Research Article
doi: 10.1590/01047760202632013709
vol(32), 2026

CERNE

Use of biochar in water and wastewater treatment: a bibliometric analysis and state-of-the-art review

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TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: Biochar has emerged as a sustainable and efficient alternative for water and wastewater treatment due to its high surface area, porosity, chemical stability, and adsorption capacity. Over time, numerous studies have proposed methods for removing contaminants from water and wastewater to enable their reuse in accordance with Sustainable Development Goals (SDGs) 6 and 14. Among the techniques reported as effective in this context is the use of biochar. Therefore, the aim of the present study was to examine the state of the art and current trends regarding the use of biochar in water and wastewater treatment. To achieve this, a bibliometric analysis was conducted using the Scopus scientific database to identify the research landscape involving biochar for water and wastewater treatment.

Results: The use of residual agroforestry biomass for biochar production was predominant, including coffee husks, açaí seeds, bamboo, wood, rice husks, corn cobs, and forest residues. In addition, muffle furnaces were the most commonly used systems in thermal degradation processes. The pharmaceutical and textile industries, followed by water treatment facilities, were identified as the sectors with the greatest research interest involving biochar-based adsorbents.

Conclusions: Biochar demonstrated significant potential and efficiency for water and wastewater treatment due to its performance in removing contaminants such as pharmaceutical compounds, dyes, heavy metals, and emerging micropollutants. The successful removal of pollutants was mainly attributed to the adsorption mechanism associated with biochar, with improved performance observed after chemical activation. Therefore, biochar stands out not only as an adsorbent material, but also as a technology aligned with environmental remediation strategies, waste valorization, and sustainable water resource management.

Keywords: *activated biochar; waste management; adsorption processes; wastewater treatment.*

PEREIRA, C. J. S.; UCELLA-FILHO, J. G. M.; SOUZA, A. M.; CARNEIRO, A. C. O.; ABREU, E. L.; CARVALHO, A. M. M. L.; BARRAL, L. H. C.; NETTO, A. M.; BOMFIM, K. E. S.; MOREIRA, R. P. L.; SANTOS, J. V. C. Use of biochar in water and wastewater treatment: a bibliometric analysis and state-of-the-art review. CERNE, v. 32, e103709, 2026. DOI: 10.1590/01047760202632013709.

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Scientific Editor: Jordão Cabral Moulin

Received: February 27 2025
Accepted: May 25 2026

CERNE
ISSN 0104-7760

UNIVERSIDADE FEDERAL DE LAVRAS

INTRODUCTION

In 2015, the United Nations (UN) established seventeen Sustainable Development Goals (SDGs) as part of the 2030 Agenda (Bäckstrand *et al*., 2022). Among them, Goals 6 and 14 address ensuring the availability and sustainable management of water and sanitation for all (Goal 6), as well as the conservation and sustainable use of oceans, seas, and marine resources for sustainable development (Goal 14). These goals provide guidance for developing countries, particularly in regions where water contamination remains high due to the lack of environmental laws and regulatory policies capable of protecting water bodies from industrial wastewater and other anthropogenic activities (Le *et al*., 2025).

Conventional wastewater treatment methods include filtration, ion exchange, advanced oxidation processes, coagulation, foam flotation, solvent extraction, adsorption, and electrolysis (Rangabhashiyam *et al*., 2014). The traditional coagulation–sedimentation–filtration–disinfection process, widely employed in water treatment plants, presents limitations regarding contaminant removal. The most critical issues associated with coagulation-based water treatment are related to the susceptibility of the process to variations in the concentration and composition of natural organic matter, as well as the consequences of using metallic salts as coagulants (Knap-Bałdyga and Żubrowska-Sudoł, 2023). Aluminum-based coagulants, for instance, have been associated with increased toxicity, while inorganic polymers exhibit even greater toxic potential. Furthermore, synthetic polymers may present carcinogenic risks in addition to very low biodegradability (Kurniawan *et al*., 2020; Lapointe and Barbeau, 2019).

To overcome these limitations, advanced technologies such as activated biochar have increasingly been adopted. However, large-scale applications with economic feasibility for the removal of low-concentration contaminants, without generating secondary pollutants while maintaining rapid treatment performance, still represent a major challenge (Rangabhashiyam and Balasubramanian, 2019; Zhang *et al*., 2025).

These global demands have stimulated research focused on enabling efficient water and wastewater treatment processes aimed at water reuse and environmental impact reduction. Nevertheless, existing practices, particularly for wastewater treatment, still lack adequate efficiency. As an emerging alternative, activated biochar has gained recognition as a promising material for contaminant removal (Chen *et al*., 2020).

Recent studies have focused on the use of low-cost and efficient precursors, such as agricultural residues, low-value plants, forest residues, and industrial by-products, for biochar production (Rangabhashiyam and Balasubramanian, 2018). This approach has demonstrated advantages over several conventional methods due to its low initial cost when inexpensive solid supports are used, as well as it's flexible and simple design, ease of operation, and tolerance to toxic pollutants (Razzak *et al*., 2023). Biochar has increasingly been recommended for wastewater treatment because it is chemically stable, low-cost, carbon-rich, highly porous, and environmentally compatible (Singh *et al*., 2023). It is a porous carbonaceous material produced through the thermochemical decomposition of biomass feedstock under limited or oxygen-free conditions. Among biomass-derived adsorbents and metal–organic frameworks (MOFs), biochar stands out because of its versatility and performance (Arfasa and Tilahun, 2025; Xiang *et al*., 2020).

Currently, agroforestry biomass is the most common feedstock for biochar production, mainly because inefficient disposal practices and increasing accumulation have turned agroforestry waste into a major global environmental issue (Bettles *et al*., 2021; Gupta *et al*., 2022a). The expansion of agricultural and/or forestry production consequently generates large amounts of agroforestry residues, leading to environmental liabilities affecting both soils and wastewater systems, including eutrophication and increased biological and chemical oxygen demand (Gupta *et al*., 2022b; Yu *et al*., 2024). Conventional disposal methods, such as incineration, landfilling, and composting, may generate atmospheric pollutants, unpleasant odors, and groundwater contamination, in addition to increasing management costs (Ferronato and Torretta, 2019; Gupta *et al*., 2022a). Therefore, there is a growing need to develop strategies capable of converting these residues into value-added coproducts.

Biochar can be produced from abundant biomass resources and waste materials, such as crop residues, wood waste, animal manure, food waste, municipal solid waste, and sewage sludge (Dissanayake *et al*., 2020). Therefore, several materials, including coffee husks, spent coffee grounds, bean husks, wood from various species (*eucalyptus*, pine, and cashew), corn cobs, and rice husks, can be used for its production (Lima *et al*., 2020).

Research on the use of biochar for water and wastewater treatment, particularly for the removal of toxic and/or heavy contaminants, has gained increasing attention due to its strong adsorption potential (Rangabhashiyam and Balasubramanian, 2019). Adsorption is recognized as an effective and economically viable approach for drinking water production because it removes micropollutants present in raw water and/or formed during disinfection processes, thereby mitigating the toxicity of treated water (Castiglioni *et al*., 2022).

According to Bhatia *et al*. (2021), biochar offers significant benefits due to its broad applicability in several fields, including heavy metal and dye removal, pollutant remediation, and energy generation. Its ability to remove multiple contaminants from aqueous solutions makes it an ideal adsorbent for water and wastewater treatment (Gwenzi *et al*., 2017). The advantages provided by biochar arise mainly from its adsorption mechanism, which is widely used for the removal of organic and inorganic pollutants without generating hazardous by-products, while remaining low-cost, easy to operate, and highly effective (Thang *et al*., 2019). Therefore, biochar plays an important role in promoting resource-use efficiency, waste valorization, and environmental sustainability within the context of the circular economy (Olugbenga *et al*., 2024).

To obtain a comprehensive overview of the use of biochar in wastewater treatment, bibliometric analysis has emerged as an appropriate method, as it provides a detailed understanding of the development and current status of this research field. This type of analysis is based on clustering keywords into specific thematic axes, enabling the construction of a database capable of identifying research trends, scientific advances, and knowledge gaps (Ucella-Filho *et al*., 2022b). This approach makes it possible to analyze research trends through the application of quantitative tools to evaluate scientific progress and identify the most influential regions, authors, journals, academic institutions, and other parameters related to a given topic. Consequently, it allows a better understanding of global research trends in a specific field based on outputs derived from academic literature databases (Kaffash *et al*., 2021; Khudzari *et al*., 2018; Ucella-Filho *et al*., 2022a, 2024).

Therefore, the aim of the present study was to evaluate the state of the art and current trends regarding the use of biochar in water and wastewater treatment through a detailed bibliometric analysis. Specifically, the study aimed to: (i) identify the leading journals and authors publishing on the topic; (ii) quantify the increase in publications from 2019 to 2023; (iii) classify the most frequently used keywords and highlight patterns of international collaboration; (iv) identify the sectors responsible for generating the largest amounts of wastewater and the pollutants most commonly treated; (v) determine the biomass types most widely used and the thermochemical conversion processes employed; and (vi) identify the main challenges associated with the use of biochar for water and wastewater treatment, emphasizing recent advances, methodological approaches, and remaining knowledge gaps

MATERIAL AND METHODS

The methodology used to develop the bibliometric analysis on the selected topic was structured as a process involving a set of predefined steps, including: (i) searching for scientific publications related to the topic in a reliable database; (ii) selecting the retrieved publications and compiling a spreadsheet containing complementary information; (iii) processing the data to obtain descriptive statistics; and (iv) writing and interpreting the results.

Bibliometric studies commonly rely on a single database to facilitate the analysis of indicators and the mapping of scientific literature (Sweileh, 2021). In the present study, the search and extraction of scientific articles were performed using the Scopus database due to its broad worldwide coverage of scientific publications. Scopus is a comprehensive multidisciplinary database of peer-reviewed scientific literature and is widely employed in bibliometric analyses because of its extensive coverage of journals and academic publications. In addition, it presents advantages over other platforms, covering nearly 100% of the content indexed in PubMed and indexing approximately twice as many journals as the Web of Science (Sweileh, 2021; Ucella-Filho *et al*., 2022a). Furthermore, this database exhibits lower methodological complexity during the file extraction process (Falagas *et al*., 2008; Ucella-Filho *et al*., 2024).

The search strategy consisted of inserting combinations of keywords related to the application of biochar in water and wastewater treatment into the Scopus search field. To ensure broad coverage, the selected keywords were organized into three categories, incorporating relevant synonyms to maximize the retrieval of publications: (TITLE-ABS-KEY ("wastewater treatment" OR "water treatment") AND TITLE-ABS-KEY ("activated carbon" OR "biochar" OR "charcoal") AND TITLE-ABS-KEY ("biomass" OR "forest biomass" OR "agricultural biomass" OR "residual biomass" OR "forest industry residues" OR "agro-industrial residues" OR "solid residues")). The bibliometric analysis was conducted during the second semester of 2024. Therefore, to provide an updated overview of the field, only articles published between 2019 and 2023 were considered for data tabulation.

After the initial data collection, a rigorous screening process was carried out to identify publications specifically addressing water and wastewater treatment, biochar, and biomass-derived residues. The main additional information extracted from each article included, but was not limited to: (a) whether the feedstock consisted of residual biomass; (b) the agroforestry species used; (c) whether activation was applied and, if so, the activation method employed; (d) the most commonly used chemical activating agents; and (e) the type of treated effluent and the adsorbed contaminant. Review articles and records not directly related to the scope of this study were excluded during the screening process.

After selecting the relevant articles, all key elements were analyzed using descriptive statistics. Bibliometric characterization and mapping were performed using VOSviewer v.1.6.15 (van Eck & Waltman, 2010) and R (R Core Team, 2021) through the Biblioshiny function of the bibliometrix package (Aria & Cuccurullo, 2017).

RESULTS

Number of Publications per Year

After applying the selected keywords in the Scopus database, a total of 410 documents were retrieved. Following the data extraction and screening procedures, 106 articles remained and were subsequently used for the bibliometric analysis. The analyses conducted using the Scopus platform revealed a significant increase in the number of scientific publications (Figure 1) addressing the application of biochar in water and wastewater treatment across different research fields

With the support of the bibliometric analyses performed using the Scopus database, it was possible to

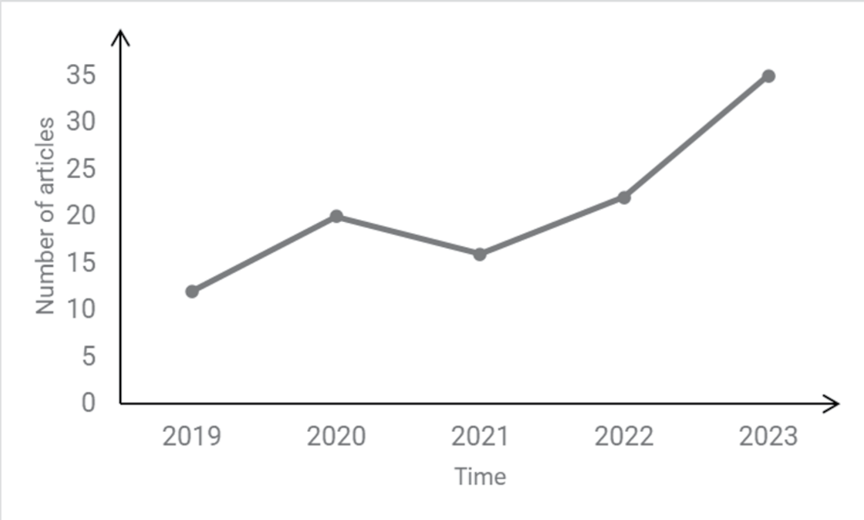

Figure 1: Temporal evolution of the number of publications between 2019 and 2023.

identify the journals that most frequently publish studies related to the topic. Furthermore, the rankings adopted by Scopus and the scientific dissemination potential associated with each journal were highlighted (Table 1).

Most Cited Studies According to Scopus

Based on Figure 1, a clear upward trend can be observed in the number of publications related to the topic addressed in this study. Another bibliometric indicator generated by the Scopus platform is the identification of the most highly cited scientific articles (Table 2). In addition to highlighting the authors of these studies, the analysis also includes information regarding the biomass feedstocks used, activating agents, application methods, research focus, and the respective citation counts.

Table 1. The 10 most cited studies in scientific publications.

Countries with the Highest Number of Publications on the Topic

Between 2019 and 2023, a publication trend was observed mainly in the following countries: China, India, the United States of America, Brazil, and South Korea (Figure 2).

Figure 3 illustrates the cooperation network among countries in scientific publications. It can be observed that several nations share knowledge and research findings in the context of water reuse, applying biochar as a key component. The main international research collaborations identified were concentrated among the following country pairs: China - United States, United States - Hong Kong, India - South Korea, China - United Kingdom, Malaysia - Saudi Arabia, China - Australia, and Italy - Tunisia.

The association between the terms biochar and adsorption is evident from the analysis of the selected studies. This relationship was further confirmed using the VOSviewer software, which generated a network visualization illustrating the interactions among indexing keywords, and Bibliometrix, which hierarchically identified the most frequent terms through a word cloud representation (Figure 4a). Figure 4b presents a graphical representation designed to highlight the frequency with which specific terms simultaneously appear within the same publications. This type of analysis, known as a co-occurrence network, is widely employed to identify emerging themes, research trends, and conceptual interrelationships within a given scientific field.

Research Areas with the Highest Number of Publications on the Topic

The adsorptive properties of biochar have been widely explored across multiple research domains. However, among the 106 scientific articles selected for this analysis, 26 studies focused on pharmaceutical industry

Table 1: Most relevant journals related to the application of biochar in water and wastewater treatment.

Newspaper	H-index	SJR	Quartile
Bioresource Technology	404	1983	Q1
Science of the Total Environment	439	2043	Q1
Chemosphere	353	1640	Q1
Journal of Environmental Chemical Engineering	172	1273	Q1
Biomass Conversion and Biorefinery	72	0.829	Q2

Table 2: The 10 most cited studies in scientific publications.

Author	Title	Commercial activated carbon	Biochar	Biomass	Activating agente	Application	Study object	Number of citations
Wu et al (2021)	A novel modified method for the efficient removal of Pb and Cd from wastewater by biochar: Enhanced the ion exchange and precipitation capacity		X	Coconut shell	Magnesium chloride ($MgCl_2$)	Heavy metal removal	Pollution and waste management	383
Huang et al (2019)	Cr(VI) removal from aqueous solution using biochar modified with Mg/Al-layered double hydroxide intercalated with ethylenediaminetetraacetic acid		X	Bamboo	Magnesium chloride hexahydrate ($MgCl_2{\cdot}6H_2O$), aluminum chloride hexahydrate ($AlCl_3{\cdot}6H_2O$)	Pharmaceutical removal	Bioengineering and waste management	239
Meng et al (2020)	Insight into the effect of lignocellulosic biomass source on the performance of biochar as persulfate activator for aqueous organic pollutants remediation: Epicarp and mesocarp of citrus peels as examples		X	Tangerine peels		Dye removal	Health, toxicology, mutagenesis, and waste management	202
Singh et al (2023)	Pyrolysis of waste biomass and plastics for production of biochar and its use for removal of heavy metals from aqueous solution		X	Bamboo, sugarcane, neem, and plastic waste		Heavy metal removal	Renewable energy, sustainability, and environment	170
Yu et al (2024)	Nanoplastics adsorption and removal efficiency by granular activated carbon used in drinking water treatment process	X		Granular coconut shell–based		Removal of amidine polystyrene nanoplastics	Pollution, waste management, and disposal	138
He et al (2019)	Facile preparation of sulfonated biochar for highly efficient removal of toxic Pb(II) and Cd(II) from wastewater		X	*Axonopus compressus (São Carlos grass)*	Sulfuric acid (H_2SO_4)	Heavy metal removal	Surface chemistry	138
Ramirez et al (2021)	Activated biochar with iron-loading and its application in removing Cr (VI) from aqueous solution		X	Bamboo and poplar	Potassium hydroxide (KOH) and iron salt solution	Heavy metal removal	Pollution and waste management	136
Queiroz et al (2020)	Activated carbon obtained from amazonian biomass tailings (acai seed): Modification, characterization, and use for removal of metal ions from water		X	Açaí seed	Potassium hydroxide (KOH)	Removal of metal ions from water	Waste management, monitoring, and disposal	132
Sun et al (2016)	Tailored design of graphitic biochar for high-efficiency and chemical-free microwave-assisted removal of refractory organic contaminants		X	Oak and apple wood		Removal of refractory organic contaminant chemicals	Industrial and manufacturing engineering	117
Cruz et al (2020)	Agrowaste derived biochars impregnated with ZnO for removal of arsenic and lead in water		X	Coffee husk and corn cob	Zinc oxide (ZnO)	Heavy metal removal	Process technology, pollution, and waste management	109

effluents (24.53%); 28 addressed water from treatment plants (26.42%); 20 investigated wastewater from the textile industry (18.87%); and 18 examined water treatment solutions for agricultural use (16.98%). As illustrated in Figure 5, the proportion of studies related to greywater, river water, and rainwater treatment remained below 10%.

During the screening process, in addition to identifying the types of effluents investigated, it was also possible to categorize the removal of specific pollutants (Figure 6). Several contaminants of interest targeted for removal from aqueous solutions were identified. However, from a broader perspective, five main groups were established, comprising the compounds most frequently removed from a given aqueous medium.

The Term "Biochar"

A significant proportion of the studies included the term biochar in their titles. However, several of these studies investigated the use of commercial activated carbon (CAC), which had been chemically or physicochemically activated for the purposes of the study, as well as activated carbons produced from biomass residues (Figure 7), among other materials.

Biomass Sources Reported in the Articles and Thermal Degradation Processes

Based on the analysis and data collection, it was inferred that one of the main advantages of biochar and activated carbon production lies in the use of residual materials as the primary biomass source (Table 3).

Additional data extracted from the studies also revealed which chemical activation methods were most frequently employed and, consequently, identified the main chemical compounds responsible for the activation of activated carbons (Figure 8).

As observed, the diversity of biomass sources used for conversion into biochar is considerable. However, it is essential that this transformation process be properly conducted to achieve the best qualitative performance of the material generated through thermal degradation. During the review of the studies, it was observed that the methodologies employed seven different types of furnaces to perform the thermal conversion process (Figure 9).

DISCUSSION

Number of Publications per Year

In 2019, 12 studies addressing this topic were published; in the following year, this number increased to 20. However, due to the COVID-19 pandemic, a decline in the number of publications was observed in 2021 and 2022. In 2023, 35 studies were published (Figure 1). This growing trend in publications related to water treatment using biomass-derived adsorbents is associated with the concept of the circular economy, a term that has been widely disseminated in recent years. According to Oliveira

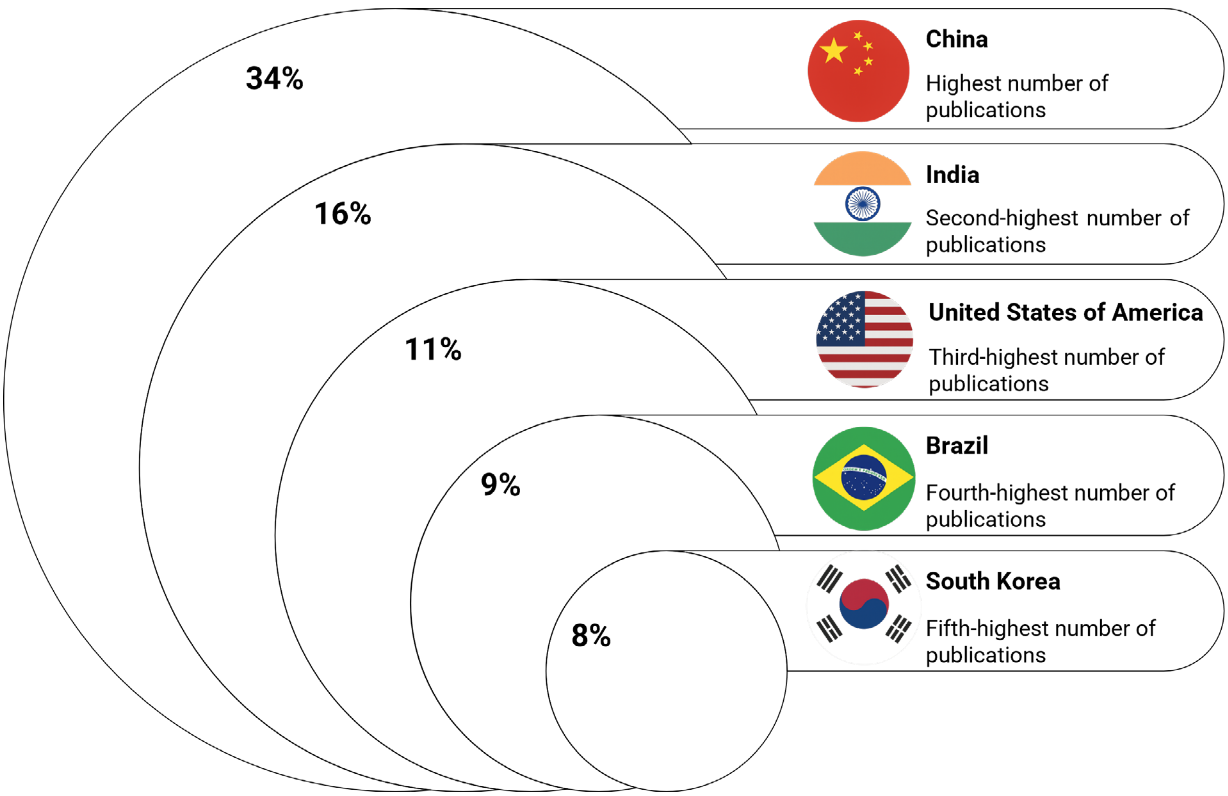

Figure 2: Leading countries in publications related to the application of biochar for water and wastewater treatment.

et al. (2019), the circular economy is based on maintaining the value of extracted and produced resources within integrated production chains by converting materials considered waste into by-products and assigning them new applications. This principle has become a guiding approach adopted by many researchers in this field. Based on the studies analyzed in the development of this work, the predominant strategy consists of converting residual biomass into activated carbon and/or biochar and applying these materials as efficient adsorbents for water treatment, mainly for wastewater remediation.

In addition to the environmental motivations supporting the application of biochar for the treatment of different waste streams, the economic aspects associated with this method must also be considered. Water treatment industries are currently seeking alternative low-cost technologies that can be implemented without significant modifications to existing processes and infrastructure, while simultaneously supporting the principles of the circular economy (Halder *et al*., 2023). As demonstrated throughout this study, biochars exhibit properties capable of addressing these challenges, since they are effective in removing contaminants from aqueous environments, including polluted soils, surface waters, and wastewater (Gupta *et al*., 2022).

Furthermore, the Scopus platform identified the scientific journals that most frequently published studies related to the application of biochar in water and wastewater treatment between 2019 and 2023 (Table 1). The journals with the highest number of publications were: Chemosphere (8 publications); Science of the Total Environment (7 publications); Biomass Conversion and Biorefinery (6 publications); Bioresource Technology (5 publications); and Journal of Environmental Chemical Engineering (4 publications).

The journals Bioresource Technology and Science of the Total Environment stand out due to their high impact indicators and the frequent publication of relevant studies on biochar and wastewater treatment. Journal of Environmental Chemical Engineering shows strong relevance for research involving contaminant removal technologies, while Biomass Conversion and Biorefinery demonstrates considerable potential for studies related to biochar production and modification, as well as the valorization of agro-industrial residues.

All these journals primarily focus on chemical compounds, environmental pollution, biomass conversion, and biorefinery processes. They promote multidisciplinary research addressing the interactions among the atmosphere, lithosphere, hydrosphere, biosphere, and anthroposphere, while maintaining an international scope and a holistic perspective on the sustainable use of biomass. Therefore, they are among the most relevant journals in the fields of environmental engineering, water treatment, biochar, and sustainability.

Table 1 also presents a ranking of the journals with the greatest relevance to the topic. The classification of these journals in the Scopus database is based on bibliometric indicators such as the H-index, which reflects the accumulated influence and historical relevance of the journal; the SJR (SCImago Journal Rank), which evaluates scientific prestige according to the quality of received citations; and the Scopus Quartile, which represents the journal's impact within its respective subject area.

Therefore, the identified journals exhibit high scientific relevance within the Scopus database, with a predominance of Q1 journals, highlighting the growing international interest in research related to the application of biochar for water and wastewater treatment. In particular, journals such as Bioresource Technology, Chemosphere, and Science of the Total Environment stand out due to their high impact and broad scientific dissemination in the environmental field.

Most Cited Studies According to Scopus

The ten most cited studies indexed in Scopus (Table 2) predominantly highlight the use of agricultural

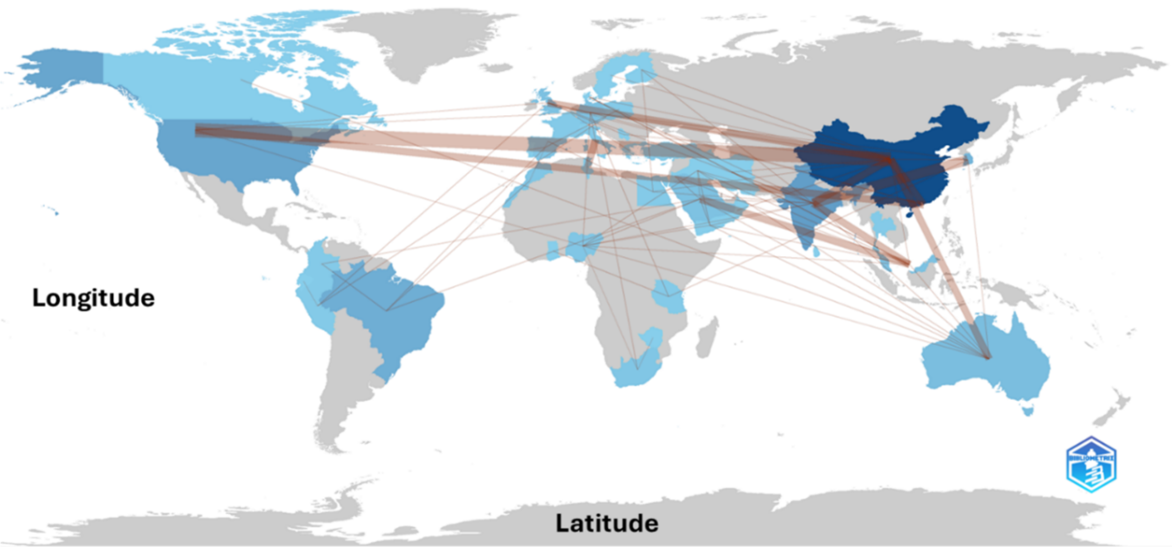

Figure 3: Countries collaborating in the publication of scientific articles. Interaction Between Indexing Keywords

and forest biomass. This recurrent utilization of residual agroforestry biomass, aimed at reducing the environmental impacts associated with waste accumulation, has been widely reported in the literature. Several studies have described efforts to convert such residues into products with commercial value (Queiroz *et al*., 2020).

The physicochemical properties of these porous carbonaceous materials depend on both the type of feedstock, such as agricultural residues, food waste, sewage sludge, and other solid biogenic residues, and the operational conditions applied during pyrolysis (Abbaspour *et al*., 2025). The use of residual biomass, including sawdust, corn residues, wheat husks, and similar materials, plays a crucial role in the effective application of bioadsorbents for wastewater treatment (Duwiejuah, 2026). Table 2 confirms the importance of residual biomass utilization, since all ten studies employed residues derived from plant species as feedstocks, with bamboo residues appearing most frequently.

Chemical activation has proven to be an efficient method for increasing the adsorption capacity of carbon materials and was the most recurrent approach among the studies analyzed in this work, according to Table 3. Chemical modification, particularly using acids, alkaline agents, and oxidizing compounds, has been extensively investigated, leading to improvements in surface characteristics, especially through the abundant introduction of surface functional groups.

Consequently, the adsorption performance toward pollutants can be significantly enhanced (Xiong *et al*., 2022). Acid treatments, in particular, modify biochar surfaces by increasing oxygen-containing functional groups, thereby improving their capacity to adsorb positively charged pollutants through specific chemical interactions (Shen *et al*., 2025).

Approximately half of the most cited studies listed in Table 2 employed biochar for heavy metal removal. Heavy metals, defined as elements with high atomic weight and density that naturally occur in geological systems (Parida and Patel, 2023), have become a major environmental threat due to their carcinogenic nature, potential for bioaccumulation within the food chain, and harmful effects on living tissues (Duwiejuah, 2026).

The most highly cited studies share two central aspects: waste generation and waste management, either

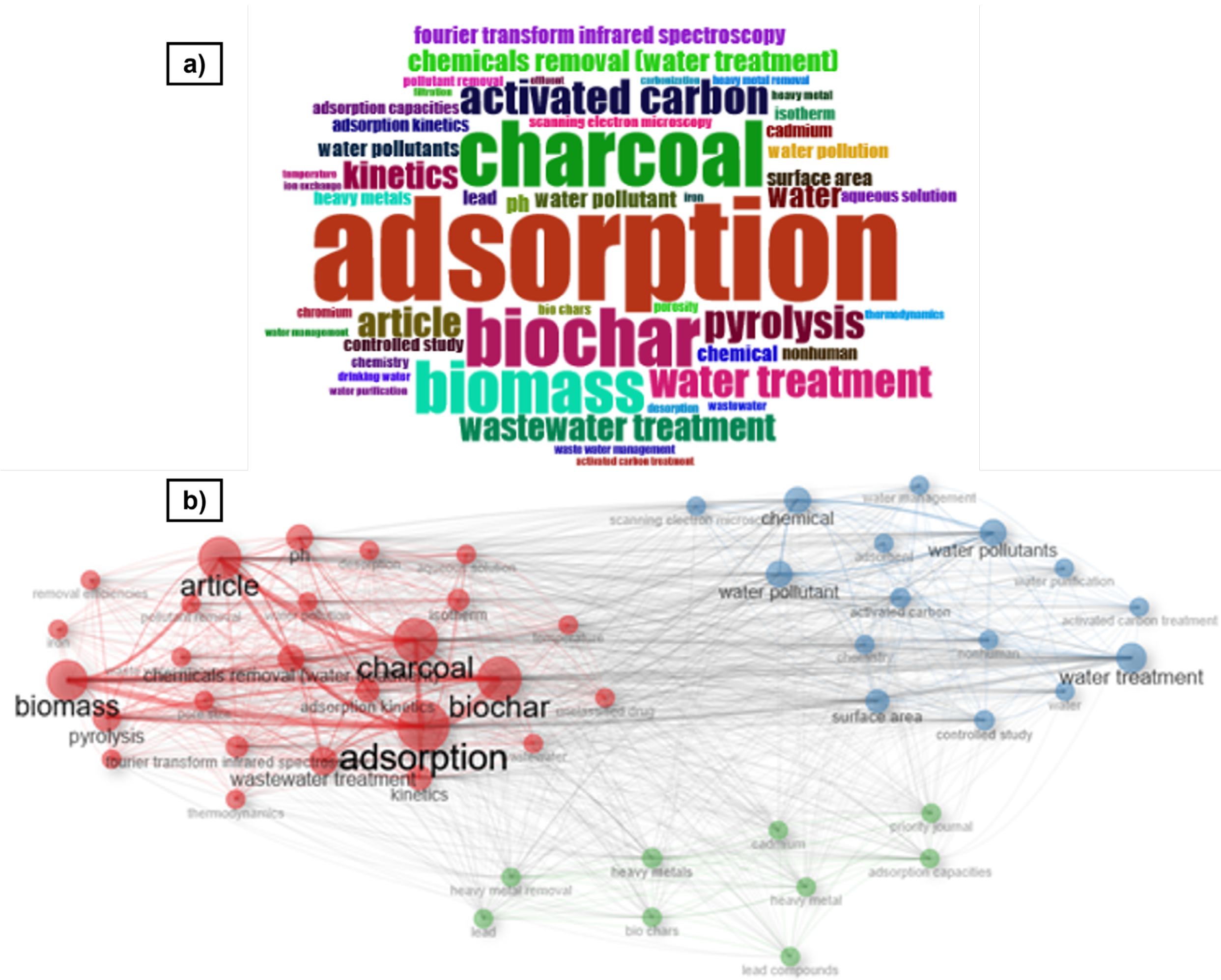

Figure 4: (a) Word cloud showing the most relevant keywords identified in the analyzed scientific articles; (b) Co-occurrence network based on the frequency of terms found in the analyzed publications.

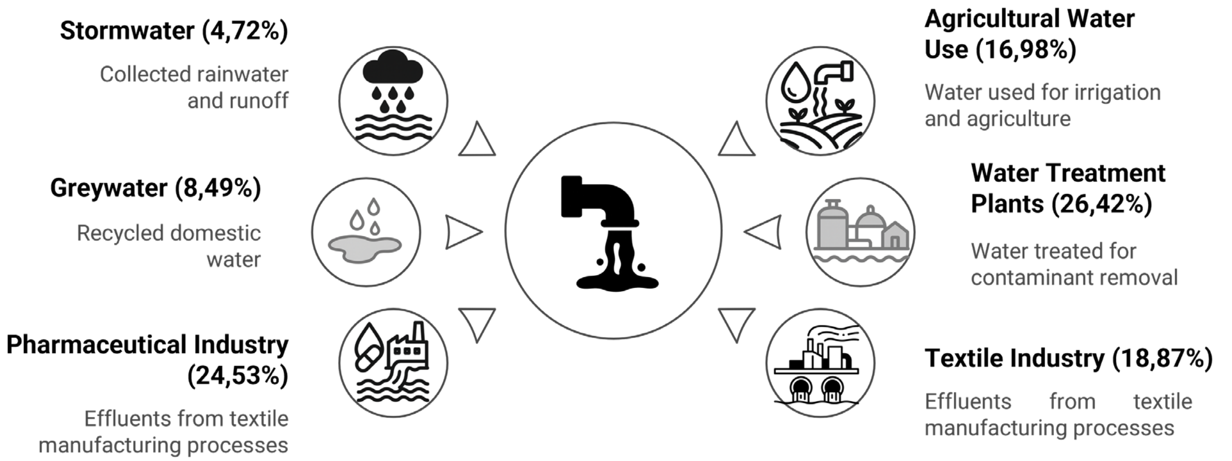

Figure 5: Sources of effluents treated using biochar or chemically activated carbon.

from the perspective of producing value-added materials or promoting environmental balance. These aspects are aligned with multiple objectives of the United Nations Sustainable Development Goals (SDGs) (Bäckstrand *et al.*, 2022). Furthermore, the development of innovative technologies to improve water and wastewater treatment methodologies is relevant not only for environmental protection but also for public health, since the proper treatment of municipal and industrial wastewater is essential for safeguarding ecosystems and human well-being (Baral *et al.*, 2020). Therefore, the scenario described becomes inherently multidisciplinary and comprehensive, reinforcing the importance of the SDGs within this research context.

Countries with the Highest Number of Publications

China and India were the countries with the highest number of publications related to the topic, followed by the United States and Brazil (Figure 2). A common characteristic observed among these regions is their large population size, suggesting that research on water and wastewater treatment is directly associated with countries experiencing intense population growth, where increasing demographic pressure intensifies the demand for sustainable water management solutions.

The high publication rate observed in Asian countries may be associated with their elevated population density and industrial intensity. The Asia-Pacific region accounts for approximately 60% of the world's population but possesses only 36% of global freshwater resources. Consequently, water availability, allocation, and quality remain major challenges, making research initiatives focused on water use and reuse particularly prominent in this region (United Nations World Water Assessment Programme, 2012). India, which holds only 4% of global freshwater resources, must meet the demands of 17.7% of the world's population (Agnihotri *et al.*, 2025).

Deng *et al.* (2025) conducted an in-depth analysis of how both seasonal and chronic water demand and scarcity evolved spatially and temporally in the world's three most

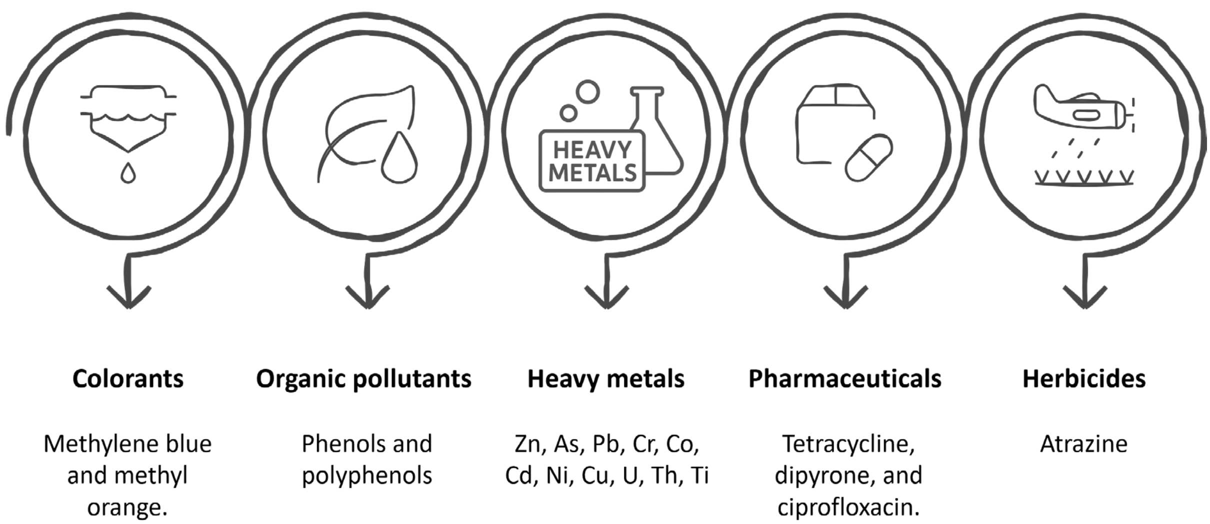

Figure 6: Types of aquatic pollutants removed by biomass-derived adsorbents.

Table 3: Biomass species used, frequency of use, and type of activation

	Activation			
Species	**Chemical**	**Physical**	**Physicochemical**	**Without activation**
Bambusoidea Luerss.	x			
Quercus L.				x
Quercus robur	x			
Eucalyptus ssp.	x			
Calophyllum inophyllum L.	x			
Acorus calamus L.			x	
Artocarpus heterophyllus Lam.				x
Zea *mays* L.	x	x		
Allophylus pauciflorus. Radlk				x
Oryza sativa L.	x			
Manihot esculenta Crantz	x			
Humulus scandens (Lour.) Merr	x			
Pennisetum purpureum Schumach.				x
Euterpe oleracea Mart.	x			
Coffea sp.	x			
Ageratum conyzoides L.				x
Eichhornia crassipes (Mart.)	x			
Azadirachta indica A.Juss.	x			
Brachystegia eurycoma (Harms.)				x
Gossypium L.				x
Brassica L.				x
Arachis hypogaea L.				x
Musa paradisiaca L.				x
Phragmites karka (Retz.)				x
Carya illinoinensis (Wangenh.) K.Koch				x
Acacia nilotica (L.) Willd. ex Delile				x
Delonix regia (Hook.) Raf.				x
Axonopus compressus (Sw.) P. Beauv.				x
Saccharum officinarum L.				x
Pinus taeda	x			
Daphnia magna Straus.	x	x		
Populus (L.)				x
Prunus persica		x		
Amorphophallus konjac				x
Citrus reticulata Blanco		x		
Syzygium cumini (L.) Skeels				x

populous countries: China, India, and the United States. Together, these nations account for 41% of the global population, 49% of surface and groundwater consumption, and 39% of global food production.

Several factors influence urban water consumption, including population density, economic activity, lifestyle patterns, infrastructure, and climate conditions. However, the prevalence of water contamination in developing countries remains high due to insufficient regulatory frameworks protecting water bodies from industrial wastewater and anthropogenic activities (Le *et al*., 2025; Maleki *et al*., 2025). Economic growth also contributes to increasing water demand by raising per capita consumption and altering consumption patterns, particularly through dietary shifts toward more water-intensive products (Frontuto *et al*., 2025; Montoya *et al*., 2023).

Globally, water consumption, regardless of its application, is directly linked to population growth. The world population is currently approximately 8.0 billion and is projected to reach 9.7 billion by 2050. This rapid demographic expansion has been one of the main driving forces behind the development of green technologies and environmentally oriented processes capable of reducing pollution and mitigating climate impacts (Liu *et al*., 2025; Timothy *et al*., 2021).

The international collaboration network related to research on biochar as an adsorbent indicates that China leads in scientific contributions, followed by the United States, India, and South Korea (Figure 3). These findings highlight the fundamental role of scientific cooperation among countries, providing valuable insights for researchers seeking potential collaborations and the development of future research partnerships.

Furthermore, the analysis of the articles revealed a direct association with the production of biochar from residual biomass, an aspect particularly relevant in Brazil due to the wide availability of agro-industrial and forest residues. This scenario favors waste valorization and the development of sustainable technologies applied to water and wastewater treatment.

Interaction Between Indexing Keywords

The most relevant keywords identified were carbon, biochar, and biomass, followed by other prominent terms such as pyrolysis, wastewater, and activated carbon (Figure 4a). These terms are directly interconnected, since efforts to enhance the efficiency of biochar-based adsorbents through chemical and physical modifications have attracted considerable scientific interest (Elmezayen *et al*., 2025).

A total of 1,558 indexing keywords were recorded. Considering a minimum threshold of five occurrences per keyword, 122 terms were included in the interaction network (Figure 4a). Among these, adsorption, biochar, carbon, pyrolysis, and wastewater treatment appeared consistently. The term adsorption was identified by Bibliometrix as the most relevant keyword among the indexing terms. Adsorption is considered one of the most effective treatment techniques due to its low energy consumption, applicability over a wide range of

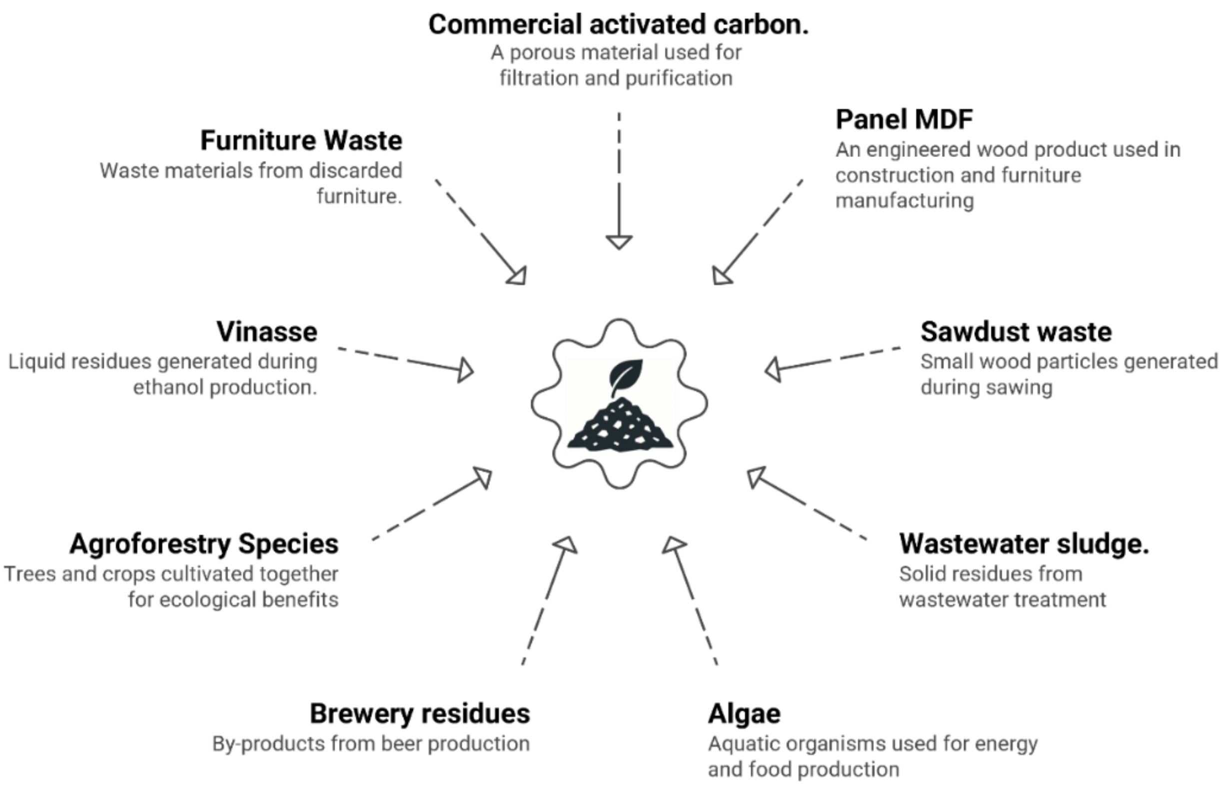

Figure 7: Types of biomass reported in the publications and their frequency of use.

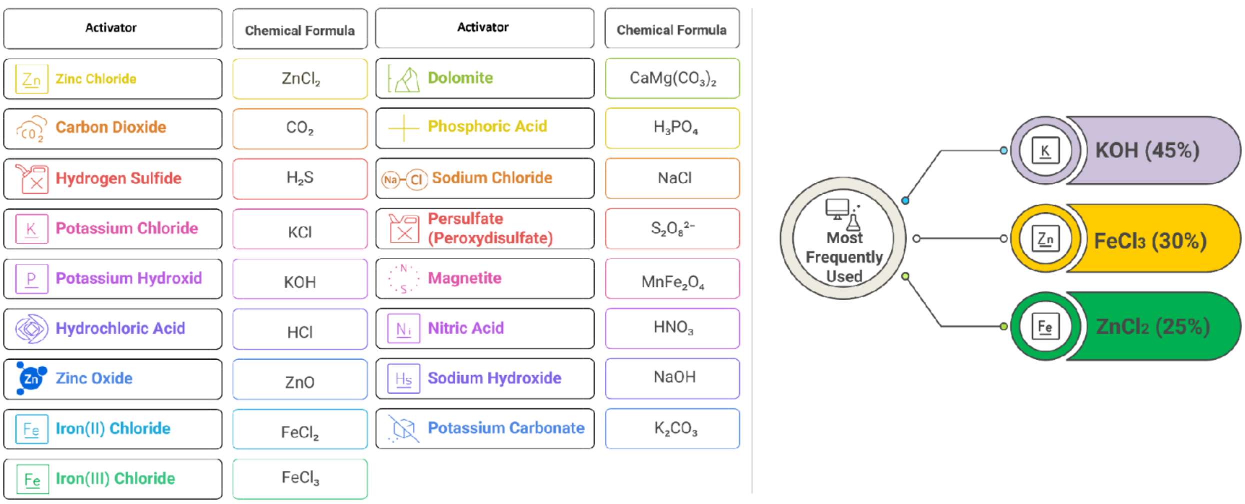

Figure 8: Chemical compounds used for the activation of activated carbons.

temperatures and pressures, and the ease of adsorbent regeneration without generating undesirable by-products (Dissanayake *et al.*, 2020). In addition, adsorption technology is widely implemented in coal-fired power plants because of its simple equipment requirements, operational convenience, and high degree of automation.

The co-occurrence analysis (Figure 4b) revealed three main clusters, distinguished by the colors red, blue, and green, indicating groups of terms that frequently appeared together. The red cluster (central thematic area) represents the core focus of the research field. Terms such as biochar, adsorption, biomass, charcoal, wastewater treatment, pyrolysis, and adsorption kinetics are associated with biochar production, its physicochemical characteristics, and its subsequent application as an adsorbent, particularly for wastewater treatment. The blue cluster (adsorbent efficiency and physicochemical properties) includes the terms water treatment, water pollutants, activated carbon, surface area, water purification, and chemistry, relating the use of biochar as an adsorbent to wastewater treatment processes, often in comparison with commercial activated carbon. The green cluster (heavy metal removal) comprises the terms heavy metals, cadmium, lead, and adsorption capacities, emphasizing the application of biochar-based adsorbents for heavy metal removal, highlighting adsorption mechanisms and practical applicability.

Main Application Areas Publishing on the Topic

The analysis indicates that the effluents most frequently investigated and treated using activated carbons (Figure 5), including both commercial and biomass-derived materials, as well as biochars, predominantly originate from industrial sources and contain significant concentrations of chemical elements. Industrial effluents are considered highly critical due to their complex composition, and the responsibility for their collection and treatment lies with the generating entity (Rocha *et al.*, 2019).

Among industrial wastewaters, pharmaceutical effluents have received particular attention. According to Wang and Wang (2016), pharmaceutical compounds persist in the environment due to their extensive use and the limited removal efficiency of conventional biological wastewater treatment plants. The diversity and structural complexity of these compounds, including antibiotics, analgesics, hormones, and psychotropic substances, make their disposal and environmental degradation especially challenging (Pandey *et al.*, 2025). Conventional treatment technologies are often inadequate for handling this specific class of pollutants, which is characterized by high concentrations of complex organic compounds, elevated salinity, microbial toxicity, and low biodegradability (Mylapilli & Reddy, 2019).

The increasing generation of pharmaceutical effluents is directly associated with the global rise in medication consumption, driven by population growth, aging, and expanded access to healthcare services. As a result, substantial quantities of pharmaceutical residues are generated in hospitals, clinics, veterinary services, and households (Pandey *et al.*, 2025). Notably, antibiotics have been recognized as an important group of emerging micropollutants (Sousa *et al.*, 2022), and their incomplete removal in treatment systems may contribute to the spread of antibiotic resistance in aquatic environments (Chaturvedi *et al.*, 2021).

The textile industry is another major contributor to wastewater pollution. Widely distributed across both developed and developing countries, it is one of the largest consumers of water and generates substantial volumes of highly polluted effluents, whose characteristics depend on the specific production processes employed (Amato *et al.*, 2025). The increasing demand for synthetic dyes further intensifies wastewater discharge. Textile effluents typically contain a complex mixture of pollutants, including residual fibers, sizing agents, and various dye compounds (Lin *et al.*, 2026).

Dyes represent significant aquatic pollutants, particularly those released by textile industries. Exposure to dye-contaminated water poses risks to human health, including skin disorders, digestive disturbances, and potential carcinogenic effects (Mosbah *et al*., 2019; Santoso *et al*., 2020). Among these compounds, methylene blue is widely used in paper coloring, cotton, silk, wool, and hair product industries. It has been associated with ocular, respiratory, digestive, and neurological disorders. Its removal has been extensively investigated using adsorption techniques, including biomass-derived adsorbents (Santoso *et al*., 2020).

The expansion of the dye industry is attributed to the broad applicability of pigments and dyes in plastics, paints, paper, construction materials, ceramics, cosmetics, pharmaceuticals, fuels, oils, and textiles (Mosbah *et al*., 2019). In addition, pharmaceutical compounds such as tetracycline and ciprofloxacin are frequently investigated due to their persistence in wastewater treatment systems (Yang *et al*., 2024).

Agriculture is the world's largest consumer of water, accounting for approximately 90% of humanity's water footprint, and irrigated agriculture continues to expand (Deng *et al*., 2025; Zhang *et al*., 2023). Historically, the global crop water footprint reached 7,404 billion cubic meters per year between 1996 and 2005, with wheat and rice accounting for approximately 45% of the global blue water footprint (surface and groundwater flows) (Zhang *et al*., 2023). The increasing agricultural demand for water intensifies pressure on freshwater resources and contributes to the runoff of nutrients and agrochemicals into water bodies.

Domestic water demand, particularly in urban areas, is also expected to increase substantially despite the worsening deficits in surface water availability (Deng *et al*., 2025). An important component of this demand is greywater, defined as wastewater generated from sinks, showers, bathtubs, and washing machines in households, commercial establishments, and industries. Greywater generally contains fewer contaminants than blackwater and can be treated and reused, thereby helping to reduce pressure on freshwater resources. It typically represents 50–80% of the total volume of domestic wastewater (Agnihotri *et al*., 2025).

Several industries contribute to environmental pollution through the discharge of effluents containing

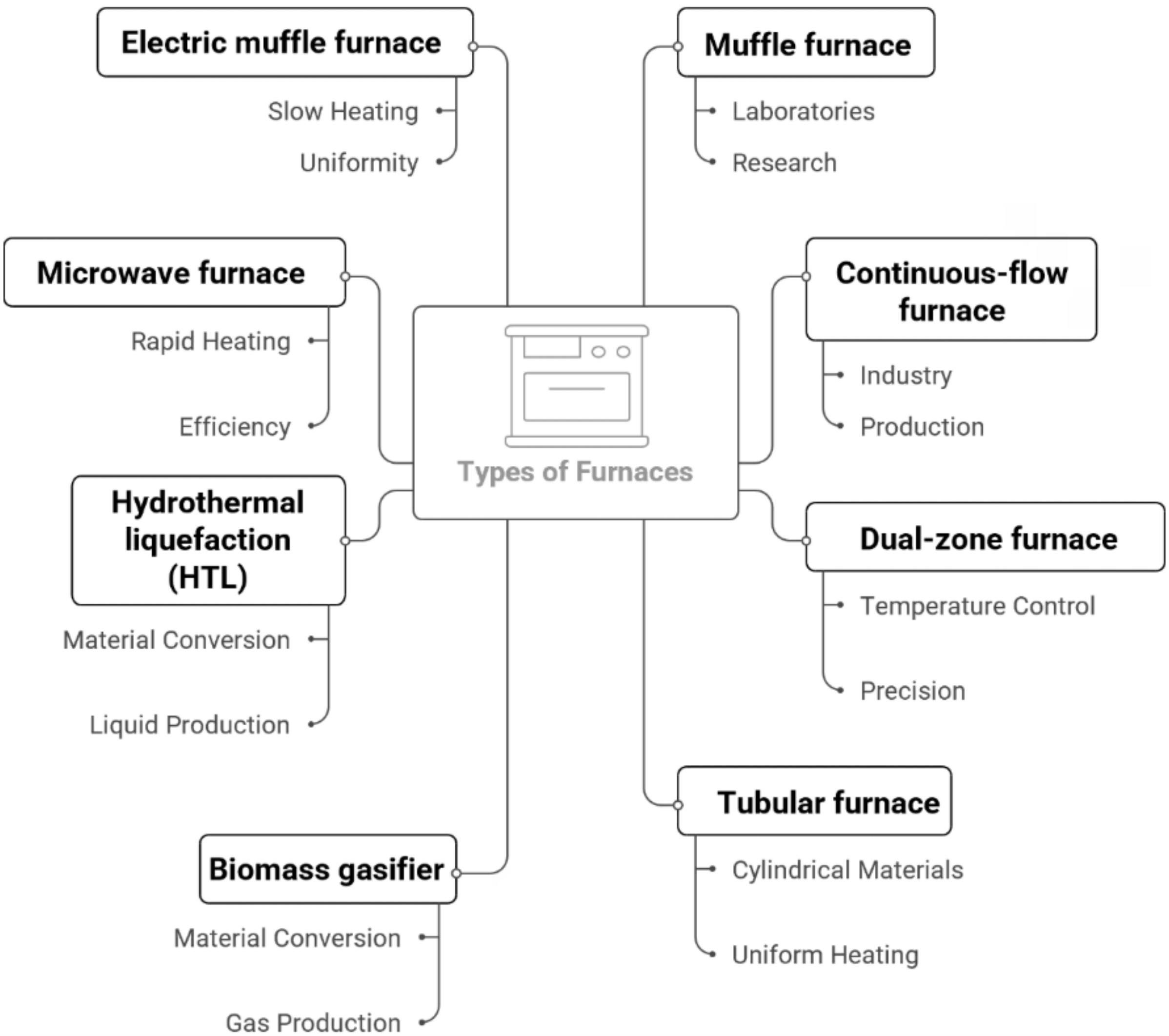

Figure 9: Thermal degradation methods applied to the biomass used in the studies.

heavy metals. The most prevalent contaminants (Figure 6) include cadmium (Cd), zinc (Zn), lead (Pb), chromium (Cr), nickel (Ni), copper (Cu), vanadium (V), platinum (Pt), silver (Ag), tin (Sn), and titanium (Ti) (Shrestha *et al*., 2021). Heavy metal toxicity poses significant health risks, including impaired growth and development, organ damage, neurological disorders, cancer, and, in severe cases, death when exposure thresholds are exceeded (Oladimeji *et al*., 2024).

Overall, the literature demonstrates that industrial, pharmaceutical, textile, agricultural, and domestic effluents constitute the main application areas in which activated carbons and biochars are investigated as adsorption-based treatment technologies.

The Term "Biochar"

Several carbonaceous materials used as adsorbents were identified (Figure 7); therefore, clarification of the terminology is necessary, particularly in cases where biochars are modified after production, for which some sources employ the term "activation" (Lehmann & Joseph, 2024). However, such post-treatment processes are often poorly defined and should be explicitly described, specifying what "biochar activation" means within the context of a given study. The use of the term "activated biochar" is generally discouraged.

Commercial activated carbon (CAC) has frequently been used interchangeably with biochar in the literature, as have chemically treated materials resulting in activated carbons. In this context, it is essential to clearly distinguish between these materials. Biochar is defined as a carbon-rich material, similar to charcoal, produced by heating residual organic matter (biomass) at high temperatures under oxygen-limited conditions (Lehmann & Joseph, 2024). In contrast, activated carbon is a carbonaceous material characterized by a highly porous structure containing small amounts of heteroatoms, mainly oxygen, bonded to carbon atoms (Nobre *et al*., 2015).

According to Cuba *et al*. (2021), chemical activation can be applied either directly to the biomass precursor or to the already-produced biochar. This dual possibility may have contributed to the misinterpretation and inconsistent use of the terms "biochar" and "activated carbon."

More specifically, biochar refers to pyrolyzed biomass materials, whereas the broader category of "biomass-derived adsorbents" encompasses other biomass-based sorbents that are not strictly classified as biochar. These include hydrochar (produced through hydrothermal carbonization), chemically activated carbons derived from agricultural residues, and untreated or minimally processed biosorbents, such as coconut husks, crop residues, and sawdust (Arfasa & Tilahun, 2025).

Biomass Sources Reported in the Articles and Thermal Degradation Pathways

Table 3 presents several species whose residues were predominantly used as feedstocks. A notable predominance of agricultural residues was observed, in agreement with the perspective of Lehmann and Joseph (2024), who highlighted the wide variety of materials that can be processed through different pyrolysis technologies. These materials include woody biomass, leaves, grasses, animal manure, human waste, and crop residues such as nut shells, kernels, pits, bagasse, rice husks, and straw. This approach not only adds value to agro-industrial and organic residues, but also contributes to sustainable waste management and the principles of resource recovery. It is noteworthy that materials previously considered to have little or no economic value have been successfully utilized for biochar production. This represents a significant step toward sustainability and ecological balance while also offering potential economic benefits (Olugbenga *et al*., 2024).

The activation methods described in Table 3 are critical determinants of the quality and characteristics of the resulting adsorbents. Physical activation of biochar involves subjecting the material to high temperatures under oxygen-free conditions. This process promotes the removal of volatile compounds and results in the formation of a highly porous structure (Sun *et al*., 2016).

Chemical activation, in contrast, involves treating the biomass or biochar with activating agents such as acids, bases, or salts (Olugbenga *et al*., 2024). Among the activating agents reported (Figure 8), potassium hydroxide, zinc chloride, and ferric chloride were the most frequently employed in thermal degradation methodologies aimed at enhancing adsorptive properties, and they have been widely applied in the pre-treatment of the feedstock used for biochar production (François *et al*., 2023). Although chemical modification increases the production costs of biochar, potassium hydroxide treatment, for example, enhances surface oxygen content, pore volume, specific surface area, pH, dissolved ash content, and organic functional groups (Kumari *et al*., 2025).

Zinc chloride, on the other hand, has the ability to assist in the production of materials with high surface areas by improving not only the pore structure but also the surface functional groups of biochar materials, and it has been successfully used in the production of adsorbents for water treatment. Likewise, ferric chloride activation has been reported as a simple and effective method, since the fixation of iron salts onto the biochar surface results in solids with high surface area (Thue *et al*., 2022; Zeng and Kan, 2022).

Chemical activation is often considered more advantageous than physical activation because it is carried out at lower temperatures and generally produces higher activated carbon yields (Aliakbari *et al*., 2018). According to Kula *et al*. (2008), chemical activation offers two major advantages over physical activation: (i) lower operational temperature and (ii) higher overall yield, since extensive carbon consumption is not required. In addition, chemical activation may outperform physical activation in terms of energy efficiency and processing time (Attia *et al*., 2025).

Table 3 not only demonstrates the diversity of residual products that can be converted into biochar-based adsorbents, but also highlights biomass as a widely accepted and promising candidate due to its renewability, durability, abundance, low cost, and high utilization potential (Timothy *et al*., 2021). Biomass is also considered a key component of the circular economy, emphasizing the principles of reduction, reuse, and recycling in order to minimize waste generation and maximize resource value (Adeleye *et al*., 2019).

Although several technologies are available for converting organic residues into value-added products, renewed interest has emerged in thermochemical conversion processes, in which biomass is exposed to high temperatures under oxygen-limited conditions (Hernandez-Charpak *et al*., 2024). The predominance of chemical activation methods observed in the reviewed studies reflects the need to tailor biochar properties for environmental applications. Both chemical and physical activation processes are commonly applied to modify or improve biochar functionality, pore structure, and specific surface area, thereby enhancing its adsorption performance (Cuba *et al*., 2021).

Another important factor in biochar production is the equipment used for thermal conversion. Eight different thermal degradation technologies were identified (Figure 9), which, excluding gasification and hydrothermal liquefaction methods, rely on pyrolysis technology. Pyrolysis can be classified as either slow or fast pyrolysis, differing mainly in heating rate, residence time, and operating temperature (Campion *et al*., 2023). Pyrolysis variables directly influence the production costs of biochar (Amenaghawon *et al*., 2021). Therefore, understanding the different pyrolysis techniques and reactor configurations available is essential, since their selection is associated with economic feasibility, reaction time, and the desired properties of the final product (Cuevas; Leiva-Candia; Dorado, 2024).

The muffle furnace is the most widely used equipment in laboratories and scientific research, despite its relatively high acquisition and operational costs. Among the advantages of this type of furnace are the cleaner conditions provided for thermal treatments, reducing the risk of sample contamination, as well as it's relatively simple operation and control, which do not require a high level of operational expertise when compared to other furnace systems (Castro *et al*., 2019; Veiga *et al*., 2021). Tubular furnaces, similarly to muffle furnaces, are also commonly employed at the laboratory scale due to the simplicity of the technique and their relatively low operational cost. On the other hand, the limited production capacity of these furnaces is a factor that restricts broader investigations into biochar properties and large-scale applications (Silva *et al*., 2023; Veiga *et al*., 2021).

The biochar production process using continuous-flow furnaces is primarily oriented toward industrial-scale applications, which explains the higher operational and equipment costs associated with this technology. This process is characterized by ease of operation, consistency in product quality, reduced labor costs, shorter processing times, lower temporary storage expenses, simplified control throughout the production cycle, and stable continuous operation (Qureshi *et al*., 2018).

The kiln furnace stands out for promoting slow pyrolysis and process uniformity, in addition to presenting low acquisition and operational costs, making it suitable for obtaining larger solid yields (Rego *et al*., 2022). In contrast, dual-zone furnaces provide independent temperature control in both heating zones and offer greater experimental precision. However, these advantages are associated with high equipment and operational costs. Nevertheless, this technology is expected to promote the production of high-quality biochar (Illankoon *et al*., 2023).

The hydrothermal liquefaction (HTL) method involves a more sophisticated production process; consequently, both acquisition and operational costs are higher, which limits its broader application. In addition, HTL generally results in lower biochar yields (Haider *et al*., 2020). Thermal conversion through microwave furnaces exhibits greater efficiency due to rapid heating; however, studies indicate elevated production costs under all evaluated scenarios when compared with other technologies (Campion *et al*., 2023; Giwa *et al*., 2019).

Gasification is another thermochemical route for biomass conversion, although it is more suitable for gas production, as illustrated in Figure 9. This methodology is based on slow pyrolysis and is primarily intended for the recovery of non-solid fractions. Regarding char production, gasification does not outperform technologies based on fast pyrolysis (Arregi *et al*., 2016; Campion *et al*., 2023).

Future Perspectives

Technological advances, combined with the growing number of studies and scientific publications focused on the reuse of industrial effluents, particularly from the textile, pharmaceutical, and agricultural sectors, have highlighted the potential of biochar for contaminant removal in aqueous media. Its physicochemical properties favor efficient and environmentally responsible recirculation processes, reflecting increasing industrial concerns regarding sustainable water management.

Given the current limitations associated with potable water consumption and water availability for other uses, the future scenario involving the application of biochar produced from various residual biomasses as a treatment medium for aqueous systems demands greater research efforts. Such advances may drive the development of technologies capable of reintegrating treated effluents into the same processes from which they originated, demonstrating an efficient cycle aligned with the principles of the circular economy by transforming waste into valuable by-products while minimizing the fraction that cannot be reused.

According to the results presented, the use of biochar for water and wastewater treatment has gained considerable prominence and continues to be widely investigated and disseminated. However, based on current knowledge, further research is still required to synthesize information, fill existing gaps, and expand the field beyond theoretical advances. Strengthening these efforts is essential for transforming these approaches into practical and scalable solutions for water and wastewater treatment.

CONCLUSIONS

Studies addressing advances in water and wastewater treatment technologies are of paramount importance for sustaining human, animal, and plant life, especially given the rapid pace of population growth in contrast to the limited availability of freshwater resources.

An inaccurate identification of the term biochar was observed in many of the evaluated studies, where it was frequently confused with commercial activated carbon (CAC). This issue may result from the widespread use of chemical activating agents added to various biomasses with the aim of enhancing their properties. Nevertheless, it is essential to clearly distinguish between these materials and their respective definitions.

Most studies reported the use of activation processes to improve biochar efficiency, particularly chemical activation, which consistently emerged as the most effective strategy for adsorption purposes. Among the chemical activators, potassium hydroxide was the most commonly employed. The selected thermal conversion method also influenced the quality of the adsorbent, with kiln furnaces playing a significant role in the production of activated biochars suitable for effluent treatment.

A wide variety of residues was employed as biomass for the production of bioadsorbents; however, agroforestry residues were the most commonly used. This trend may be associated with the predominant agricultural and forestry activities in the countries where the studies were conducted. Furthermore, the bibliometric analysis presented here highlights the potential of diverse residues for biochar production. Although these materials are capable of multiple applications, they demonstrated exceptional suitability for water and wastewater treatment.

AUTHORSHIP CONTRIBUTION:

Project idea: CJSP; JGMUF
Funding: ACOC
Database: CJSP; JGMUF
Processing: CJSP; JGMUF; AMS; LHCB
Analysis: CJSP; KESB; AMS
Writing: CJSP
Review: JGMUF; ELA; ACOC; AMMLC; AMN; RPLM; JVCS

DATA AVAILABILITY:

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

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