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REVIEW PAPERS

A two-decade comprehensive bibliometric analysis of charcoal and biochar as adsorbents for dye removal (2003-2023)

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Abstract
The treatment of wastewater has been the subject of increasing studies aimed at developing less costly and more efficient methods to be applied as can be observed in the present article. Today, with industrial growth, the discharge of dyes, medications, pesticides, and other harmful substances into the aquatic environment, there is a perception that improving the quality of water bodies is an emerging need worldwide, given that the evolution of industrial processes tends to increase the disposal of these materials into water. It should be highlighted that the use of alternative methods for treating contaminated water, such as adsorption, has sparked interest in various research institutions worldwide. This is because the processes currently used have a high cost but lack high efficiency for some types of contaminants. Consequently, the search for an efficient and low-cost material is increasingly growing, with an annual growth rate of 32,33% between 2003 and 2023. For example, in the last five years, 792 articles have been published, which represents 79% of the articles published between 2003 and 2023. This observed increase in annual production shows how important it is to develop new technologies for wastewater treatment.

Keywords Adsorbent materials · Bibliometric analysis · Biochar · Charcoal · Data science · Dye removal · Wastewater

Introduction

The rapid expansion of the textile industry and the subsequent use and disposal of textile dyes have caused an environmental imbalance, which has become a challenge in recent years [1]. Commercial synthetic dyes are utilized across diverse industries including pharmaceuticals, textiles, paper printing, paint, food, plastics, leather, and cosmetics, boasting an annual consumption exceeding 700,000 metric tons [2, 3]. Dyes discharged in water makes water become murkier, potentially changes its pH balance, and increases its coloration, which negatively affects aquatic environments [4]. In large quantities, dyes can also harmfully impact humans, causing symptoms ranging from skin irritations, excessive sweating, and headaches to stomach pain, nausea, dizziness, and an increased heart rate [5, 6]. Hence, there is a necessity for techniques that remove pollutant substances before they are discharged into the environment. As a cationic dye, for example, methyl violet is toxic, mutagenic, and carcinogenic [7].

Given this scenario, there has been an increase in the search for methods to treat contaminated wastewater [8]. However, current treatments are costly and face challenges such as residual toxic sludge. Therefore, it is necessary to identify cost-effective and efficient methods [9]. A recent review has underscored the importance of employing emerging technologies, such as biosorption and biodegradation [10]. Due to factors such as flexibility and high separation efficiency [11], besides their insensitivity to toxic substances, adsorption has proven to possess considerable potential [12]. The adsorption presents high retention and low cost, among other equally important properties [13]. It is interesting to evaluate biomass derived from waste for

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dye removal from water bodies, as it represents a promising alternative [12].

The Greek historian Herodotus documents mankind's earliest use of charcoal in ancient Egyptian civilizations [14]as material for cooking and metal making [15], besides its use in medicine as an adsorbent against toxic diet [16]. Presently, is employed across the cosmetic industry to treat acne, and insect bites, relieve scalp itchiness, and combat seborrheic dermatitis [16]. Charcoal derived from discarded biomass has the potential to act as an adsorbent due to its low cost and effectiveness, given its high availability and conducive surface [11]. Activated Charcoal is very environmentally friendly and one of the most efficient physical methods for decolorization of textile wastewater [8]. Agricultural wastes are used as adsorbents for dye removal as activated charcoal, which stands out as one of the most efficient and inexpensive, due to the high volume of porosity within its microstructure, thereby facilitating an efficient adsorption process [7].

Biochar is a highly porous type of charcoal, used as a soil amendment (Hunt et al., 2010). The material has emerged as an environmentally friendly adsorbent to remove toxic material such as metal from wastewater [17]. Also, biochar production consumes less energy than it releases (Hunt et al., 2010). Combining characteristics such as chemical structure, porosity, and a high cation and anion exchange [18], in addition to a large surface area [19], the biochar is a low-cost and high-efficiency adsorbent [20].

This article is substantiated by the need to systematically assess and synthesize the existing literature on biochar and charcoal use as a dye adsorbent over the past two decades. While prior studies as Wang et al. [21] and Kamath et al. [7] have explored related themes, our research distinguishes itself through the pioneering use of the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P). This methodological choice enhances the transparency and rigor of our analysis. Notably, this study stands out for its comprehensive approach, utilizing diverse databases to gather relevant literature. Moreover, we have uniquely unified these databases, employing cutting-edge techniques in the R programming language, and meticulously removed duplicates. This novel approach ensures a robust and consolidated foundation for bibliometric analysis, setting our work apart in its methodological innovation and analytical rigor.

Despite the extensive experimental and review-based literature on adsorption processes, there remains a lack of quantitative, large-scale mapping of research trends in this field. Bibliometric analysis provides a systematic approach to evaluate scientific production, collaboration networks, and thematic evolution, offering insights that are not accessible through conventional narrative reviews.

Therefore, this study aims to answer the following research questions: (i) how has research on charcoal and biochar adsorption evolved over time? (ii) what are the main contributors and collaboration patterns? (iii) what thematic trends and emerging directions can be identified? and (iv) how do charcoal and biochar research trajectories differ?

The bibliometric study, elucidated within this article, can be described as the utilization of statistical methodologies to examine and comprehend the worldwide research productivity within a specific field, drawing upon publications obtained from an academic literature database [22]. The "Materials and Methods" section describes the research process, starting with information about the used databases and the terms utilized in the research. Besides the data, this section also describes the bibliometric procedures, such as the data analysis with a PRISMA diagram and the database unification process. The "Results and Discussion" section discusses and compares the material obtained from the bibliometric analysis to demonstrate trends and evolution of the research in this area.

Materials and methods

Data sources

"Web of Science" and "Scopus" were chosen as database platforms for this research since both are highly reputable academic journal systems among various data sources used for research and analysis.

"Web of Science" is an online database platform that is an important research engine with a main collection that covers 6 main databases and more than 250 disciplines with 1.5 billion references of thousands of peer-reviewed journals, academic books, research articles, and editorials [23]. This platform provides the number of references and the number of citations, besides informing the impact factor of the articles, so being an important source of research for theoretical references. It has gained renown as the oldest citation resource, housing the most prestigious academic journals used for analysis [24], once that covers a large part of scientific domains, it has authority in the areas of Engineering and Natural Sciences [25].

"Scopus", produced by Elsevier since 2004, is an international database with a large representation of scientific research. It is, therefore, indispensable for the bibliographic review of most topics. In the search area, it is possible to carry out detailed searches on the subject, due to its tools to direct research quickly and accurately. It is a database of abstracts and citations with around 78 million records [23]. "Scopus" has greater general coverage of academic journals [26], therefore, it is a multidisciplinary citation resource that

Table 1 The search protocol to collect data from the target literature

Search string	(“Adsorption”) OR (“Biosorption”) AND (“Charcoal”) OR (“Biochar”) AND (“Dye”) AND (“wastewater”)
Searched in	Topic
Database	Web of science
The last update	July 3, 2024
First result	756 articles
Inclusion criteria	(i) 2003-2023, (ii) Articles and Review Articles, (iii) English documents
Final sample	654 articles
Searched in	Topic: author, title, source and abstract
Database	Scopus
The last update	July 3, 2024
First result	984
Inclusion criteria	(i) 2003-2023, (ii) Articles and Review Articles, (iii) English documents
Final sample	770 articles
Duplicated	400 articles
Other removal	22 articles
Final merged screened	998 articles

includes journal articles, books, and conference proceedings, where it has greater coverage than others in Social Sciences [25]. In addition, it offers more research metrics, and the user can measure impact factors, analyze trends, and carry out more accurate assessments of authors [27].

Data collection

The search strategy employed Boolean operators as follows: (“adsorption” OR “biosorption”) AND (“charcoal” OR “biochar”) AND (“dye”) AND (“wastewater”). The selection of Web of Science and Scopus was based on their complementary coverage and reliability in bibliometric studies. Data preprocessing included duplicate removal, standardization of author names and keywords (keyword harmonization), and exclusion of non-relevant document types. All steps were conducted to ensure reproducibility.

A search was conducted on the “Web of Science” and on the “Scopus” portal using the following terms: (“adsorption”) OR (“biosorption”) AND (“charcoal”) OR (“biochar”) AND (“dye”) AND (“wastewater”). In both cases, the first result was filtered by year (2003–2023), then by type of documents “Articles” and “Reviews”, and then by only results written in English. The results of the searching process are presented on Table 1.

Bibliometric procedures

Bibliometrix® is a tool that can quantify previously published works in a specific area of interest, thereby highlighting possible gaps, indicating trends, and providing a comprehensive understanding of the conduct of research already undertaken (Aria et al., 2017). A procedure was carried out to compile.

the results from “Web of Science” and “Scopus”, resulting in the unification of documents to be analyzed. Using the PRISMA protocol (Fig. 1), 400 duplicates were excluded from the repositories, resulting in 1020 publications. After that, 22 documents were excluded for not being articles or reviews, despite initial filtering as shown in Table 1.

The data analyzed the period from 2003 to 2023, during which 998 documents were collected from 270 sources.

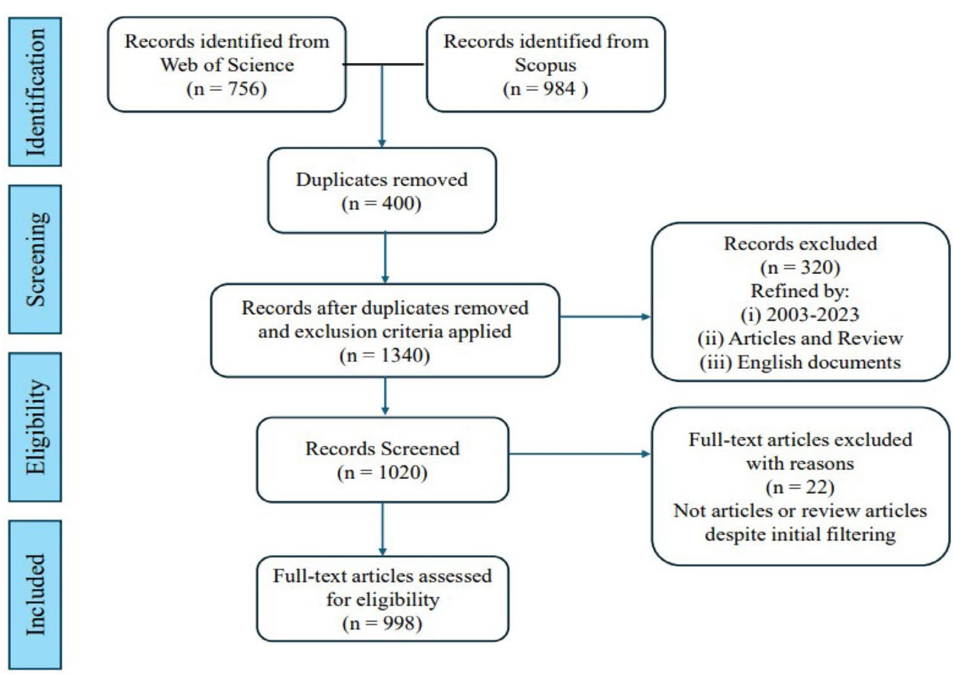

Fig. 1 Prisma flow diagram

The annual growth rate is 32.33%, with an average document age of 4.03 years and an average of 43.94 citations per document. Concerning document content, 4584 Keywords Plus and 2244 Author's Keywords were identified. The total number of authors involved is 3717, with 12 documents written by a single author. Author collaboration showed that 13 documents were single authored, while the average number of co-authors per document is 5.74, and the percentage of international co-authorships is 19.44%. In terms of document types, 913 articles, 7 conference papers, and 78 reviews were found.

Results and discussion

Publications

A clearer differentiation between charcoal and biochar research trajectories reveals distinct scientific directions. While charcoal-based studies have historically focused on low-cost adsorption and conventional activation processes, biochar research has increasingly emphasized tunable surface chemistry, functionalization, and integration into composite materials. This divergence reflects not only differences in production routes but also the growing alignment of biochar with sustainability frameworks and circular economy strategies. Consequently, biochar has experienced a more rapid thematic expansion, particularly in advanced adsorption systems and environmentally oriented applications.

Figure 2 shows that Elsevier is the leading publisher, responsible for 433 publications, which corresponds to 44% of the total analyzed. It is followed by Wiley (30%), Springer (14%), MDPI (8%), Taylor & Francis (3%), and IWA (3%). Also, a significant portion of 25% is attributed to other publishers, indicating a broad diversity of editorial sources in that field of research.

The annual growth in publications indicates an increase in academic production over time. From 2015 onwards, a more pronounced growth is observed, peaking in 2023, the year with the highest number of publications. The cumulative curve in the graph reinforces that over 75% of the publications occurred after 2017, reflecting a growing interest in the topic over the last decade and highlighting its relevance.

The analysis of citations per publication reveals that 385 publications, representing the most works, only received between 0 and 10 citations, while 98 publications exceeded 50 citations. The cumulative curve shows that about 75% of the citations are concentrated in publications with up to 30 citations. These findings suggest that, although the volume of production is high, a relatively small proportion of studies has achieved significant academic impact in the major scenario. Therefore, there are gaps that need to be addressed through further studies and approaches.

As for the distribution of thematic categories, it highlights the interdisciplinarity of the subject. The most prominent areas include Environmental Sciences and Ecology, with 100 publications, followed by Chemistry, with 71 and Engineering with 57. Other areas, such as Microbiology,

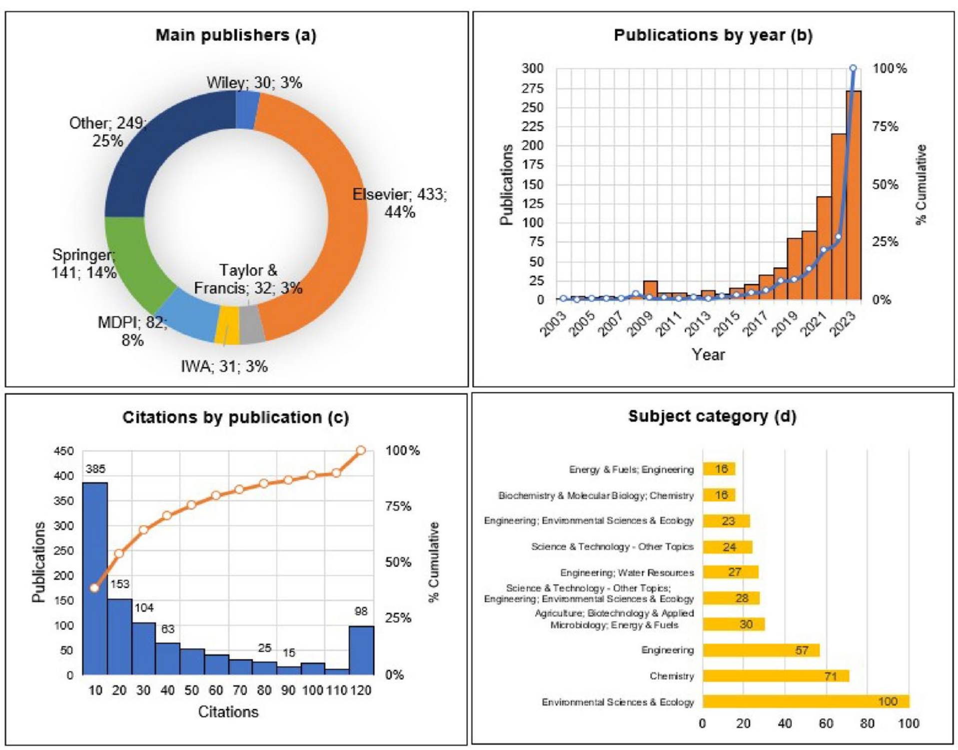

Fig. 2 **a** Main publishers; **b** Publications by year; **c** Citations by publication; **d** Subject category − 2003–2023 (Data were obtained from "Web of Science" and "Scopus" database)

Table 2 Most global cited documents – 2003–2023 (Data were obtained from "WOS" and "Scopus" database)

Publisher	Year	TC	Author	Doi
Journal of Hazardous Materials	2004	711	Malik, Pradip Kumar	10.1016/j.jhazmat.2004.05.022
Journal of Hazardous Materials	2009	679	Demirbas, Ayhan Hilal	10.1016/j.jhazmat.2008.12.114
Chemical Engineering Journal	2012	591	Kołodyńska, Dorota et al	10.1016/j.cej.2012.05.025
Environment International	2019	516	Rasheed, Tahir et al	10.1016/j.envint.2018.11.038
Journal of Hazardous Materials	2009	480	Amin, Nevine Kamal	10.1016/j.jhazmat.2008.09.067
Chemosphere	2020	460	Xiang, Wei	10.1016/j.chemosphere.2020.126539
Water Resources and Industry	2015	451	Adegoke, Kayode Adesina	10.1016/j.wri.2015.09.002
J. of Environmental Chemical Engineering	2017	442	Fan, Shisuo et al	10.1016/j.jece.2016.12.019
Journal of Colloid and Interface Science	2005	418	Bhatnagar, Amit	10.1016/j.jcis.2004.08.076
Separation Science and Technology	2003	392	Jain, Ajay Kumar	10.1081/SS-120016585

Agriculture and Biotechnology, and Energy & Fuels, are also represented, with contributions ranging from 16 to 30 publications each.

The results demonstrate substantial growth in academic production and highlight the increasing relevance of the topic in recent years. The predominance of areas suggests a focus on technological and environmental applications. Despite that, the academic impact remains moderate, suggesting potential for deepening and increasing the relevance of future and continuous research.

Sources

Analyzing the sources, Bioresource Technology stands out with 54 articles, followed by Journal Hazardous Materials with 47, Environmental Science and Pollution Research with 45 and Chemosphere with 43. It is noteworthy that the combined document count from the first and second most significant sources represents over 30%. Moreover, it is noticeable the evolution of source production over time presents the Journal of Hazardous Materials prominently featured in the first peak period of scientific production

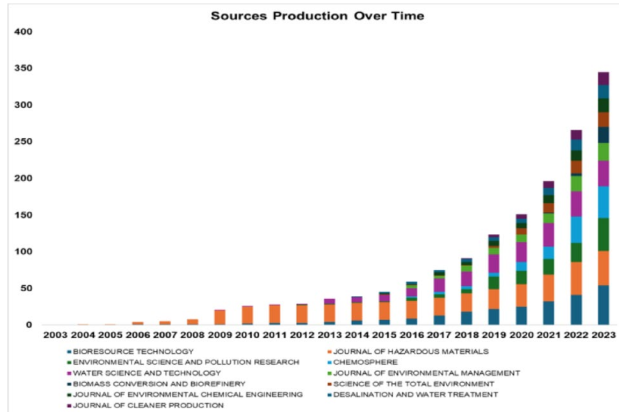

Fig. 3 Sources' production over time – 2003–2023 (Data were obtained from"Web of Science" and "Scopus" database)

observed in 2009. This also reflects something evident in the most global cited documents demonstrating that those who produced the most over time are consequently the ones with the highest number of citations. Observing the evolution of source production over time, it is evident that "Hazardous Materials" was the first during almost the complete analyzed period, followed by "Water science and technology" closely between 2018 and 2021. In 2021 "Bioresource technology" assumes the second place, taking the first position in the half of 2022 (Table 2).

Figure 3 presents the Sources' production over time and illustrates the significant increase in scientific production in journals focused on environmental topics, bioenergy, and water treatment between 2003 and 2023. From 2015 onwards, academic output shows exponential growth, with notable contributions in journals such as "Bioresource Technology" and "Journal of Hazardous Materials," which lead in publication volume. This growth is accompanied by a broader diversification of sources, reflecting not only the maturation of the field but also the consolidation of an interdisciplinary foundation. That trend suggests topics such as sustainable technologies and waste management have gained prominence.

in the global scientific agenda, likely driven by emerging environmental demands and the increasing urgency to address climate and resource crises.

However, the concentration in a few leading journals indicates an editorial centralization that might limit the diversity of perspectives. Additionally, the rapid rise in scientific production in recent years raises questions about quality and originality of publications, as high volumes do not necessarily translate into meaningful advancements. While the exponential growth reflects a growing interest in the field, it also demands a critical analysis of how effectively this increase contributes to solving environmental challenges.

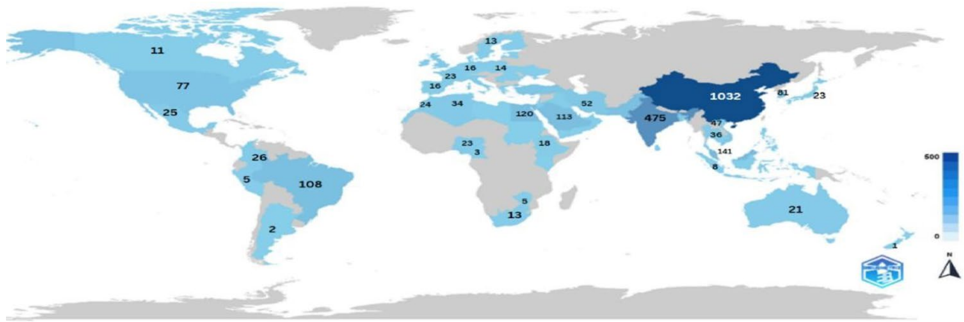

Fig. 4 Countries' scientific production – 2003–2023 (Data were obtained from "Web of Science" and "Scopus" database)

Fig. 5 **a** Most relevant affiliations; **b** Most relevant authors; **c** Affiliations production over time; **d** Corresponding authors countries 2003–2023 (Data were obtained from "Web of Science" and "Scopus" database)

Authors and affiliations

Figure 4 displays the production profile by countries, where despite the cooperation among authors, the production involving multiple countries is very low when compared to individual country production, as displayed in Fig. 5d. Furthermore, this initial collaboration aligns with the trend of globalization in research efforts towards seeking new technologies.

It is evident that the areas of interest are all associated with the countries China and India, which are linked to almost all the presented keywords, with an advantage for China. Figure 7 also illustrates how the Chinese Authors are linked to other countries in their collaboration network, an information that is depicted in Fig. 5d. Figure 6 illustrates too in a global map, the collaboration network between countries and the few countries with scientific production in this field, that are not linked to any other country in collaboration (Table 3).

Figure 5 provides a comprehensive overview of the most relevant institutions, authors, and countries, covering the period from 2003 to 2023. The first subfigure highlights the ten institutions with the highest number of publications, where Zhejiang Ocean University leads with 36 articles, followed by Guangxi University with 27 and King Saud University with 24. Other institutions, such as University Teknologi Malaysia, Alexandria University, and Duy Tan University, have made significant contributions, ranging from 15 to 23 articles. These patterns suggest that the concentration of scientific production in key Asian institutions is likely driven by coordinated national research policies, substantial investment in environmental technologies, and region-specific environmental pressures, which collectively accelerate research output and thematic specialization.

Regarding author productivity the second subfigure identifiesWang Y as the most prolific author, with 30 articles, followed by Li Y (25) and Li X (22). Additionally, the analysis of fractionalized articles reveals varying proportional

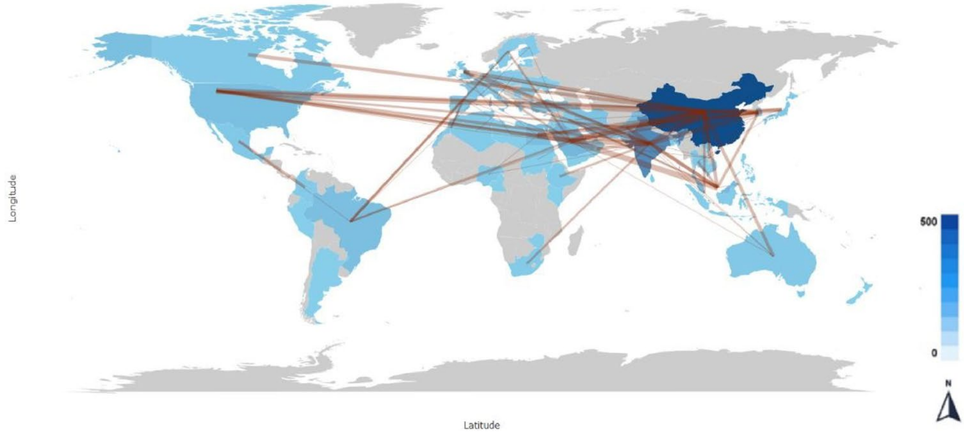

Fig. 6 Country collaboration map – 2003–2023 (Data were obtained from "Web of Science" and "Scopus" database)

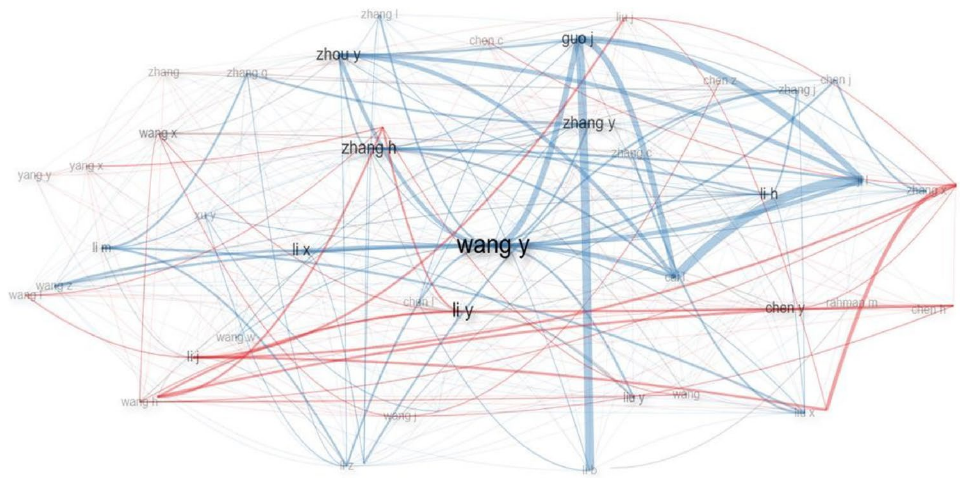

Fig. 7 Collaboration network of authors based on co-authorship patterns – 2003–2023 (Data were obtained from "Web of Science" and "Scopus" database)

Table 3 Countries' scientific production – 2003-2023 (Data were obtained from "Web of Science" and "Scopus" database)

Country	Frequency
China	1032
India	475
Malaysia	141
Egypt	120
Saudi Arabia	113
South Korea	81
USA	77
Turkey	61
Brazil	108
Pakistan	105

contributions among authors, suggesting different levels of involvement in co-authorship. This may indicate a centralization of scientific leadership within specific research groups, contributing to the continuity and impact of ongoing investigations.

The temporal evolution of publications, illustrated in the third subfigure, shows a significant increase after 2015, with Wuhan University and University Teknologi Malaysia emerging as the most prominent contributors in recent years. This growth reflects a rising academic interest and an intensification of research efforts in that field, likely driven by its environmental and industrial relevance.

The geographical distribution of corresponding authors, as shown in Fig. 4, highlights the concentration of scientific production in specific regions. China leads in publication volume, represented by the deep blue shading, with over 80% being Single Country Publications (SCP), indicating strong domestic research activity. The network lines show China's limited but growing international collaborations, mainly with neighboring Asian countries and regions in Africa and Europe. Countries such as Egypt and Malaysia exhibit a more balanced ratio of Single Country Publications and Multiple Country Publications (MCP), as indicated by the connections to various regions. These patterns reflect broader international partnerships, which contribute to expanding the scope of research.

The map underscores the prominent role of China and other Asian countries in the field while highlighting the importance of international collaborations to enhance the diversity and global impact of scientific research.

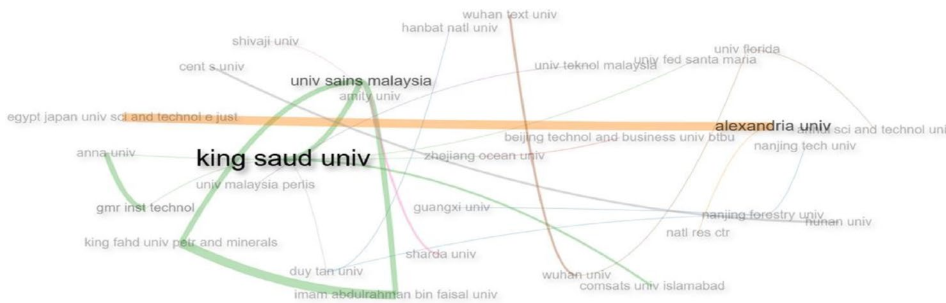

Fig. 8 Collaboration network of institutions based on co-authorship patterns – 2003–2023 (Data were obtained from "Web of Science" and "Scopus" database)

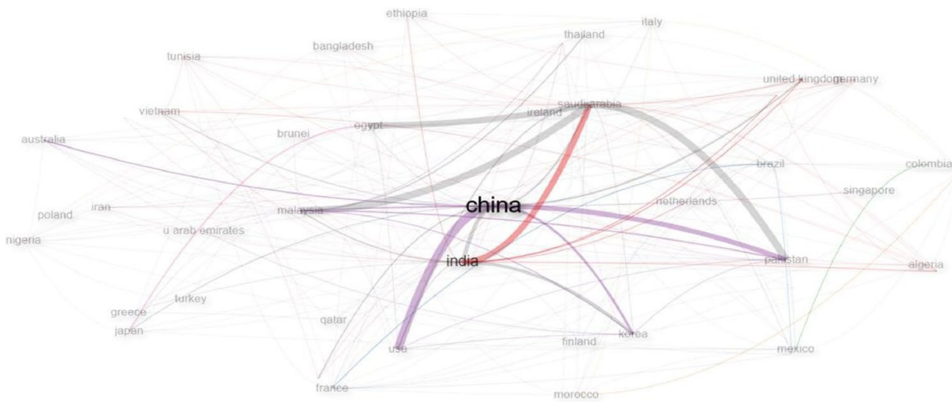

Fig. 9 International collaboration network based on country co-authorship patterns – 2003–2023 (Data were obtained from "Web of Science" and "Scopus" database)

Collaboration

These collaboration patterns also suggest a structural imbalance in global knowledge production. While leading countries benefit from strong internal networks and resource availability, limited international integration may restrict the transferability of adsorption technologies across different environmental contexts. Expanding collaborative frameworks could enhance the adaptability and scalability of solutions, particularly in regions facing distinct wastewater challenges.

The analysis of collaborations in scientific research provides important insights into the academic production within the analyzed topic. The first subfigure highlights the network of co-authorships among researchers, with Wang Y emerging as the most prolific and influential author, establishing a significant number of connections with other scholars, such as Li Y and Zhang Y. The density and thickness of the connections reflect varying levels of collaboration, indicating the existence of well-structured research groups and key leadership figures that concentrate scientific output, thereby contributing significantly to the continuity and impact of investigations.

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At the institutional level, as illustrated in the second subfigure, universities such as King Saud University, Alexandria University, and Universiti Sains Malaysia stand out as hubs of collaboration. The presence of strong connections between these institutions suggests strategic partnerships that enhance the advancement of research, particularly in regions such as the Middle East and Southeast Asia. This integration reflects a collective effort from different regions to make meaningful contributions to scientific knowledge, fostering both the exchange of ideas and the strengthening of academic networks (Fig. 8).

Lastly, the geographic analysis of collaborations, represented in the third subfigure, identifies China as the primary center of scientific production, with a clear position of leadership. The high volume of domestic publications and the predominance of Single Country Publications (SCP) underscore the country's role in independent research. However, international collaborations, particularly with countries such as India and Egypt, indicate growing efforts to diversify and amplify the global impact of its scientific endeavors. This analysis underscores the importance of collaborative networks and geographic leadership in shaping emerging topics within scientific research (Fig. 9).

Figure 10 is a Sankey diagram illustrating the connections between research topics, countries, and leading authors. On the left side, the key research topics include "adsorption," "biochar," and "wastewater treatment," accompanied by terms such as "methylene blue," "kinetics," "thermodynamics," and "dye removal." These topics suggest a significant focus on the practical applications of biochar as an adsorbent material and on theoretical models describing adsorption processes.

At the center, the diagram highlights the dominance of China and India as global leaders in academic production in this field. While other countries, such as Egypt, Malaysia, Brazil, Pakistan, and the United States, also contribute, their representation is relatively minor, indicating a geographic concentration of research in specific regions. This uneven distribution likely reflects not only differences in research priorities but also disparities in infrastructure and funding. Notably, underrepresented regions such as Latin America and Africa, which face severe environmental challenges, exhibit limited participation in this research area.

On the right side, the most prolific authors are predominantly from China, including Wang Y., Zhou Y., and Zhang X. This pattern underscores China's academic leadership and coordinated research efforts. However, it also reveals limited participation from other regions, potentially narrowing the diversity of perspectives and hindering the development of globally adaptable solutions. A lack of broader international collaboration may limit the contextualization of technologies to diverse local conditions, reducing their effectiveness in regions with distinct environmental and economic realities.

While the diagram points to progress in research on adsorption and biochar, it also raises critical issues. The excessive centralization in leading countries risks creating a bottleneck for global innovation, as underrepresented nations—often the most affected by environmental issues—remain on the periphery of technological advancements. This scenario underscores the need for policies that foster more inclusive international collaborations and enhance access to funding and infrastructure for research in neglected regions. Furthermore, the strong focus on established topics, such as biochar's application in dye removal, may constrain the exploration of alternative approaches or materials with innovative potential. Dealing with these challenges requires a more balanced and diverse global research effort that responds to local needs.

The Sankey diagram (Fig. 11) illustrates the evolution of authors' keywords in adsorption research across four timeframes: 2003–2008, 2009–2013, 2014–2018, and 2019–2023. It highlights how research themes have evolved, with the connections between nodes representing the continuity or shifts in focus over time.

In the earliest period (2003–2008), "adsorption" emerged as the central keyword, serving as the foundation for subsequent themes. Keywords like "activated charcoal," "kinetic," and "charcoal" indicate a strong focus on fundamental studies related to adsorption processes and materials. Moving into the second period (2009–2013), new themes such as "biochar" and "dye removal" begin to appear, pointing to a growing interest in innovative adsorbents and environmental applications, particularly in addressing dye pollution in wastewater.

During 2014–2018, the thematic landscape broadens further. Terms like "magnetic biochar," "carbonization," and "adsorption mechanism" gain prominence, reflecting advances in material modifications and deeper exploration of adsorption mechanisms. By the final period (2019–2023), the focus shifts more explicitly toward practical and sustainable applications, with keywords such as "wastewater treatment," "environmental remediation," and "organic dyes" taking center stage.

The diagram also reveals interesting patterns of continuity and change. For instance, materials like "activated charcoal" and "biochar" remain highly relevant across all

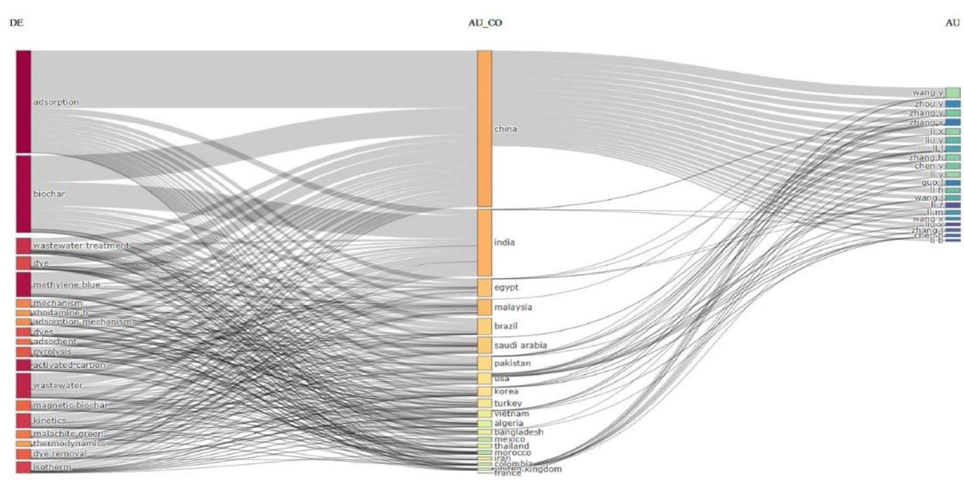

Fig. 10 Three-field plot – 2003–2023 - (Data were obtained from "Web of Science" and "Scopus" database)

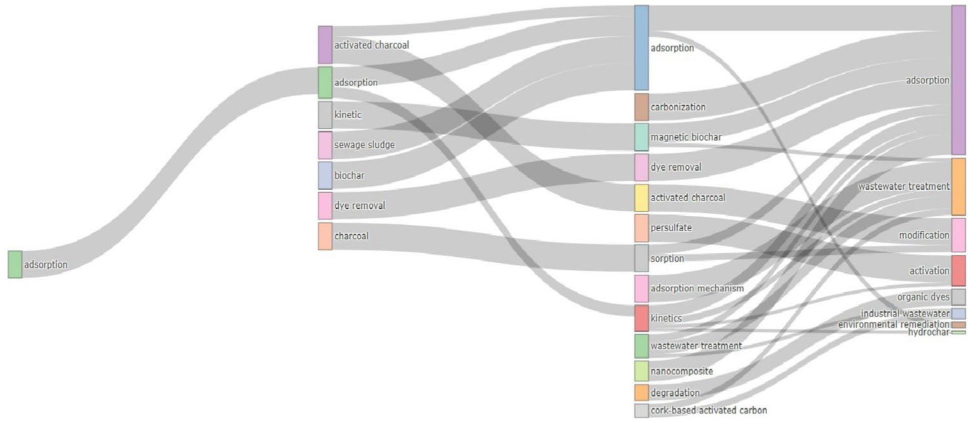

Fig. 11 Evolution of author's keywords from **a** 2003-2008; **b** 2009-2013; **c** 2014-2018; **d** 2019-2023 (Data were obtained from "Web of Science" and "Scopus" database)

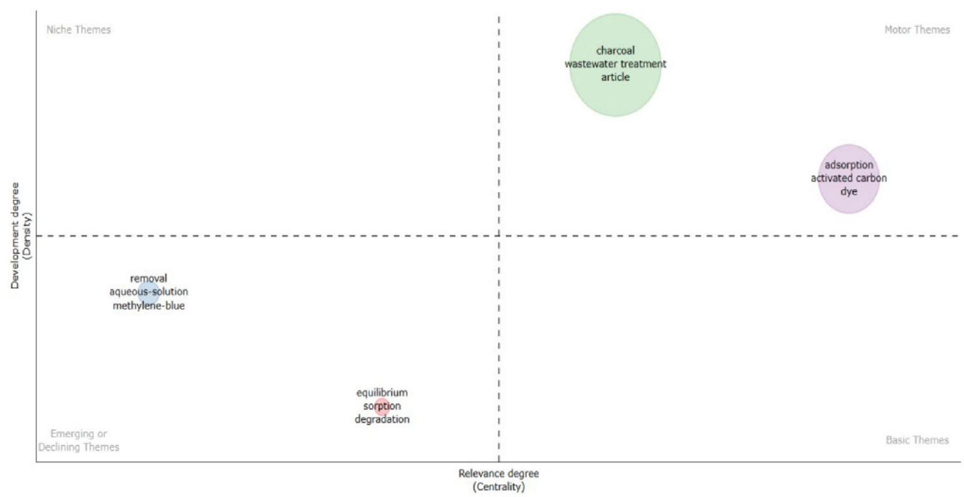

Fig. 12 Thematic map keywords – 2003–2023 (Data were obtained from "Web of Science" and "Scopus" database)

periods, showcasing their enduring importance. At the same time, newer concepts like "nanocomposite," "cork-based activated carbon," and "industrial wastewater" emerged in later years, signaling the growing sophistication of materials and applications.

Certain keywords, such as "sewage sludge," appear less frequently in later periods, potentially reflecting shifts in research priorities or material preferences. On the other hand, the growing prominence of terms like "environmental remediation" highlights the increasing focus on addressing broader environmental challenges (Fig. 12).

Figure 13 illustrates the temporal evolution of key terms associated with the analyzed research topic over the period from 2003 to 2023, starting to have occurrences only in 2007. Each term is represented as a dot, with horizontal bars indicating the duration of its use in publications, while the size of the dots reflects the frequency of the term each year.

Terms like "activated carbon," "adsorption," and "aqueous solution" exhibit a steady increase in usage frequency, particularly after 2015, aligning with the observed growth in research. Other terms, such as "industrial wastewater" and "color removal" show an earlier appearance, demonstrating that the ambiental concerns were the initial central issues.

The introduction of more specialized terms, such as "Langmuir isotherm model" and "batch adsorption experiments," from 2010 onwards indicates an increasing emphasis on methodological rigor and experimental validation in the field. However, terms like "green" and "bagasse" which appear only in the later years of the timeline, highlight the growing concern for environmentally sustainable approaches.

Despite the comprehensive representation of key terms, the figure also shows gaps in continuity for certain terms, reflecting variations in research trends and potentially the niche or transient nature of some topics. For instance, the limited temporal coverage of terms such as "granular activated carbon" suggests either a narrower focus or less attention within the broader research scope. Overall, the temporal distribution underscores both the consolidation of core concepts and the diversification of research themes over time.

From a chemical and materials science perspective, the observed bibliometric trends can be associated with the evolution of adsorption mechanisms and material design strategies. Early studies focusing on charcoal were largely centered on physical adsorption driven by surface area and porosity. In contrast, the increasing prominence

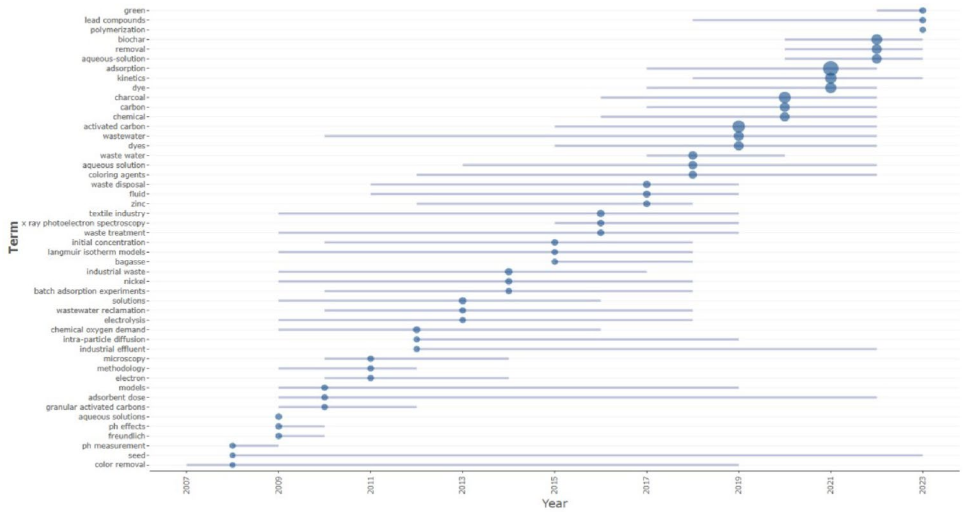

Fig. 13 Trend topics – 2003–2023 (Data were obtained from "Web of Science" and "Scopus" database)

of biochar-related keywords such as "functionalization," "nanocomposites," and "magnetic biochar" reflects a shift toward chemically engineered surfaces, where adsorption is governed not only by pore structure but also by surface functional groups, electrostatic interactions, and complexation mechanisms. This transition highlights a broader movement in the field toward structure–property relationships and targeted material optimization.

Theme and word analysis

The keyword co-occurrence network illustrates the thematic structure of the research field, with nodes representing keywords and edges reflecting their co-occurrence within the analyzed dataset. The size of each node corresponds to the frequency of the keyword, while the edge thickness indicates the strength of the association between terms. The network is organized into color-coded clusters, which group related keywords and highlight distinct thematic focuses.

At the center of the network, "adsorption" emerges as the dominant keyword, underscoring its central role in the field. Surrounding this node, three main clusters are identified. The red cluster includes keywords such as "kinetics," "dye," and "biochar," which are closely associated. This grouping suggests a focus on the mechanisms of adsorption, particularly in the context of dye removal from aqueous systems, with biochar frequently highlighted as an adsorbent material. The green cluster emphasizes terms like "charcoal," "chemical," and "wastewater treatment," representing studies on adsorbent materials and their applications in water pollution control and wastewater remediation. Finally, the blue cluster comprises terms such as "aqueous solutions," "equilibrium," and "isotherms," reflecting theoretical and modeling studies that explore adsorption dynamics, equilibrium behaviors, and solution interactions.

The connections between the red and green clusters indicate a strong link between research on adsorbent materials and their practical applications in wastewater treatment. However, the blue cluster appears more isolated, suggesting that theoretical studies are less frequently integrated with experimental and applied research. This separation may reflect a gap in interdisciplinary approaches, where modeling efforts could better inform practical implementations.

Additionally, terms related to sustainability and environmental impacts, such as "environment" are notably underrepresented despite the relevance of adsorption studies to broader environmental challenges. It highlights potential opportunities for future research to address these critical aspects more explicitly. The presence of generic terms such as "article" further suggests possible limitations in the dataset's curation, indicating the need for careful refinement of bibliometric analyses.

Overall, the network provides valuable insights into the thematic organization of the field, highlighting the dominance of adsorption-related studies and identifying potential areas for greater integration between theoretical, experimental, and sustainability-focused research.

The word clouds illustrate the evolution of keywords research terms related to adsorption, biochar, and wastewater treatment over four time periods: 2003–2008, 2009–2013, 2014–2018, and 2019–2023. Across all periods, "adsorption" and "activated carbon" remain dominant, reflecting a consistent focus on adsorption processes and the use of activated carbon as a primary material. However, terms such as "biochar" and "methylene blue" gain prominence in the later periods, particularly from 2014 onwards, indicating a diversification of materials and target pollutants in adsorption studies. The increasing emphasis on "kinetics," "isotherm," and "thermodynamics" suggests a growing interest in the theoretical and mechanistic understanding of

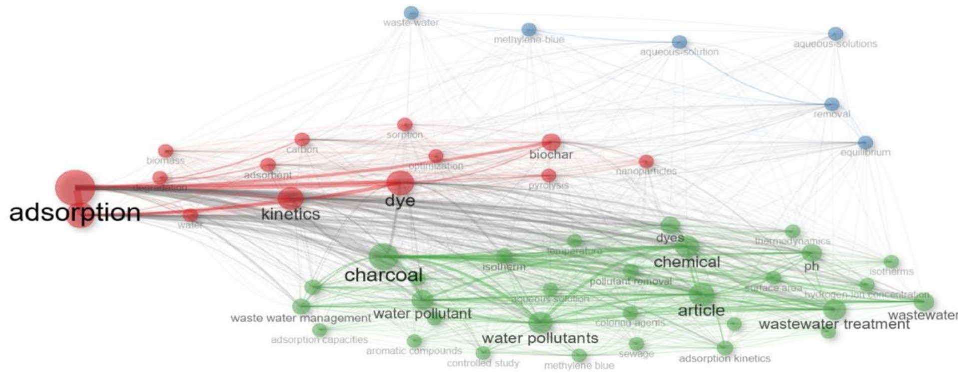

Fig. 14 Co-occurrence network – 2003–2023 (Data were obtained from "Web of Science" and "Scopus" database)

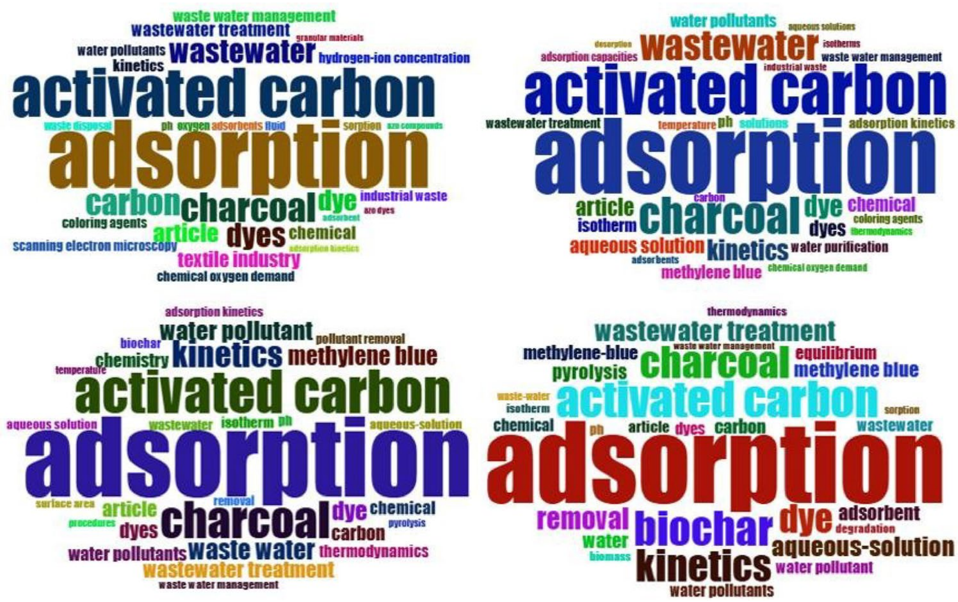

Fig. 15 Word cloud overtime – **a** 2003–2008; **b** 2009–2013; **c** 2014–2018; **d** 2019–2023 - (Data were obtained from "Web of Science" and "Scopus" database)

adsorption processes, alongside practical applications for wastewater treatment (Fig. 14).

Despite this progression, the word clouds reveal certain limitations in the field's evolution. The focus on well-established materials such as activated carbon may indicate a lag in exploring novel or alternative adsorbents, potentially limiting breakthroughs in performance or cost-efficiency. Additionally, recurring terms like "wastewater," "dyes," and "methylene blue" highlight the repetitive targeting of specific pollutants and applications, potentially neglecting emerging contaminants of concern. While the increased frequency of terms related to "biochar" suggests some diversification, the relatively limited presence of terms associated with cutting-edge technologies or interdisciplinary approaches points to the need for broader exploration in adsorption research to address evolving environmental challenges.

It is important to note that bibliometric indicators such as publication counts and citation frequency do not directly reflect research quality or material performance. These metrics should be interpreted cautiously, as they may be influenced by database coverage, citation practices, and publication trends (Fig. 15).

Conclusion

After bibliometric analysis, it can be understood that this area holds great relevance for industrial development, as it aims to solve a problem that grows alongside industrial development and increasingly impacts the quality of life of animal communities living in waters receiving contaminants, indirectly affecting human health directly and it is worth noting that the guiding element of this research is sustainable development, as observed in countries experiencing significant industrial and technological growth leading the research seeking solutions to this problem. It is important to consider that the main countries leading the research have larger populations than others, but there is also an interest in seeking solutions to prevent and mitigate negative impacts on public health.

The findings presented in this article highlight a notable gap within the research domain, particularly in the utilization of biochar for adsorption and removal of dyes from wastewater. Researchers have responded to this gap by conducting increasingly frequent and pertinent studies. The escalating environmental concerns, possibly influenced by the expanding industrial developments and their impact on aquatic environments, are evident. Consequently, the trend suggests that the exponential growth observed in the past 5 years is poised to persist as this research field continues to advance.

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Data availability The data supporting this study are available from the corresponding author upon reasonable request. All raw and processed data have been securely stored and can be provided for verification or further analysis.

Declarations

Conflict of interest The authors have no conflicts of interest to declare.

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