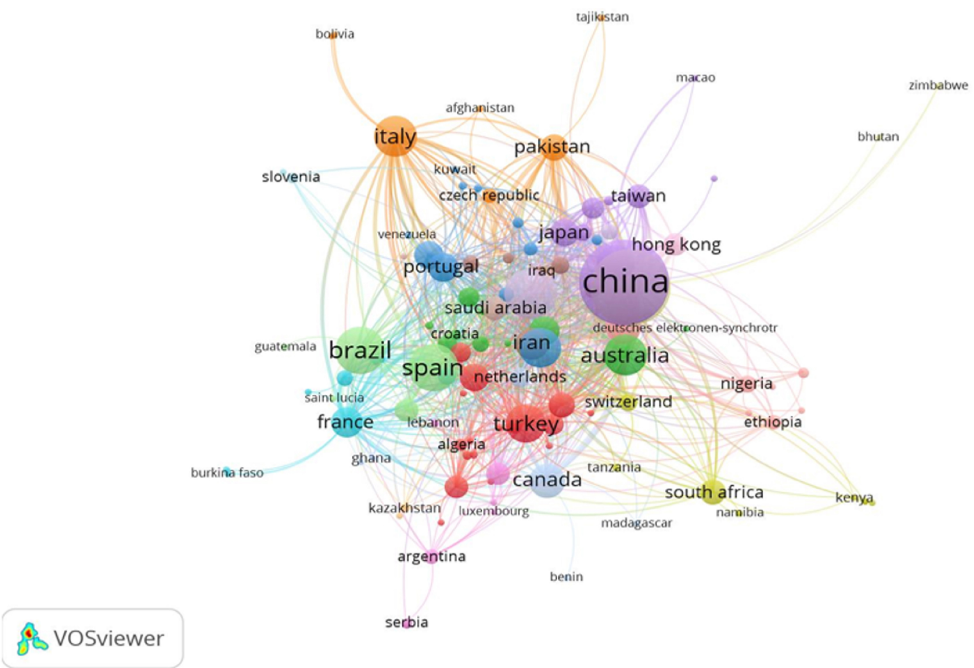

Figure 6. VOSviewer Visualization Networks for collaboration based on co-authorship by countries

Finally, Figure 7 illustrates the number of documents published on HIW management across selected South American countries. Brazil leads significantly, accounting for approximately 75% of the total publications represented in the graph. Chile ranks second with around 50 publications, followed by Argentina with approximately 30 documents, and Colombia with fewer than 25.

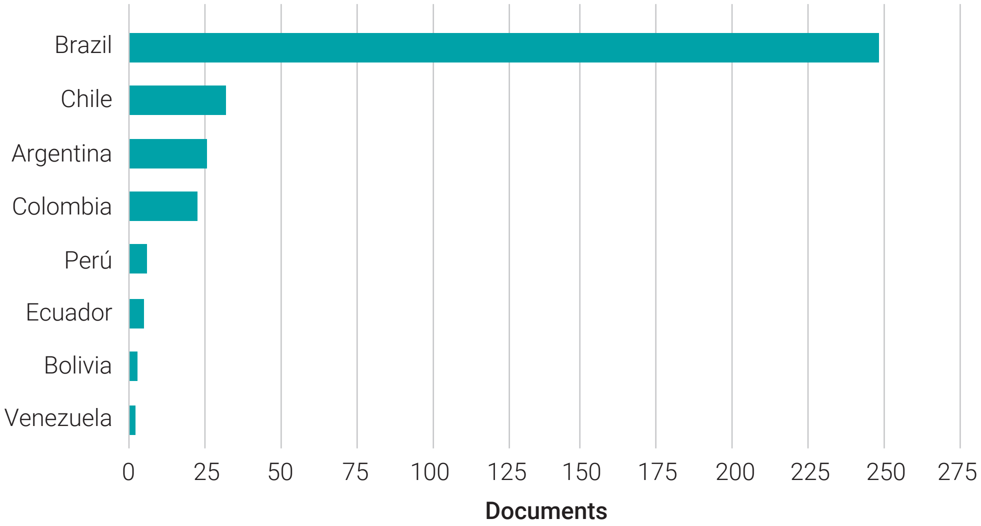

Figure 7. Literary production of South American countries on the topic

4. DISCUSSION AND CONCLUSIONS

The results of this study reveal a notable increase in literature production on industrial hazardous waste (HIW) management, reflecting growing interest in investigating HIW treatment methods across various industries. This trend may be attributed to heightened environmental awareness, the introduction of new and more stringent environmental regulations on HIW [40, 49], increased research investments, and the development of clean technologies for HIW management [6, 7, 38, 39]. These efforts aim to reduce the environmental and occupational risks posed by highly toxic and polluting chemical wastes [25]. A significant peak in publications was observed in 2016, demonstrating exponential growth in the subject area. However, a considerable decline in scientific output occurred from 2016 to 2019. This decline can be explained by several interrelated factors such as research field saturation [69], shifting research priorities towards climate change and energy sustainability during that period [70], and increased environmental regulations that may have redirected economic resources away from publication efforts toward compliance [71]. Since 2019, a gradual recovery in publications and renewed scientific interest in innovative HIW management methods has been evident [2, 46, 47].

This study identifies the metallurgical industry as the most investigated sector, aligning with concerns over the heavy metals produced by this industry [48]. This finding concurs with ongoing research emphasizing the importance of effective, less environmentally impactful treatments for heavy metals [8, 22, 26, 60]. The review highlights the predominance of sustainable HIW treatment methods that promote circular economy (CE) principles, as reflected in influential contemporary studies emphasizing the implementation of circular management practices to mitigate environmental impacts [1, 4, 10, 31, 54]. This shift reflects a dual focus on waste elimination and on recycling and reuse within the production cycle [3, 17, 19, 27].

Global co-authorship and collaboration are critical drivers for advancing HIW management knowledge. China and India, in particular, lead in both publication volume and citation metrics, indicating the fundamental role of collaborative networks in fostering innovative, effective solutions to global environmental challenges [72]. The influence of Chinese research is especially pronounced, consistent with findings from similar studies that position China as the largest academic contributor in HIW management publications [15, 16, 20, 21]. In South America, Brazil dominates HIW research output, likely due to its relatively advanced industrial development and greater investment capacity in this field [73]. Chile, Argentina, and Colombia contribute to a lesser extent, while countries such as Peru, Ecuador, Bolivia, and Venezuela show very limited research activity, potentially reflecting low prioritization, funding, or scientific capacity focused on HIW [74, 75].

This analysis, spanning both developed and emerging economies, provides a foundation for future research and offers valuable input for the formulation of governmental policies on environmental management of HIW.

In conclusion, the novelty of this systematic review combined with bibliometric analysis lies in the creation of a knowledge matrix for HIW management, offering a comprehensive view of current trends that increasingly emphasize circular economy applications and sustainable industrial practices. Nonetheless, substantial challenges remain to be addressed for effective implementation. For emerging and developing countries, overcoming barriers such as limited knowledge and research capacity, labor informality, inadequate legal frameworks, insufficient funding, and low public awareness of CE benefits is imperative. As environmental concerns intensify, it is critical that researchers and policymakers collaborate closely to resolve issues related to industrial waste.

Despite notable advances documented in global HIW management literature, several limitations must be acknowledged when interpreting this review. Much of the existing research, especially in developing countries, focuses predominantly on environmental and technical aspects of CE adoption, often neglecting socio-economic and policy-related barriers crucial to sustainable implementation [24, 27]. This underscores the need for tailored regulatory reforms and capacity-building efforts to support CE transitions in resource-constrained environments [39].

Finally, future research could strengthen the comprehensiveness of reviews by broadening database coverage. Incorporating additional sources such as Web of Science, Dimensions, and relevant regional databases alongside Scopus and Google Scholar would improve literature coverage and yield a more representative synthesis of global HIW management practices and CE adoption across diverse contexts. Such approaches would enhance the robustness of findings and deepen understanding of the complexities involved in advancing sustainable waste management worldwide.

ACKNOWLEDGMENTS

The authors would like to thank the Fundación Universitaria de Popayán, Sede Álvaro Ulcué Chocué, for their support in carrying out this work.

CONFLICTS OF INTEREST

The authors declare that they have no financial, professional or personal interests.

AUTHORSHIP CONTRIBUTION

FJBR conceptualization, research design and development, use of software, drafting and final revision of the manuscript. AHS and AFIB conceptualization, part of the method and final revision of the manuscript.

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