Wang et al. Environmental Sciences Europe (2024) 36:25
https://doi.org/10.1186/s12302-024-00859-z

Environmental Sciences Europe

REVIEW

Open Access

Research status, trends, and mechanisms of biochar adsorption for wastewater treatment: a scientometric review

Yuyao Wang[1,2], Liang Chen[3], Yuanrong Zhu[1*], Wen Fang[2,4], Yidan Tan[1], Zhongqi He[5] and Haiqing Liao[1]

Abstract

In the last decade, biochar application research has emerged as a hot topic in water treatment studies, which made biochar adsorption one of the primary wastewater treatment strategies. This paper presents a global bibliometric analysis of 2673 publications from the Web of Science database, spanning 2011–2022. For a comprehensive understanding of the research status and trends in biochar adsorption for wastewater treatment, the advanced quantitative and visual analysis tools (i.e., CiteSpace and ArcGIS) were employed. The results showed that China emerged as the leading country with the most published articles. The key research area is on the magnetic adsorption of biochar in wastewater. The articles summarized in the review demonstrated unequivocally that biochar can treat a wide range of wastewater even though the adsorption mechanisms of biochar on heavy metals, inorganic salts and organic pollutants in wastewater are not entirely consistent. The review further analyzes the factors affecting the performance of biochar in adsorbing pollutants from wastewater and the improvement measures of biochar functional characteristics, proposing the future research directions focusing on the improvement of the adsorption capacity of biochar products. The information synthesis and discussion would provide valuable insights on the historical, current, and future trends in biochar research, beneficial to solve the practical problems of water pollution and improve the quality of the environment.

Keywords Biochar, Adsorption, Wastewater, Pollutant, CiteSpace

Introduction

While there is no settled scientific definition, biochar typically refers to biomass-derived char by its nominal meaning [1]. Biochar is a dark (black) porous solid that consists mainly of amorphous carbon and is obtained as a residue when the materials such as woody residues [2], agricultural byproducts [3], animal bones [4], or other biomass materials [e.g., sewage sludge, and animal manure] are pyrolyzed (i.e., partially burned or heated) with limited access to air [5, 6]. In last couple of decades, biochar has been intensively explored for its potential applications as a durable soil healthy enhancer and an environmental remediator [1, 7]. Currently, wastewater treatment is one of the hot topics in biochar application research [8–10] as the rapid development of industry and urbanization worldwide produces a great

*Correspondence:
Yuanrong Zhu
zhuyuanrong07@mails.ucas.ac.cn
[1] State Key Laboratory of Environment Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China
[2] College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730070, China
[3] School of Water Conservancy and Environment, University of Jinan, Jinan 250022, China
[4] Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[5] USDA-ARS, Southern Regional Research Center, 1100 Allen Toussaint Blvd., New Orleans, LA 70124, USA

deal of wastewater and water pollution, which, if not treated properly, will endanger the living environment and human health [11]. Per their origins, wastewater can be further categorized as industrial wastewater, urban wastewater, agricultural wastewater and rainwater. It should be noted that these different wastewaters require different treatment methods because the chemical natures of these pollutants are different [12, 13].

As a porous granular solid material, biochar has a large specific surface area, a rich pore structure, wealthy surface functional groups. It is an excellent material for adsorption [14]. For example, the adsorption effect of biochar on heavy metal ions, phosphoric acid, and ammonia nitrogen is often good [15–17]. Compared to the original biochar, the chemically modified biochar generally has a larger surface area, rich functional groups, and a higher adsorption capacity [18]. The adsorption potential of biochar is high for both organic and inorganic pollutants, which involves a variety of mechanisms such as pore filling, electrostatic interactions, ion exchange, precipitation, and surface adsorption, among others [19]. These mechanisms depend not only on the type of pollutants, but also on changes in the physicochemical properties of biochar, such as the amount of addition used as biochar, and the temperature of pyrolysis is associated with the pH of the substrate under treatment [11, 20, 21].

Despite extensive research on biochar adsorption for wastewater treatment in recent decades, most of them are qualitative rather than quantitative, and there has not been a systematic and comprehensive summary and review of the evolutionary trends in this field. Understanding these aspects is essential for the efficient allocation of resources to accelerate the development of effective wastewater treatment technologies. To offset the lack of quantitative visual review in this field, this paper makes innovative use of scientometric to analyze the latest status of biochar and related technologies. The purpose is to provide some references for researchers to further development of the biochar application as a lower-cost treatment method with less likely potential of secondary pollution. While it is known that biochar can adsorb industrial wastewater, urban wastewater, agricultural wastewater and rainwater, and effectively removing heavy metal ions, inorganic salts and organic pollutants in wastewater, a quantitative bibliometric analysis of relevant biochar articles would present this research process visually and deduce future emerging trends [22]. Similarly, CiteSpace is a piece of software that presents the structure, rules and distribution of scientific knowledge in a visual manner [23, 24], has been used extensively in hotspot change research and trend analysis [25, 26]. This CiteSpace analysis allows the structure of knowledge in the biochar field and its historical development to make biochar application in wastewater more widespread.

Specifically, this paper presents the bibliometric analysis of biochar adsorption for wastewater treatment research published from 2011 to 2022, using the bibliometric visualization tools provided by the CiteSpace software. Furthermore, the information on biochar adsorption of pollutants including heavy metals, inorganic salt, and organic pollutants in wastewater and improvement measures for biochar were also synthesized and discussed. Our objectives are: (i) to analyze the significant contributors to biochar adsorption for wastewater treatment worldwide; (ii) to identify the current research hotspots and development trends in biochar adsorption for wastewater treatment; and (iii) to pinpoint potential future research directions in this area. As an utmost purpose, we look forwarding to this paper being beneficial to solve the "real world" problems of water environment pollution and improve the quality of the environment.

Methods and data acquisition

Data collection and data processing

The Web of Science (WoS) is a global citation database developed independently by the world's most trusted publishing houses, and an information-dominated research platform for science, the arts and the humanities [27]. With WoS (2011–2022) as the science database, articles were picked up with the combination of three topics keywords "*Biochar*", "*Adsorption*", and "*Wastewater*". Chronologically, the first and the last papers meeting these search criteria were from January 2011 and December 2022, respectively. To ensure accurate and objective analysis, irrelevant materials (e.g., conference calls to journal articles, prefaces and book reviews) were removed, leaving two categories of articles (i.e., research papers and reviews) accounted [28]. In this way, a total of 2673 related publications were identified. The record is exported as a "complete record and references" and contains information such as authors, affiliations, titles, source publications, abstracts, keywords and references.

Scientific quantitative analysis method

CiteSpace brings various features to researchers by identifying themes, finding hot spots, and so forth, and automatically labelling clusters using terms in selected documents [29, 30]. In the current study, CiteSpace software was used to perform a detailed analysis of identified 2673 papers [31]. From a data processing perspective, the time frame chosen is January 2011 to December 2022, with a time slice of 1 year, a threshold value of Top = 30, and other parameters as default values. Data from the literature are analyzed in terms of circulation, country, institution, periodical, research focus and research hotspot. Interpreting the outcomes of these analyses allows us to describe the trend of biochar adsorption development for wastewater and to predict issues and breakthroughs that may be worth noting in the future. Within these visualizations, greater cooperation corresponds to higher betweenness centrality (BC). Nodes with high BC values are considered key contributors [30]. BC is calculated by the following equation:

$$\mathrm{BC}_{\mathrm{node}_k} = \sum_{i \neq m \neq n} \frac{\rho_{mn}(k)}{\rho_{mn}}, \tag{1}$$

where ρ_{mn} is the number of shortest paths between node_m and node_n, and $\rho_{mn}(k)$ is the number of those paths passing through node_k.

Results and discussion

Analyses of the baseline characteristics of articles published

Annual changes of article publication

The annual numbers of papers published reflect the development trend in biochar adsorption for wastewater treatment research [32]. The paper count on biochar adsorption for wastewater treatment has grown substantially over the years (Fig. 1a). This phenomenon

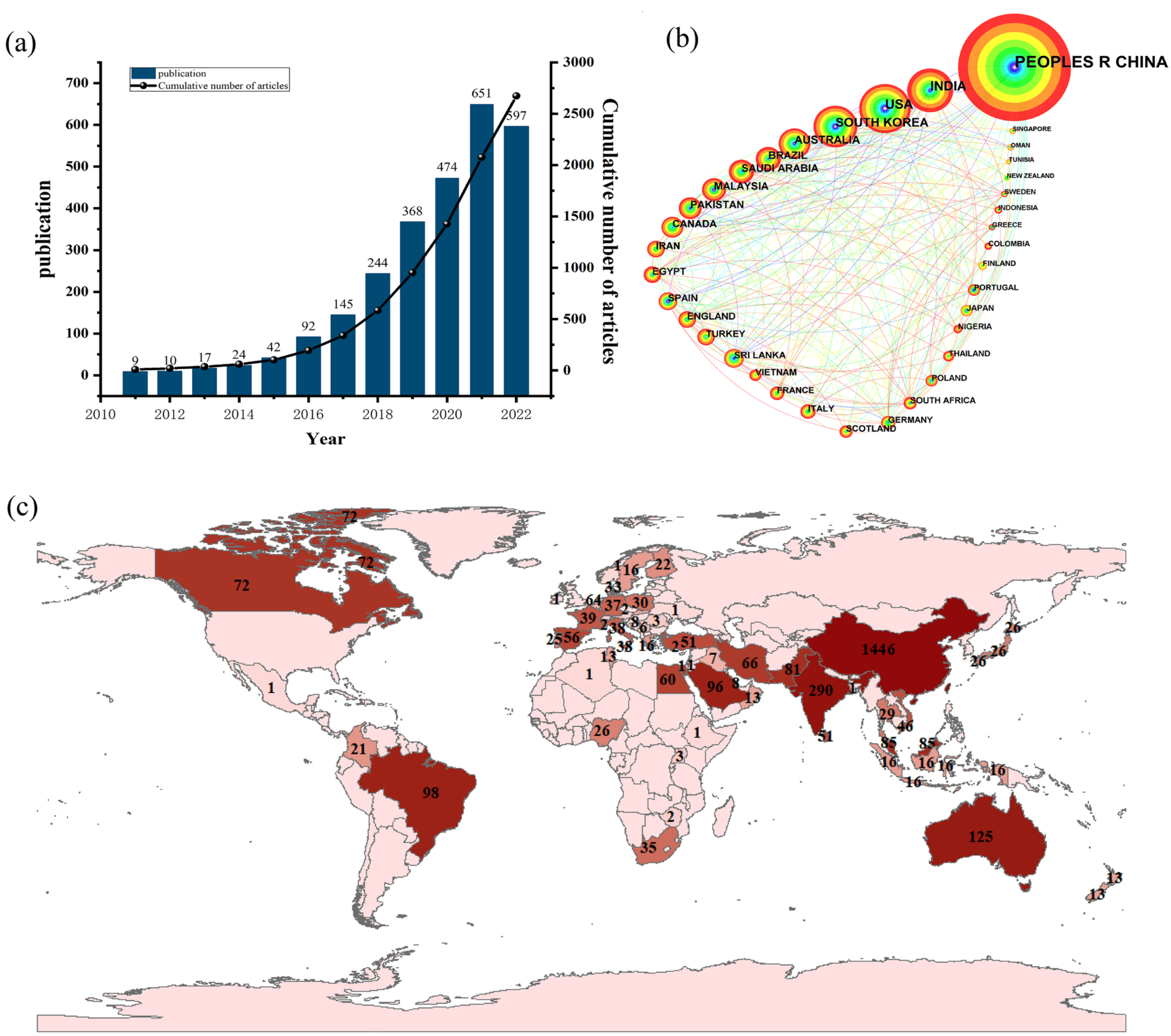


Fig. 1 Number and geographic distribution of publications on biochar adsorption of wastewater treatment. **a** Annual publications. **b** Visualisation of countries contributions. **c** Global geographic distribution map of published papers by country. The darker the color, the more papers are published

demonstrated that research into biochar adsorption for wastewater treatment has gradually been given attention and development. The mean number of articles was 223, and the total number increased stepwise. The initial phase of this study, between 2011 and 2013, had an average of 12 articles per year. The earliest publication in this period was titled as "*A new magnetic biochar effectively sorbs organic pollutants and phosphate*", that has been published in the *Journal of Bioresource Technology* [33]. Others have reported that Fe^{3+}/Fe^{2+} and orange peel magnetic biochar were prepared to have the ability to remove organic pollutants and phosphate from wastewater simultaneously and phosphate from the water. Magnetic biochar is also shown to be a potential adsorbent with the capacity to remove organic pollutants and phosphate from wastewater simultaneously [34]. Between 2014 and 2017, the number of papers showed a significant growth trend, and researchers gradually increased, with a mean of 75 papers. The average number of papers per year between 2018 and 2021 exceeds 400, indicating a boom in research on biochar adsorption wastewater. However, the number of papers published in 2022 is less than that published in the previous year for the first time. This may be due to the lagging impact of COVID-19 on reducing the research activities in 2021–2022. Overall, studies on biochar adsorption for wastewater treatment have received a great deal of attention in recent years. On the other words, biochar is widely explored for the purpose to remove wastewater pollutants due to its excellent physical and chemical properties that make it an efficient adsorbent [35].

Country contributions

Visual analysis of countries with authors' affiliations can not only identify countries central to the field of research, but also reflect relevant academic cooperation between different countries [22]. For this study, countries were selected for analysis in CiteSpace, and a county-level analysis map (Fig. 1b) was got. Country contributions were represented by frequency of occurrence, and the state's position in the domain is denoted by centrality [22]. As the number of publications increases, so does the richness of country studies [25]. China is in absolutely first place in terms of the number (1392) of papers published (Additional file 1: Table S1), revealing that China has extensive research in the surveying biochar area. This is because China has significantly strengthened ecological and environmental governance, thus increasing the research and application of biochar adsorption for wastewater treatment. Due to those reported positively impacting adsorption characteristics, biochar has rapidly become the focus of China's environmental remediation field, and has rapidly begun to be researched in numerous scientific research institutions [36]. Furthermore, the higher the centrality, the greater the number of partnerships, and the more central the country's research in its field [37]. South Korea has the highest degree of centrality (0. 28), indicating that South Korea is at the centre of research in its field and is more inclined to cooperate with other countries. Judging from the geographic distribution of articles published by countries worldwide (Fig. 1c), the focus on biochar adsorption for wastewater treatment is unevenly distributed across the globe, concentrated primarily in Asia, North America, and Western Europe.

Institution-level contributions

The analysis node chooses "Institution" this time, and a county-level analysis map (Additional file 1: Fig. S1) has been achieved [38]. A relatively dense set of nodes in the map with a total of 93 connections points to the fact that research institutions in this area have cooperated very frequently [39]. The top 10 research institutions in terms of the number of articles published in this area between 2011 and 2022 are listed in Additional file 1: Table S2. Of which, the Chinese Academy of Sciences holds the most publications, followed by Hunan University and Korea University. The fact that six of the top 10 publications are from China shows that Chinese research institutions have the most extensive research in their areas of expertise. The centrality of the Chinese Academy of Sciences is the highest in terms of the degree of centrality, reaching 0.20, indicating that the Chinese Academy of Sciences has played a significant role in promoting cooperation in this area [40]. It can also be seen from Additional file 1: Table S2 that the Half-Value Period of the Chinese Academy of Sciences is 8.5 years, placing it first in the list, showing that the researches of the Chinese Academy of Sciences have achieved great results, and the institution has great potential for future research in this area [41]. The degree of centrality and the frequency of occurrence did not always appear in the same proportion [42]. It has been noted that the centrality of China Agricultural University, while the number of articles published by this institution is not remarkable, they are still very influential in their field due to close cooperation [43].

Authorship

A quantitative analysis of the author contributions can reveal the leading research representative academics in biochar wastewater adsorption [44]. Using the software CiteSpace, define "Author" as the node and draw the knowledge map of the contributions of the authors' (Fig. 2) [45]. First, judging by the link between the authors, each link is relatively dense, indicating that the authors are very closely cooperating in this area and

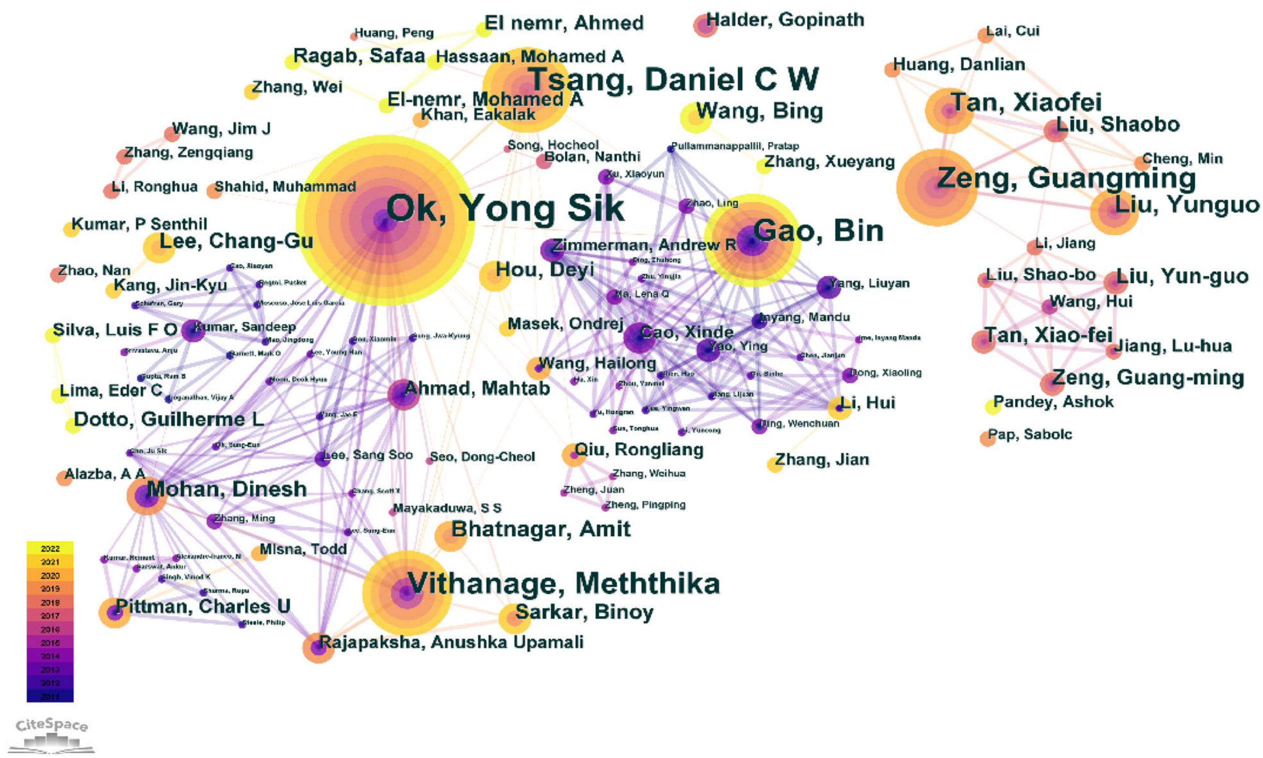


Fig. 2 Biochar adsorption for wastewater treatment research author visualization

that exchanges between academics in biochar adsorption wastewater are relatively common [25]. Price's law states that the core group of authors in the research area can be obtained [40]. The formula is

$$M = 0.749\sqrt{N_{\max}}, \tag{2}$$

where M refers to the minimum number of publications that an outstanding author should achieve, and refers to the number of publications by the most prolific author.

Accounting for more than or equal to 50% of all articles, indicating the formation of a core set of perpetrators [46]. As shown in Additional file 1: Table S3, Ok, Yong Sik is the author with the most publications in this field since 2011 with 75 publications. Inserting this into the formula (2), we can obtain $M = 6.48$, and there are 42 authors with more than seven papers, which are categorized as core authors. A total of 569 articles were published by the above-core authors, representing 28% (i.e., less than 50%) of the total number of articles, indicating that a core group of writers in the field has yet to form [47]. This may be due to the many avenues of research in a broader biochar area, so that certain research academics have not engaged in intensive and in-depth exploration on the targeting adsorption-wastewater issue. Thus, there is a need for getting more researchers on board for the in-depth research on the biochar adsorption for wastewater treatment.

Diversity of disciplines and periodicals

In biochar adsorption wastewater research, the overlay of the dual map can clearly show the relationship between citations and citations between different disciplines [48] (Additional file 1: Fig. S2). The colored curves in the figure link citing and being cited, with citing disciplines on the left and cited disciplines on the right [49]. The ellipse size in the figure depends on the number of papers in the subject, and the internal value indicates the number of papers [50]. It can be concluded from Additional file 1: Fig. S2 that research in the area of biochar adsorption for wastewater is concentrated primarily in the topic groups of physics, metals, chemistry, animals and science. Most papers cited are concentrated in chemistry, metals, physics, environment, toxicology, and other topic groups. The group whose citation curves are labelled "Animals, Science, and Veterinary Medicine" has the most outward citation paths, and this group of topics is the primary group of citing journals. When the environmental, toxicological, and nutritional groups of journals are cited, the corresponding animal, scientific, and veterinary discipline groups have the most citations, with a z-score of 5.7043614.

In biochar adsorption for wastewater treatment research, the top 10 journals with the number of papers published in this field was list (Additional file 1: Table S4), which number of published articles accounts for 42.05% of the total number of papers. It can be inferred that while there are many published articles in this area, the distribution of published journals is relatively concentrated [51]. While the top ten journals have a mean impact factor of 9.9744, five journals retain an impact factor of 10. The impact factors for the top two "*Chemical Engineering Journal*", and "*Journal of Hazardous Materials*", are 16.744 and 14.244, respectively. It can be seen that the research output is mainly spread over a small number of journals with higher impact factors, and it can be inferred that biochar adsorption wastewater research has been favored by high-impact factor-level journals [52].

Analysis of research hotspots

Keywords network

The high-frequency word co-occurrence map is generated in CiteSpace with the keyword as the object of analysis, and keywords are aggregated to obtain research hotspots and emerging research trends of wastewater related to biochar adsorption [53]. The high-frequency keyword co-occurrence map (Fig. 3) and the high-frequency keyword table (Additional file 1: Table S5) of biochar adsorption wastewater research have been generated by using CiteSpace software [54].

The keyword frequencies represent the sizes of the nodes and tags. As the frequency of keywords increases, nodes and labels become larger [55]. Different colors represent different years, the thicker the line, the more connections between keywords [22]. It can be seen that the keyword that has the highest co-occurrence frequency in the field of biochar adsorption wastewater research is "wastewater". The keyword "wastewater" in the analysis has the highest frequency of occurrence and centrality, showing that "wastewater" is the most important basic research and has received much scholarly attention. Followed by in the order, "adsorption", "aqueous", "solution removal", and "activated carbon" have also topped in the hot research list of biochar adsorption wastewater. The keywords analysis revealed that the research content in the area of biochar revolves primarily around the adsorption of pollutants in wastewater, such as using biochar to adsorb pollutants (e.g., methylene blue and heavy metals) into water columns, with a focus on analyzing its mechanism of adsorption and the effect of pyrolytic temperature during biochar preparation on adsorption [56, 57].

Keyword clustering

Using the log-likelihood rate (LLR) algorithm allows for the clustering of keywords in the biochar adsorption wastewater field (Additional file 1: Fig. S3). The information for each cluster is shown in Table 1 [58]. In the keyword clustering, the field of biochar adsorption wastewater research is divided into ten categories, namely #0 magnetic biochar, #1 waste water, #2 heavy

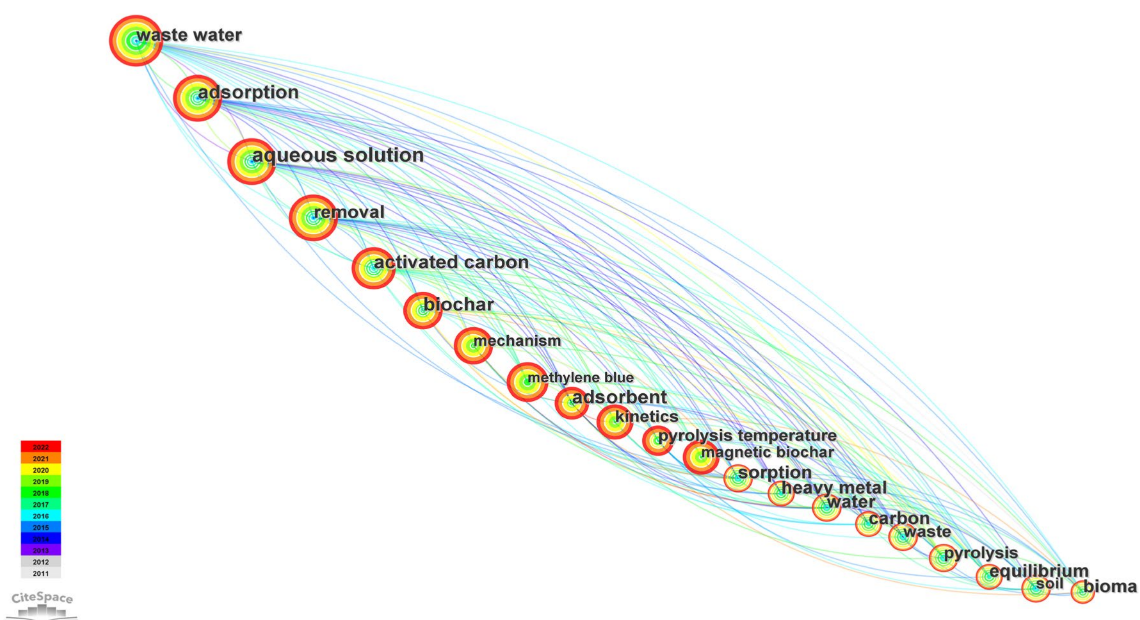


Fig. 3 Keywords network co-occurrence of biochar adsorption for wastewater treatment

Table 1 Keywords information in biochar adsorption for wastewater treatment

Ranking	Number of nodes	Mean contour value	Average year	Main content		
0	33	0.881	2012	Magnetic biochar	Graphene oxide	Pb(II)
1	27	0.931	2012	Tetracycline	Hexavalent chromium	Nanoparticle
2	22	0.964	2012	Heavy metal	Cadmium	Zinc
3	21	0.981	2012	Degradation	Dye	Desorption
4	21	0.91	2011	Adsorbent	Methylene blue	Kinetics
5	19	0.955	2012	Temperature	Behavior	Steam
6	17	0.98	2012	Biochar	Charcoal	Organic matter
7	16	0.92	2012	Biosorption	Crop residue	Slow pyrolysis
8	12	0.915	2012	Adsorption	Mechanism	Copper
9	12	0.966	2012	Pyrolysis	Nitrogen	Manure

metal, #3 pyrolysis, #4 methylene blue, #5 temperature, #6 biochar, #7 crop residue, #8 lignocellulosic biomass, #9 nitrogen.

With each cluster covering a distinct keyword (Table 1), the largest cluster may be found depending on how many keywords each cluster covers [59]. A greater than 0.7 of the average silhouette value for a cluster in the domain indicates that a good cluster has formed [39]. Mean publication times for keywords within the cluster are expressed as mean years, indicating if the subject is near the front [22]. In the area of biochar adsorption wastewater, the average year for keyword clustering is predominantly 2012, indicating that this area has long ago formed a stable research system. On the other hand, the average search time for each cluster is very close. For this reason, it is impossible at present time to judge which cluster is closer to the state-of-the-art search [60].

Consisting mainly of papers on the preparation and use of magnetic biochar for the adsorption of pollutants in water, #0 magnetic biochar is the largest cluster. Magnetic biochar is an adsorbent that uses magnetic metals (mainly Fe) and their metal oxides for addition to the biochar matrix and uses its characteristics to remove pollutants [61]. Indeed, various types of magnetic biochar can remove heavy metals and Pb(II) from the water [62, 63]. #1 waste cluster includes important keywords such as tetracycline, hexavalent chromium, and nanoparticles. The content of this cluster primarily consists of articles related to the treatment of certain pollutants present in wastewater [64–66]. Category #2 heavy metal mainly includes articles related to the biochar treatment of heavy metals in wastewaters, such as the occurrence of heavy metals like cadmium and zinc [67, 68]. Other clusters include pyrolysis temperature when biochar is prepared, the adsorption of methylene blue by biochar, the temperature of pollutants adsorbed by biochar, research on the structure of biochar, the feedstock of biochar using waste from agriculture and forestry, and the adsorption of biochar nitrogen, and so on [69–72].

Analysis of research status and future trends

Research status

To explore the history of keyword development in biochar adsorption for wastewater treatment research, we plotted a time-area map of keyword clustering (Fig. 4) [45]. The various clusters are sorted from top to bottom based on the number of keywords they contain. The top of the map is when the keywords appear while the keywords within a cluster are distributed along the same horizontal line as a function of onset time [73]. The process of evolving the keywords in each cluster can be displayed via the connecting line in the figure, and the rise and fall of the cluster search can be analyzed via the time frame of appearance and disappearance of the horizontal solid line [74]. As shown in Fig. 4, all ten keyword clusters appeared in 2011, indicating that the field of biochar adsorption wastewater was very popular in its early stages, and was the subject of extensive academic research. Of these, #0 (magnetic biochar) and #1 (wastewater) in keyword clustering have maintained a high popularity from 2011 to 2022. Both are at the heart of the biochar adsorption wastewater field, and each has achieved a great deal of research output. Magnetic biochar has consistently maintained a high level of research popularity. This research has focused on the adsorption of various pollutants by magnetic biochar, mainly covering the influence of magnetic biochar synthesis temperature on pollutants [75, 76]. Pb(II) has been shown to have efficient adsorption and is also one of the hot topics in magnetic biochar [77, 78]. The focus of wastewater research is rich in research content, and research time has been invested in a continuous mode. Although there are many early research results in the research content for other clusters, the number of search results decreases

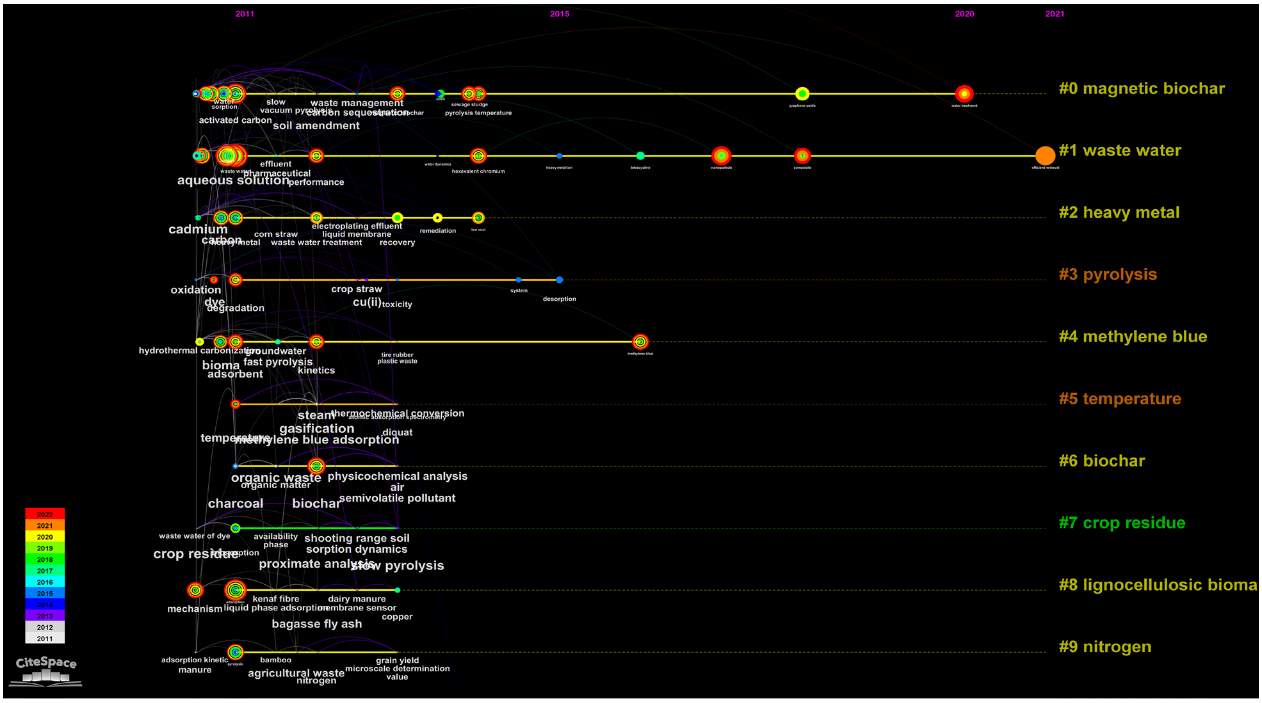


Fig. 4 Timeline visualization of the clusters

with time, implying the reducing degree of attention. For example, heavy metal and nitrogen clustering have gradually ceased since 2015.

Research trend

The time-series analysis of keyword frequency can reveal the pattern of research hotspots and help to understand the evolution of research hotspots of biochar adsorption of wastewater, to provide new insights into its development trend and future direction [79]. In Table 2, the blue line represents the time interval between emergence and termination, whereas the red line represents the time interval from the onset to the end of the hotspot [80]. Intensity denotes the intensity of the keywords. The higher the keyword intensity, the higher the search intensity and the greater the number of realizations in that period [81–83].

"Soil" is a term that emerged from 2012 to 2017, and a large number of articles have been published, and the duration is very long, showing that its contents are rich enough to be worth studying by researchers. Its main content is biochar's use as a soil improver [84–86]. It is worth paying attention to the keywords "black carbon", "cadmium", "biosorption"; and "phosphate", their search intensities were 14.04, 13.75, 18.46 and 11.43, respectively. These four keywords are characterized by the fact that word emergence is brief, but their research intensity is high, and article publication is very high. The contents explore carbon structure, and the influence of carbon structure on pollutant adsorption [87, 88], adsorption of cadmium by different modified biochars [89], adsorption characteristics and mechanism of modified biochar on Cr(VI) [90], and study on recovery of phosphate by modified biochar [91, 92]. In addition, in the research timeline of biochar adsorption of wastewater, there are also many short-term hot research contents such as tetracycline, biochar adsorption of copper, and biochar adsorption of Pb(II) [93–97]. The outcome implies that research hotspots in this field are evolved very rapidly, and scholars should pay attention to the developmental content of their field over time to capture key foci of inquiry. Currently, the most recent keywords for research hotspots are "dye", "effective removal", "composite", and "temperature", from which we can see that recent research hotspots of wastewater biochar adsorption focus primarily on the use of biochar for adsorbing pollutants into dyes, and synthetic biology effect of carbon temperature on pollutant adsorption [98–101].

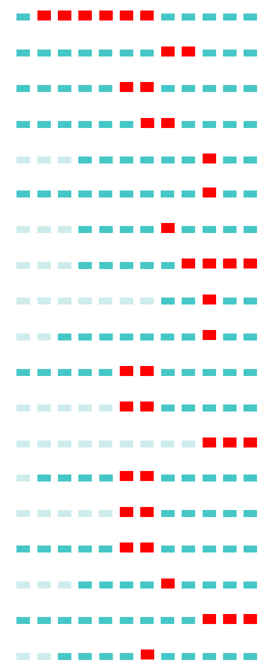
Biochar adsorption of pollutants in wastewater

Application of biochar in different types of wastewater treatment

Wastewater can be divided into industrial wastewater, urban wastewater, agricultural wastewater and rainwater [102]. Biochar in the traditional sense is produced by direct pyrolysis of organic matter, such as pure straw

Table 2 Burst word data for biochar adsorption for wastewater treatment keywords

Keywords	Strength	Year			2011–2022
		First noted	Burst		
			Onset	End	
Soil	19.57	2011	2012	2017	
Biosorption	18.46	2011	2018	2019	
Black carbon	14.04	2011	2016	2017	
Cadmium	13.75	2011	2017	2018	
Remediation	11.85	2014	2020	2020	
Hydrothermal carbonization	11.81	2011	2020	2020	
Phosphate	11.43	2014	2018	2018	
Zero valent iron	11.39	2014	2019	2022	
Graphene oxide	10.76	2018	2020	2020	
Recovery	10.06	2013	2020	2020	
Black carbon	9.86	2011	2016	2017	
Tetracycline	8.38	2016	2016	2017	
Water treatment	8.26	2020	2020	2022	
Fast pyrolysis	8.09	2012	2016	2017	
Tetracycline	7.61	2016	2016	2017	
Lead	7.49	2011	2016	2017	
Pb(ii)	6.7	2014	2018	2018	
Dye	5.64	2011	2020	2022	
Copper	5.02	2013	2017	2017	



biochar [103] and pure sludge biochar [104]. Biochar is obtained by biomass pyrolysis in an oxygen-free or -limited environment. Indeed, the thermochemical process of pyrolysis produces three coproducts of biochar, bio-oil, and syngas [105–107]. Thus, the biochar's yield and physicochemical properties are not only affected by the raw materials, but also by the pyrolysis temperature and modification method [108]. In existing research, the preparation of commonly modified biochar is shown in Fig. 5. In the process of biomass pyrolysis, to transfer heat evenly during the pyrolysis process, bulky and large size biomass materials are usually pulverized into small particles, thereby facilitating the production of particles with pores of different sizes during biomass pyrolysis (from nanometer to centimetre-sized particles) [109].

Industrial wastewater comes from various sources, including mining, smelting, battery manufacturing, chemicals, leather manufacturing, dyes, etc., and which pollutants are mainly heavy metals and organic pollutants [110]. Currently, biochar has been used in the treatment of industrial wastewater, mainly for the adsorption of heavy metals and organic dyes [111]. The adsorption process is related to the pH of the medium, contact time and dosage.

Biochar can be used directly or combined with technologies such as biological filters for urban sewage treatment. It can recover unstable nitrogen and phosphorus, and can also remove ammonia nitrogen in urban wastewater [112]. The study found that biochar derived at 450 °C had the highest ammonia nitrogen removal capacity, with 1.2 mg of NH_4-N removed per g of biochar, which was attributed to its higher surface area and functional group density, and the process was driven by chemical adsorption control [113].

Many researchers have applied biochar and its modified forms to treat agricultural wastewater pollution. The adsorption capacity of biochar to pesticides is related to biochar raw materials, functional materials and target pollutants [114]. On the other hand, biochar also has good adsorption effects on toxic heavy metals such as arsenic, chromium, copper and lead in agricultural wastewater. Through the above research, it can be found that biochar has broad application prospects for the adsorption treatment of heavy metal ions in water [115].

Stormwater runoff can significantly degrade natural water quality and require treatment prior to discharge, primarily due to increased concentrations of metals, organic matter, and biological contaminants [116]. Biochar and its modified forms have been used

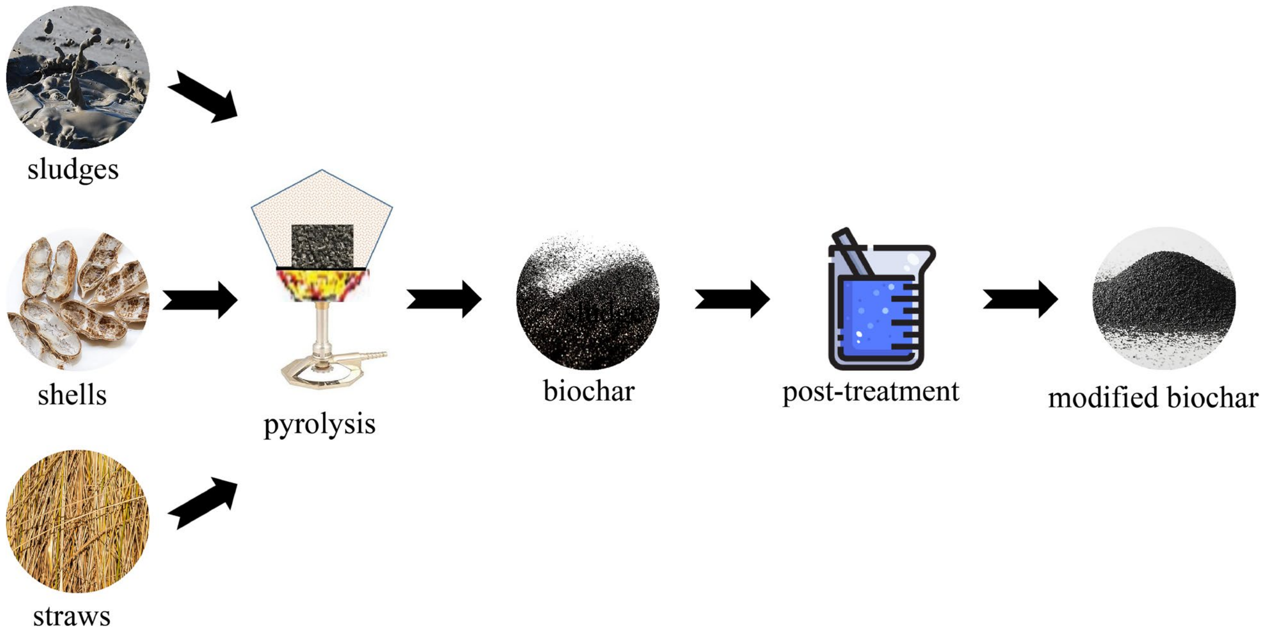


Fig. 5 Simplified process scheme of common modified biochar preparation

in stormwater treatment systems as effective media. In addition, biofilter/bioretention systems containing biochar are also effective in removing microorganisms from stormwater [117]. The various removal capabilities of pollutants from stormwater depend on the nature of the biochar, the characteristics of the pollutants, and the chemistry of the water.

Biochar adsorption of heavy metals in wastewater

Heavy metals in wastewater have adverse effects on humans, animals and plants. Studies have shown that biochar can effectively adsorb heavy metal ions in wastewater [118]. The removal mechanisms of heavy metals in water by biochar adsorbent mainly involve ion exchange, precipitation and complexation. Surface adsorption is also a mechanism for heavy metal removal [119]. As shown in Fig. 6a, the surface of biochar is usually negatively charged, providing effective adsorption sites for electrostatic attraction of heavy metal ions [120]. The efficient removal of heavy metals by biochar is the synergistic effect of multiple reaction mechanisms, mainly surface complexation of functional groups, surface precipitation, ion exchange and electrostatic attraction [121]. Ion exchange is the exchange of organic oxygen-containing functional groups such as hydroxyl and carboxyl groups on the surface of the biochar adsorbent with different anions and cations to achieve the purpose of removing these ions. Chemical precipitation is the most established and commonly used treatment technology for separating heavy metals from aquatic environments [122]. Complexation refers to the process of forming a complex between metal ions and organic functional groups on the surface of the biochar adsorbent, such as oxygen-containing functional groups such as hydroxyl, carbonyl and carboxyl groups.

Compared with other treatment technologies, adsorption technology has a significant effect in removing heavy metals from water, even at lower metal ion concentrations. The feasibility, simplicity of adsorbent preparation and better regeneration behaviour has made them a better choice [123]. This low-cost adsorption method can effectively separate toxic metals from aqueous solutions. Compared with existing activated carbon, these biochar approaches have the advantages of economical, efficient, good adsorption capacity, regeneration, and reuse of recovered metals, no secondary pollution, antibacterial properties and easy handling [124].

Biochar adsorption of inorganic salt in wastewater

Increased concentrations of nutrients such as phosphates, nitrates, and ammonium can cause serious environmental problems to the ecosystem [125]. For example, they will promote the growth of photosynthetic organisms, cause eutrophication of aquatic ecosystems, and lead to water quality degradation [126]. Among various low-cost adsorbent materials, biochar shows strong potential as an environmentally friendly adsorbent. The adsorption of inorganic salts in wastewater by biochar depends on the properties of the biochar (Fig. 6b), such as surface groups, porous structure, mineral composition

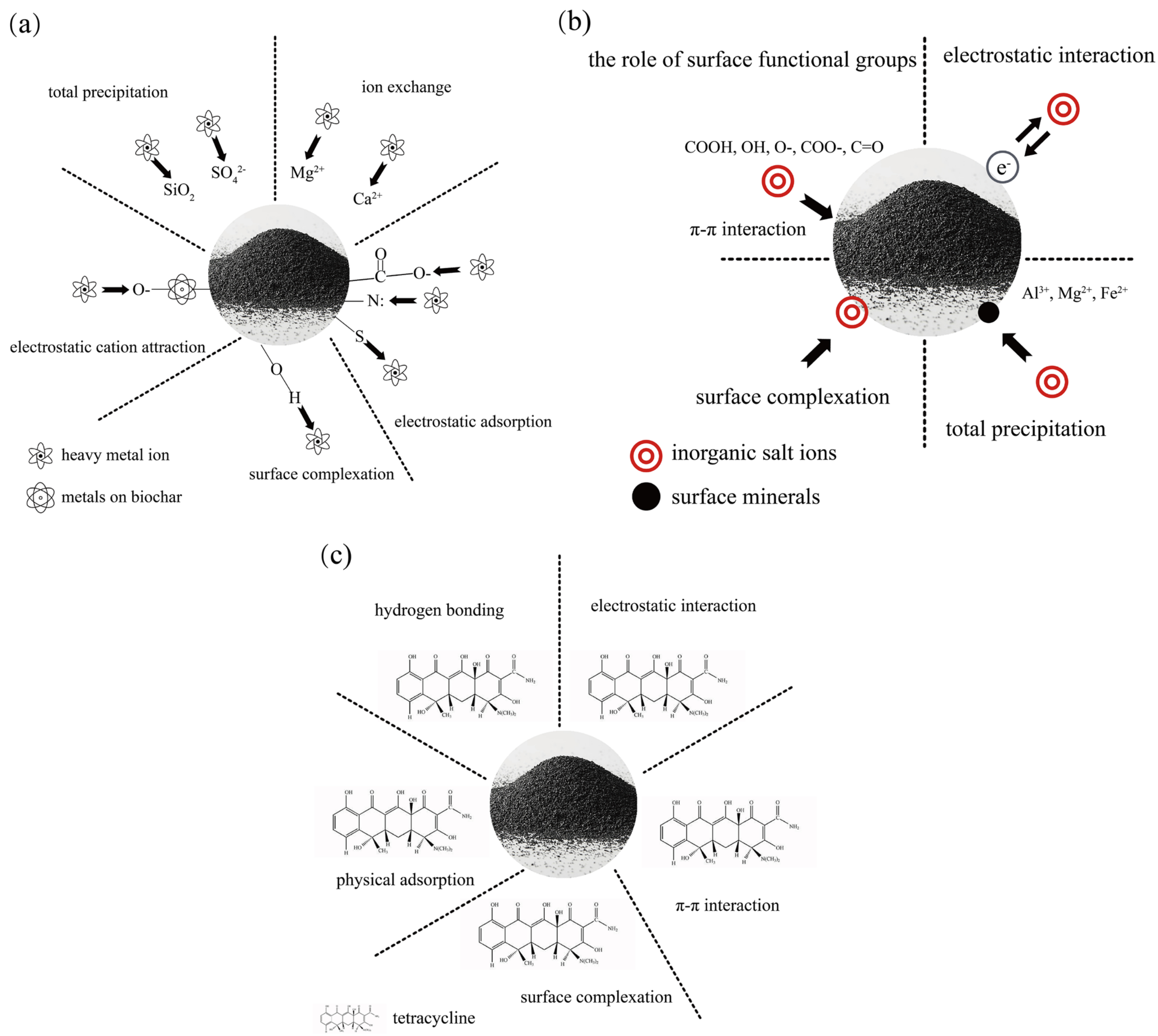


Fig. 6 Mechanisms of biochar adsorption of pollutants in wastewater. **a** Mechanisms of biochar adsorption of heavy metals. **b** Mechanisms of inorganic salt adsorption by biochar. **c** Mechanisms of tetracycline adsorption by biochar

and loaded active ingredients. The adsorption mechanism includes surface functional group interaction, electrostatic interaction, surface co-precipitation and complexation, and hydrogen bonding [127].

Taking phosphate as an example, the adsorption mechanism of phosphate by biochar is mainly determined by the specific surface area, functional groups and metal ion composition of biochar [128]. Biochar has rich microporous structure and large specific surface area, which can provide active adsorption sites for phosphate ions. Physical deposition will occur when phosphate ions diffuse to the surface of biochar. The organic functional groups on the surface of biochar –OH, –COOH, C–H, C=O [129], $-NH_2$ and $-NO_2$ [130] can combine with phosphate ions. In addition, when the surface of biochar contains oxides or hydroxides of metal elements such as Ca and Mg, phosphate will also undergo chemical adsorption on the surface of biochar [131]. For example, Park et al. [132] reported that CaO or $Ca(OH)_2$ on the surface of crayfish biochar combines with phosphate ions to form hydroxyapatite (HAP).

Biochar adsorption of organic pollutants in wastewater

In recent years, organic matter pollution in water has become severe. Common organic pollutants include but not limited to dyes and antibiotics [133]. Biochar has also been proven to have significant adsorption or degradation effects on organic pollutants in water. Dyes are one of the organic pollutants discharged into wastewater by industries such as leather, pharmaceutical, textile, paint, and paper [134]. They have complex organic structures that can cause health problems related to the skin, gastrointestinal tract, and lungs [135]. In addition, when dyes are released into water bodies, they could increase chemical oxygen demand and interfere with the light penetration of water bodies, thus causing severe damage to the living environment of aquatic animals and plants [136]. Therefore, dye compounds need to be removed or converted into harmless substances. Research has found that biochar can effectively remove dyes with different chemical structures [137]. Typically, hydrogen bonds are formed between the biocchar's oxygen-containing functional groups and the dye functional groups to play the adsorption performance. The dye removal mechanisms of biochar also involve electrostatic attraction and π–π interaction. The exact removal mechanisms differ depending on the type of dye molecules and their interaction with the specific biochar used.

The emerging contaminants antibiotic are widely used clinically in animals and humans to prevent and treat diseases. Due to the low metabolism of antibiotics and their carcinogenic, teratogenic, mutagenic or hormonal effects, their discharge into the environment through water bodies could cause ecological disasters [138]. The adsorption mechanisms of biochar to antibiotic pollutants determined by the surface functional groups, the specific surface area of biochar and the nature of the pollutants [139]. As shown in Fig. 6c, its main adsorption mechanisms are surface complexation, electrostatic attraction and hydrogen bonding, followed by multi-layer mechanisms such as pore filling and π–π interaction.

Factors affecting the performances of biochar to adsorb pollutants in wastewater

In addition to the biochar's characteristics as discussed aforenoted, the number of cycles of biochar re-use can also have a great impact on its adsorption performance [140, 141]. Recyclability performance is an important indicator for evaluating the cost-effectiveness of adsorbents and is also a consideration for large-scale applications [142]. As the number of re-use cycles increases, the decrease in adsorption rate may be related to factors such as the loss of the adsorbent itself, the reduction in pore volume and specific surface area, and the reduction in the number of its functional groups. Although the adsorption capacity decreased slightly after several cycles, its recovery and removal rates were still high, indicating that biochar has good recyclability and practical application potential.

The adsorption capacity of biochar to pollutants is affected by numerous factors, such as the pH of the solution, the concentration of adsorbent, and temperature. Research found that the pH of the solution impacts the physical and chemical properties, distribution characteristics and adsorption efficiency of biochar. Temperature is also one of the factors affecting biochar adsorption [143]. The temperature difference will have a significant impact on the morphological distribution and adsorption mode of pollutants in wastewater on the adsorbent, thus impacting the removal effect of pollutants. During the adsorption process of pollutants by biochar adsorbents, due to different types of adsorbents and adsorption mechanisms, the heat generated will also be different, resulting in insufficient ion exchange reactions between the functional groups of the adsorbents and pollutants. Therefore, it has a greater impact on the adsorption effect [144]. The adsorption capacity of biochar to pollutants is generally also related to the amount of biochar. Increasing the dosage can increase the adsorption capacity of pollutants. In the adsorption and desorption process, it is generally affected by the type of desorption liquid, desorption concentration, desorption temperature and desorption time [145]. In related research on desorption and regeneration, it was also found that the direct solvent method has the problem of poor desorption effect. Therefore, some studies use other methods combined with solvent methods, and the regeneration performance of the adsorbent is improved, including microwave methods, high-temperature roasting, ultrasonic methods, and microbial methods [146].

Summary and prospect

In this paper, a scientometric approach using CiteSpace software was used to analyze articles on biochar adsorption for wastewater treatment published in the past 12 years (2011–2022). There have been 2673 journal articles in the last 12 years related to the field. China is the most active contributor to research, producing the largest number of publications of any country, with the Chinese Academy of Sciences playing a crucial role in advancing this technology. Yong Sik Ok (Korea) was the authors who amassed the greatest numbers of published articles in biochar adsorption for wastewater treatment. Recent research hotspots suggest that heavy metal adsorption by magnetic biochar has received significant attention. This review has found that the synthesis temperature for more effective biochar preparation can be investigated in depth in the future. The adsorption properties of modified biochar can be utilized for the adsorption of dyes, tetracyclines and some new pollutants. Future research should focus on optimizing various parameters in the production process of biochar to improve the adsorption capacity of biochar. Experiments on the modification of various methods and materials can be carried out and applied to practical projects.

The adsorption mechanisms of biochar for different pollutants are not completely consistent. The adsorption mechanisms of heavy metals are mainly surface complexation, surface precipitation, ion exchange and electrostatic attraction. The adsorption mechanism of inorganic salts is mainly surface functional group interaction, electrostatic interaction, surface co-precipitation and complexation. The removal of dyes is mainly electrostatic attraction and hydrogen bonding; the removal of antibiotics is mainly surface complexation, electrostatic attraction and hydrogen bonding. Studying the adsorption mechanism is of great significance for exploring the properties and applications of adsorbents, which also can provide a theoretical basis for efficiently removing different types of pollutants. At present, further research is needed on biochar wastewater treatment technology, especially in industrial wastewater and urban sewage treatment. The results of the work in this paper may contribute to solving the practical problems of pollution of the water environment and improving the quality of the environment, thus reducing the risk of pollution to human health and living quality. While this research leveraged CiteSpace for its analysis, it is important to note some software limitations, such as challenges in consolidating different author name formats and keyword synonyms. Addressing these issues is crucial for more accurate analyses in future.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-024-00859-z.

Additional file 1: Table S1. Top 10 countries for the number of papers published. **Table S2.** Top 10 institutions in the field for the number of papers published. **Table S3.** Top 10 authors in the field for the number of papers published. **Table S4.** Top 10 journals in the field for the number of papers published. **Table S5.** Top 20 keywords with the most publications in biochar adsorption for wastewater treatment. **Figure S1.** Biochar adsorption for wastewater treatment research institute visualization. **Figure S2.** Dual map overlay of biochar adsorption for wastewater treatment. **Figure S3.** Analysis of biochar adsorption for wastewater treatment keywords co-occurrence clustering.

Acknowledgements

The authors thank the anonymous reviewers for their helpful and constructive comments and feedback. Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by USDA. USDA is an equal opportunity provider and employer.

Author contributions

YW, LC and YZ wrote the main manuscript text, YW, YZ and ZH revised the manuscript and provided constructive, WF and YT prepared all figures, and HL conducted a thesis data review.

Funding

This research was in part jointly supported by the National Key Research and Development Program of China (No. 2021YFC3200802), and the National Natural Science Foundation of China (No. 41877380, 41630645). This work was also supported in part by United States Department of Agriculture (USDA)-Agricultural Research Service internal research project 6054-41000-113-000D (ZH).

Availability of data and materials

This declaration is "not applicable".

Declarations

Ethics approval and consent to participate

This declaration is "not applicable". All participants agreed to participate.

Competing interests

The authors declare no competing interests.

Received: 27 December 2023 Accepted: 6 February 2024
Published online: 12 February 2024

References

1. Guo M, Uchimiya SM, He Z (2016) Agricultural and environmental applications of biochar: advances and barriers. Agricultural and environmental applications of biochar: advances and barriers. Soil Science Society of America, Madison, pp 495–504. https://doi.org/10.2136/sssaspecpub63.2014.0054
2. Shaheen SM, Niazi NK, Hassan NEE, Bibi I, Wang H, Tsang DCW, Ok YS, Bolan N, Rinklebe J (2019) Wood-based biochar for the removal of potentially toxic elements in water and wastewater: a critical review. Int Mater Rev 64:216–247. https://doi.org/10.1080/09506608.2018.1473096
3. He Z, Uchimiya SM, Guo M (2016) Production and characterization of biochar from agricultural by-products: overview and use of cotton biomass residues. Agricultural and environmental applications of biochar: advances and barriers. Soil Science Society of America, Madison, pp 63–86. https://doi.org/10.2136/sssaspecpub63.2014.0037.5
4. Vassilev N, Martos E, Mendes G, Martos V, Vassileva M (2013) Biochar of animal origin: a sustainable solution to the global problem of high-grade rock phosphate scarcity? J Sci Food Agric 93:1799–1804. https://doi.org/10.1002/jsfa.6130
5. Chen Y-D, Wang R, Duan X, Wang S, Ren N-Q, Ho S-H (2020) Production, properties, and catalytic applications of sludge derived biochar for environmental remediation. Water Res 187:116390. https://doi.org/10.1016/j.watres.2020.116390
6. He Z (2012) Applied research of animal manure: challenges and opportunities beyond the adverse environmental concerns. Nova Science Publishers, New York, p 325
7. Zubair M, Ihsanullah I, Abdul Aziz H, Azmier Ahmad M, Al-Harthi MA (2021) Sustainable wastewater treatment by biochar/layered double hydroxide composites: progress, challenges, and outlook. Bioresour Technol 319:124128. https://doi.org/10.1016/j.biortech.2020.124128
8. Kamali M, Appels L, Kwon EE, Aminabhavi TM, Dewil R (2021) Biochar in water and wastewater treatment—a sustainability assessment. Chem Eng J 420:129946. https://doi.org/10.1016/j.cej.2021.129946
9. Lin S-L, Zhang H, Chen W-H, Song M, Kwon EE (2023) Low-temperature biochar production from torrefaction for wastewater treatment: a review. Bioresour Technol 387:129588. https://doi.org/10.1016/j.biortech.2023.129588
10. Qambrani NA, Rahman MM, Won S, Shim S, Ra C (2017) Biochar properties and eco-friendly applications for climate change mitigation, waste

management, and wastewater treatment: a review. Renew Sustain Energy Rev 79:255–273. https://doi.org/10.1016/j.rser.2017.05.057
11. Ambaye TG, Vaccari M, van Hullebusch ED, Amrane A, Rtimi S (2021) Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater. Int J Environ Sci Technol 18:3273–3294. https://doi.org/10.1007/s13762-020-03060-w
12. Miles TR, Rasmussen EM, Gray M (2016) Aqueous contaminant removal and stormwater treatment using biochar. Agricultural and environmental applications of biochar: advances and barriers. Soil Science Society of America, Madison, pp 341–376. https://doi.org/10.2136/sssaspecpub63.2014.0048.5
13. Xiang W, Zhang X, Chen J, Zou W, He F, Hu X, Tsang DCW, Ok YS, Gao B (2020) Biochar technology in wastewater treatment: a critical review. Chemosphere 252:126539. https://doi.org/10.1016/j.chemosphere.2020.126539
14. Liang LP, Xi FF, Tan WS, Meng X, Hu BW, Wang XK (2021) Review of organic and inorganic pollutants removal by biochar and biochar-based composites. Biochar 3:255–281. https://doi.org/10.1007/s42773-021-00101-6
15. Xue S, Zhang X, Ngo HH, Guo W, Wen H, Li C, Zhang Y, Ma C (2019) Food waste based biochars for ammonia nitrogen removal from aqueous solutions. Biores Technol 292:121927. https://doi.org/10.1016/j.biortech.2019.121927
16. Yang YK, Luo X, Zhang J, Ma XK, Sun PZ, Zhao L (2022) Sewage sludge-coconut fiber co-pyrolysis biochar: mechanisms underlying synergistic heavy metal stabilization and ciprofloxacin adsorption. J Clean Prod 375:10. https://doi.org/10.1016/j.jclepro.2022.134149
17. Zhuo S-N, Dai T-C, Ren H-Y, Liu B-F (2022) Simultaneous adsorption of phosphate and tetracycline by calcium modified corn stover biochar: Performance and mechanism. Bioresour Technol 359:127477. https://doi.org/10.1016/j.biortech.2022.127477
18. Shakoor MB, Ye Z-L, Chen S (2021) Engineered biochars for recovering phosphate and ammonium from wastewater: a review. Sci Total Environ 779:146240. https://doi.org/10.1016/j.scitotenv.2021.146240
19. Aftab B, Ok YS, Cho J, Hur J (2019) Targeted removal of organic foulants in landfill leachate in forward osmosis system integrated with biochar/activated carbon treatment. Water Res 160:217–227. https://doi.org/10.1016/j.watres.2019.05.076
20. Almanassra IW, McKay G, Kochkodan V, Ali Atieh M, Al-Ansari T (2021) A state of the art review on phosphate removal from water by biochars. Chem Eng J 409:128211. https://doi.org/10.1016/j.cej.2020.128211
21. Zhong Y, Igalavithana AD, Zhang M, Li X, Rinklebe J, Hou D, Tack FMG, Alessi DS, Tsang DCW, Ok YS (2020) Effects of aging and weathering on immobilization of trace metals/metalloids in soils amended with biochar. Environ Sci Process Impacts 22:1790–1808. https://doi.org/10.1039/d0em00057d
22. Li M, Jia X, Wang L, Gao G, Feng X, Li C (2022) Research on modified carbon nanotubes in wastewater treatment. Catalysts 12:1103. https://doi.org/10.3390/catal12101103
23. Chen B, Shin S, Wu M, Liu Z (2022) Visualizing the knowledge domain in health education: a scientometric analysis based on CiteSpace. Int J Environ Res Public Health 19(11):23. https://doi.org/10.3390/ijerph19116440
24. Chen H, Fang T, Liu F, Pang L, Wen Y, Chen S, Gu X (2020) Career adaptability research: a literature review with scientific knowledge mapping in web of science. Int J Environ Res Public Health. https://doi.org/10.3390/ijerph17165986
25. Ouyang W, Wang Y, Lin C, He M, Hao F, Liu H, Zhu W (2018) Heavy metal loss from agricultural watershed to aquatic system: a scientometrics review. Sci Total Environ 637:208–220. https://doi.org/10.1016/j.scitotenv.2018.04.434
26. Wu P, Ata-Ul-Karim ST, Singh BP, Wang H, Wu T, Liu C, Fang G, Zhou D, Wang Y, Chen W (2019) A scientometric review of biochar research in the past 20 years (1998–2018). Biochar 1:23–43. https://doi.org/10.1007/s42773-019-00002-9
27. Liu X, Zhao S, Tan L, Tan Y, Wang Y, Ye Z, Hou C, Xu Y, Liu S, Wang G (2022) Frontier and hot topics in electrochemiluminescence sensing technology based on CiteSpace bibliometric analysis. Biosens Bioelectron 201:113932. https://doi.org/10.1016/j.bios.2021.113932
28. Zhuang QD, Hussein MK, Ariffin NFM, Yunos MYM (2022) Landscape character: a knowledge mapping analysis using CiteSpace. Int J Environ Sci Technol 19:10477–10492. https://doi.org/10.1007/s13762-022-04279-5
29. Li C, Wu K, Wu J (2017) A bibliometric analysis of research on haze during 2000–2016. Environ Sci Pollut Res 24:24733–24742. https://doi.org/10.1007/s11356-017-0440-1
30. Wang Y, Cao J, Biswas A, Fang W, Chen L (2024) Acid mine wastewater treatment: a scientometrics review. J Water Process Eng 57:104713. https://doi.org/10.1016/j.jwpe.2023.104713
31. Zheng Z, Zhang P, Yuan F, Bo Y (2022) Scientometric analysis of the relationship between a built environment and cardiovascular disease. Int J Environ Res Public Health 19(9):18. https://doi.org/10.3390/ijerph19095625
32. Zhang L, Dong J, Dong Z, Li X (2022) Research hotspots and trend analysis in the field of regional economics and carbon emissions since the 21st century: a bibliometric analysis. Sustainability 14(18):25. https://doi.org/10.3390/su141811210
33. Chen BL, Chen ZM, Lv SF (2011) A novel magnetic biochar efficiently sorbs organic pollutants and phosphate. Bioresour Technol 102:716–723. https://doi.org/10.1016/j.biortech.2010.08.067
34. Devi P, Saroha AK (2014) Synthesis of the magnetic biochar composites for use as an adsorbent for the removal of pentachlorophenol from the effluent. Bioresour Technol. https://doi.org/10.1016/j.biortech.2014.07.062
35. Abhishek K, Shrivastava A, Vimal V, Gupta AK, Bhujbal SK, Biswas JK, Singh L, Ghosh P, Pandey A, Sharma P, Kumar M (2022) Biochar application for greenhouse gas mitigation, contaminants immobilization and soil fertility enhancement: a state-of-the-art review. Sci Total Environ 853:24. https://doi.org/10.1016/j.scitotenv.2022.158562
36. Gul S, Whalen JK, Thomas BW, Sachdeva V, Deng H (2015) Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions. Agric Ecosyst Environ 206:46–59. https://doi.org/10.1016/j.agee.2015.03.015
37. Wang X, Zhang Y, Zhang J, Fu C, Zhang X (2021) Progress in urban metabolism research and hotspot analysis based on CiteSpace analysis. J Clean Prod 281:125224. https://doi.org/10.1016/j.jclepro.2020.125224
38. Yong C, Jinlong D, Fei G, Bin T, Tao Z, Hao F, Li W, Qinghua Z (2022) Review of landslide susceptibility assessment based on knowledge mapping. Stoch Environ Res Risk Assess 36:2399–2417. https://doi.org/10.1007/s00477-021-02165-z
39. Yang X, Yan S, He J, Dong J (2022) Review and prospects of enterprise human resource management effectiveness: bibliometric analysis based on Chinese-language and english-language journals. Sustainability 14(23):16. https://doi.org/10.3390/su142316112
40. Wu Z, Xue R, Shao M (2022) Knowledge graph analysis and visualization of AI technology applied in COVID-19. Environ Sci Pollut Res 29:26396–26408. https://doi.org/10.1007/s11356-021-17800-z
41. Wei H, Wang M, Ya M, Xu C (2022) The denitrifying anaerobic methane oxidation process and microorganisms in the environments: a review. Front Mar Sci 9:14. https://doi.org/10.1007/10.3389/fmars.2022.1038400
42. Vasconcelos MW, Gonçalves S, Oliveira ECD, Rubert S, Ghisi NDC (2022) Textile effluent toxicity trend: a scientometric review. J Clean Prod 366:132756. https://doi.org/10.1016/j.jclepro.2022.132756
43. Xu Z, Shao T, Dong Z, Li S (2022) Research progress of heavy metals in desert—visual analysis based on CiteSpace. Environ Sci Pollut Res 29:43648–43661. https://doi.org/10.1007/s11356-022-20216-y
44. Yang Y, Qu G, Hua L, Wu L (2022) Knowledge mapping visualization analysis of research on blockchain in management and economics. Sustainability 14(22):24. https://doi.org/10.3390/su142214971
45. Xu J, Li M, Gao Y, Liu M, Shi S, Shi J, Yang K, Zhou Z, Tian J (2022) Using Mendelian randomization as the cornerstone for causal inference in epidemiology. Environ Sci Pollut Res 29:5827–5839. https://doi.org/10.1007/s11356-021-15939-3
46. Yang JJ, Deng YH, Cai YZ, Chen XY, Li DX (2022) Visual analysis on regulation of necroptosis with Chinese medicine based on VOSviewer and CiteSpace knowledge graphs. China J Chin Materia Medica 47:3933–3942. https://doi.org/10.19540/j.cnki.cjcmm.20220428.501
47. Shi X, Zhang J, Lu S, Wang T, Zhang X (2022) China carbon neutralization research status and research frontier tracking. Front Environ Sci 10:13. https://doi.org/10.3389/fenvs.2022.896524

48. Yao L, Hui L, Yang Z, Chen X, Xiao A (2020) Freshwater microplastics pollution: detecting and visualizing emerging trends based on Citespace II. Chemosphere 245:125627. https://doi.org/10.1016/j.chemosphere.2019.125627
49. Qiu Y, Liao K, Zou Y, Huang G (2022) A bibliometric analysis on research regarding residential segregation and health based on CiteSpace. Int J Environ Res Public Health 19(16):21. https://doi.org/10.3390/ijerph191610069
50. Sales VR, Azevedo P, Zucchi MI, Nocelli RCF (2022) A systematic review of research conducted by pioneer groups in ecotoxicological studies with bees in Brazil: advances and perspectives. Environ Sci Pollut Res 29:62711–62732. https://doi.org/10.1007/s11356-022-21609-9
51. Nageshwari K, Balasubramanian P (2022) Evolution of struvite research and the way forward in resource recovery of phosphates through scientometric analysis. J Clean Prod 357:131737. https://doi.org/10.1016/j.jclepro.2022.131737
52. Li T, Cui L, Scotton M, Dong J, Xu Z, Che R, Tang L, Cai S, Wu W, Andreatta D, Wang Y, Song X, Hao Y, Cui X (2022) Characteristics and trends of grassland degradation research. J Soils Sediments 22:1901–1912. https://doi.org/10.1007/s11368-022-03209-9
53. Xiang C, Wang Y, Liu H (2017) A scientometrics review on nonpoint source pollution research. Ecol Eng 99:400–408. https://doi.org/10.1016/j.ecoleng.2016.11.028
54. Li M, Wang Y, Xue H, Wu L, Wang Y, Wang C, Gao X, Li Z, Zhang X, Hasan M, Alruqi M, Bokhari A, Han N (2022) Scientometric analysis and scientific trends on microplastics research. Chemosphere 304:13. https://doi.org/10.1016/j.chemosphere.2022.135337
55. Prochaska C, Gallios G (2021) Nano-adsorbents for cobalt removal from wastewater: a bibliometric analysis of research articles indexed in the Scopus database. Processes 9:1177. https://doi.org/10.3390/pr9071177
56. Ding GY, Wang BY, Chen LY, Zhao SJ (2016) Simultaneous adsorption of methyl red and methylene blue onto biochar and an equilibrium modeling at high concentration. Chemosphere 163:283–289. https://doi.org/10.1016/j.chemosphere.2016.08.037
57. Hodgson E, Lewys-James A, Ravella SR, Thomas-Jones S, Perkins W, Gallagher J (2016) Optimisation of slow-pyrolysis process conditions to maximise char yield and heavy metal adsorption of biochar produced from different feedstocks. Bioresour Technol 214:574–581. https://doi.org/10.1016/j.biortech.2016.05.009
58. Yang Z, Yuan X, Liu C, Nie R, Liu T, Dai X, Ma L, Tang M, Xu Y, Lu H (2022) Meta-analysis and visualization of the literature on early identification of flash floods. Remote Sens 1414:28. https://doi.org/10.3390/rs14143313
59. Azam A, Ahmed A, Kamran MS, Hai L, Zhang Z, Ali A (2021) Knowledge structuring for enhancing mechanical energy harvesting (MEH): an in-depth review from 2000 to 2020 using CiteSpace. Renew Sustain Energy Rev 150:111460. https://doi.org/10.1016/j.rser.2021.111460
60. Yang D, Zhou J, Shi D, Pan Q, Wang D, Chen X, Liu J (2022) Research status, hotspots, and evolutionary trends of global digital education via knowledge graph analysis. Sustainability 14(22):20. https://doi.org/10.3390/su142215157
61. Yi Y, Huang Z, Lu B, Xian J, Tsang EP, Cheng W, Fang J, Fang Z (2020) Magnetic biochar for environmental remediation: a review. Bioresour Technol 298:122468. https://doi.org/10.1016/j.biortech.2019.122468
62. Chandraiah M (2016) Facile synthesis of zero valent iron magnetic biochar composites for Pb(II) removal from the aqueous medium. Alex Eng J. https://doi.org/10.1016/j.aej.2015.12.015
63. Harikishore Kumar Reddy D, Lee S-M (2014) Magnetic biochar composite: facile synthesis, characterization, and application for heavy metal removal. Colloids Surf A Physicochem Eng Asp 454:96–103. https://doi.org/10.1016/j.colsurfa.2014.03.105
64. Chabi N, Baghdadi M, Sani AH, Golzary A, Hosseinzadeh M (2020) Removal of tetracycline with aluminum boride carbide and boehmite particles decorated biochar derived from algae. Bioresour Technol 316:9. https://doi.org/10.1016/j.biortech.2020.123950
65. Chen T, Zhou ZY, Xu S, Wang HT, Lu WJ (2015) Adsorption behavior comparison of trivalent and hexavalent chromium on biochar derived from municipal sludge. Bioresour Technol 190:388–394. https://doi.org/10.1016/j.biortech.2015.04.115
66. Fu D, Kurniawan TA, Li H, Wang LY, Chen Z, Li W, Wang YP, Wang HT, Li QB (2019) Applicability of HDPC-supported Cu nanoparticles composite synthesized from anaerobically digested wheat straw for octocrylene degradation in aqueous solutions. Chem Eng J 355:650–660. https://doi.org/10.1016/j.cej.2018.08.188
67. Chen D, Wang XB, Wang XL, Feng K, Su JC, Dong JN (2020) The mechanism of cadmium sorption by sulphur-modified wheat straw biochar and its application cadmium-contaminated soil. Sci Total Environ 714:8. https://doi.org/10.1016/j.scitotenv.2020.136550
68. Chen XC, Chen GC, Chen LG, Chen YX, Lehmann J, McBride MB, Hay AG (2011) Adsorption of copper and zinc by biochars produced from pyrolysis of hardwood and corn straw in aqueous solution. Bioresour Technol 102:8877–8884. https://doi.org/10.1016/j.biortech.2011.06.078
69. Qi X, Yin H, Zhu MH, Yu XL, Shao PL, Dang Z (2022) MgO-loaded nitrogen and phosphorus self-doped biochar: high-efficient adsorption of aquatic Cu2+, Cd2+, and Pb2+ and its remediation efficiency on heavy metal contaminated soil. Chemosphere 294:11. https://doi.org/10.1016/j.chemosphere.2022.133733
70. Xu QY, Liu TZ, Li L, Liu BY, Wang XD, Zhang SY, Li LL, Wang B, Zimmerman AR, Gao B (2021) Hydrothermal carbonization of distillers grains with clay minerals for enhanced adsorption of phosphate and methylene blue. Bioresour Technol 340:8. https://doi.org/10.1016/j.biortech.2021.125725
71. Zhao CH, Liu L, Yang XN, Liu CX, Wang B, Mao XY, Zhang J, Shi J, Yin WQ, Wang XZ, Wang SS (2022) Pyrolysis temperature and feedstock affected Cr(VI) removal capacity of sulfidated zerovalent iron: Importance of surface area and electrical conductivity. Chemosphere 296:8. https://doi.org/10.1016/j.chemosphere.2022.133927
72. Zhao RH, Wang B, Zhang XY, Lee XQ, Chen M, Feng QW, Chen SW (2022) Insights into Cr(VI) removal mechanism in water by facile one-step pyrolysis prepared coal gangue-biochar composite. Chemosphere 299:10. https://doi.org/10.1016/j.chemosphere.2022.134334
73. Li Y, Abdul-Rashid SH, Raja Ghazilla RA (2022) Design methods for the elderly in Web of Science, Scopus, and China national knowledge infrastructure databases: a scientometric analysis in CiteSpace. Sustainability 14(5):18. https://doi.org/10.3390/su14052545
74. Li J, Sun X, Dai X, Zhang J, Liu B (2022) Knowledge map analysis of industry–university research cooperation policy research based on CNKI and WOS visualization in China. Sustainability 14(13):26. https://doi.org/10.3390/su14137862
75. Wang L, Wang JY, Wang ZX, He C, Lyu W, Yan W, Yang L (2018) Enhanced antimonate (Sb(V)) removal from aqueous solution by La-doped magnetic biochars. Chem Eng J 354:623–632. https://doi.org/10.1016/j.cej.2018.08.074
76. Yin YB, Yang SQ, Jia ZY, Zhang H, Gao Y, Zhang XC, Zhong HJ, Zhou ZQ, Zhang X, Zhou HF (2023) Magnetic biochar based on furfural residue as an excellent candidate for efficient adsorption of Tetracycline, Bisphenol A, Congo red, and Cr6+. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-022-23978-7
77. Dong J, Shen LF, Shan SD, Liu WP, Qi ZF, Liu CH, Gao X (2022) Optimizing magnetic functionalization conditions for efficient preparation of magnetic biochar and adsorption of Pb(II) from aqueous solution. Sci Total Environ 806:12. https://doi.org/10.1016/j.scitotenv.2021.151442
78. Li H, Mahyoub SAA, Liao WJE, Xia SQ, Zhao HC, Guo MY, Ma PS (2017) Effect of pyrolysis temperature on characteristics and aromatic contaminants adsorption behavior of magnetic biochar derived from pyrolysis oil distillation residue. Bioresour Technol 223:20–26. https://doi.org/10.1016/j.biortech.2016.10.033
79. Busygina T, Rykova V (2020) Scientometric analysis and mapping of documentary array on the issue "oil and petroleum products in soil and groundwater." Environ Sci Pollut Res 27:23490–23502. https://doi.org/10.1007/s11356-020-08717-0
80. Ji Z, Pei Y (2019) Bibliographic and visualized analysis of geopolymer research and its application in heavy metal immobilization: a review. J Environ Manag 231:256–267. https://doi.org/10.1016/j.jenvman.2018.10.041
81. Luo J (2022) A bibliometric review on artificial intelligence for smart buildings. Sustainability 14(16):22. https://doi.org/10.3390/su141610230
82. Qu G, Zhang Y, Tan K, Han J, Qu W (2022) Exploring knowledge domain and emerging trends in climate change and environmental audit: a scientometric review. Int J Environ Res Public Health 19(7):22. https://doi.org/10.3390/ijerph19074142

83. Zhang Z, Jin G, Hu Y, He N, Niu J (2022) Performance management of natural resources: a systematic review and conceptual framework for China. Water 14(20):17. https://doi.org/10.3390/w14203338
84. Doumer ME, Arizaga GGC, da Silva DA, Yamamoto CI, Novotny EH, Santos JM, dos Santos LO, Wisniewski A, de Andrade JB, Mangrich AS (2015) Slow pyrolysis of different Brazilian waste biomasses as sources of soil conditioners and energy, and for environmental protection. J Anal Appl Pyrolysis 113:434–443. https://doi.org/10.1016/j.jaap.2015.03.006
85. Sadasivam BY, Reddy KR (2015) Adsorption and transport of methane in landfill cover soil amended with waste-wood biochars. J Environ Manag 158:11–23. https://doi.org/10.1016/j.jenvman.2015.04.032
86. Wang DY, Mukome FND, Yan DH, Wang H, Scow KM, Parikh SJ (2015) Phenylurea herbicide sorption to biochars and agricultural soil. J Environ Sci Health Part B-Pesticides Food Contam Agric Wastes 50(8):544–551. https://doi.org/10.1080/03601234.2015.1028830
87. Guo HQ, Bi CY, Zeng CC, Ma WT, Yan LS, Li KX, Wei K (2018) Camellia oleifera seed shell carbon as an efficient renewable bio-adsorbent for the adsorption removal of hexavalent chromium and methylene blue from aqueous solution. J Mol Liq 249:629–636. https://doi.org/10.1016/j.molliq.2017.11.096
88. Hagemann N, Spokas K, Schmidt HP, Kagi R, Bohler MA, Bucheli TD (2018) Activated carbon, biochar and charcoal: linkages and synergies across pyrogenic carbon's ABCs. Water 10:19. https://doi.org/10.3390/w10020182
89. Salmani MH, Miri M, Ehrampoush MH, Alahabadi A, Hosseini-Bandegharaei A (2017) Comparing cadmium removal efficiency of a magnetized biochar based on orange peel with those of conventional orange peel and unmodified biochar. Desalin Water Treat 82:157–169. https://doi.org/10.5004/dwt.2017.20973
90. Li Y, Wei YN, Huang SQ, Liu XS, Jin ZH, Zhang M, Qu JJ, Jin Y (2018) Biosorption of Cr(VI) onto *Auricularia auricula* dreg biochar modified by cationic surfactant: characteristics and mechanism. J Mol Liq 269:824–832. https://doi.org/10.1016/j.molliq.2018.08.060
91. Xu KN, Lin FY, Dou XM, Zheng M, Tan W, Wang CW (2018) Recovery of ammonium and phosphate from urine as value-added fertilizer using wood waste biochar loaded with magnesium oxides. J Clean Prod 187:205–214. https://doi.org/10.1016/j.jclepro.2018.03.206
92. Zhu ZQ, Huang CP, Zhu YN, Wei WH, Qin H (2018) A hierarchical porous adsorbent of nano-alpha-Fe_2O_3/Fe_3O_4 on bamboo biochar (HPA-Fe/C-B) for the removal of phosphate from water. J Water Process Eng 25:96–104. https://doi.org/10.1016/j.jwpe.2018.05.010
93. Ahmad Z, Gao B, Mosa A, Yu HW, Yin XQ, Bashir A, Ghoveisi H, Wang SS (2018) Removal of Cu(II), Cd(II) and Pb(II) ions from aqueous solutions by biochars derived from potassium-rich biomass. J Clean Prod 180:437–449. https://doi.org/10.1016/j.jclepro.2018.01.133
94. Batool S, Idrees M, Hussain Q, Kong J (2017) Adsorption of copper (II) by using derived-farmyard and poultry manure biochars: efficiency and mechanism. Chem Phys Lett 689:190–198. https://doi.org/10.1016/j.cplett.2017.10.016
95. Qin TT, Wang ZW, Xie XY, Xie CR, Zhu JM, Li Y (2017) A novel biochar derived from cauliflower (*Brassica oleracea* L.) roots could remove norfloxacin and chlortetracycline efficiently. Water Sci Technol 76:3307–3318. https://doi.org/10.2166/wst.2017.494
96. Wang H, Chu YX, Fang CR, Huang F, Song YL, Xue XD (2017) Sorption of tetracycline on biochar derived from rice straw under different temperatures. PLoS ONE 12:14. https://doi.org/10.1371/journal.pone.0182776
97. Zhou N, Chen HG, Xi JT, Yao DH, Zhou Z, Tian Y, Lu XY (2017) Biochars with excellent Pb(II) adsorption property produced from fresh and dehydrated banana peels via hydrothermal carbonization. Bioresour Technol 232:204–210. https://doi.org/10.1016/j.biortech.2017.01.074
98. Wang YY, Lyu HH, Hu YD, Liu YX, He LL, Luo FC, Yang SM (2022) Graphene-biochar composite for effective Congo red dye removal from water. J Environ Eng 148:11. https://doi.org/10.1061/(asce)ee.1943-7870.0002009
99. Yang XD, Wang LL, Shao XQ, Tong J, Chen R, Yang Q, Yang XZ, Li GD, Zimmerman AR, Gao B (2022) Preparation of biosorbent for the removal of organic dyes from aqueous solution via one-step alkaline ball milling of hickory wood. Bioresour Technol 348:7. https://doi.org/10.1016/j.biortech.2022.126831
100. Zeng XY, Wang Y, Li RX, Cao HL, Li YF, Lu J (2022) Impacts of temperatures and phosphoric-acid modification to the physicochemical properties of biochar for excellent sulfadiazine adsorption. Biochar 4:14. https://doi.org/10.1007/s42773-022-00143-4
101. Zhao BW, Zhang JX (2022) Tetracycline degradation by peroxydisulfate activated by waste pulp/paper mill sludge biochars derived at different pyrolysis temperature. Water 14:13. https://doi.org/10.3390/w14101583
102. Flilissa A, Laouameur K, HammoudI N-E, Tamam N, Yadav KK, Achouri B, Alyami AY, Flilissa O, Algethami JS, Abbas M, Jeon B-H, Benboudiaf S, Benguerba Y (2024) Bentonite SDBS-loaded composite for methylene blue removal from wastewater: an experimental and theoretical investigation. Environ Res 241:117544. https://doi.org/10.1016/j.envres.2023.117544
103. Luo L, Wang G, Shi G, Zhang M, Zhang J, He J, Xiao Y, Tian D, Zhang Y, Deng S, Zhou W, Lan T, Deng O (2019) The characterization of biochars derived from rice straw and swine manure, and their potential and risk in N and P removal from water. J Environ Manag 245:1–7. https://doi.org/10.1016/j.jenvman.2019.05.072
104. Liu M, Li R, Wang J, Liu X, Li S, Shen W (2022) Recovery of phosphate from aqueous solution by dewatered dry sludge biochar and its feasibility in fertilizer use. Sci Total Environ 814:152752. https://doi.org/10.1016/j.scitotenv.2021.152752
105. Ahmad M, Rajapaksha AU, Lim JE, Zhang M, Bolan N, Mohan D, Vithanage M, Lee SS, Ok YS (2014) Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99:19–33. https://doi.org/10.1016/j.chemosphere.2013.10.071
106. Guo M, He Z, Uchimiya SM (2016) Introduction to biochar as an agricultural and environmental amendment. Agricultural and environmental applications of biochar: advances and barriers. Soil Science Society of America, Madison, pp 1–14. https://doi.org/10.2136/sssaspecpub63.2014.0034
107. Mao A, He Z, Wan H, Li Q (2017) Preparation, properties, and bonding utilization of pyrolysis bio-oil. Bio-based Wood Adhesives, CRC Press, Boca Raton, p 260–279. https://doi.org/10.1201/9781315369242-11
108. Sharma GK, Jena RK, Hota S, Kumar A, Ray P, Fagodiya RK, Malav LC, Yadav KK, Gupta DK, Khan SA, Ray SK (2020) Recent development in bioremediation of soil pollutants through biochar for environmental sustainability. In: Singh JS, Singh C (eds) Biochar applications in agriculture and environment management. Springer International Publishing, Cham, pp 123–140. https://doi.org/10.1007/978-3-030-40997-5_6
109. Zungu V, Hadebe L, Mpungose P, Hamza I, Amaku J, Gumbi B (2022) Fabrication of biochar materials from biowaste coffee grounds and assessment of its adsorbent efficiency for remediation of water-soluble pharmaceuticals. Sustainability 14:16. https://doi.org/10.3390/su14052931
110. Kumar R, Liu C, Ha G-S, Kim KH, Chakrabortty S, Tripathy SK, Park Y-K, Khan MA, Yadav KK, Cabral-Pinto MMS, Jeon B-H (2023) A novel membrane-integrated sustainable technology for downstream recovery of molybdenum from industrial wastewater. Resour Conserv Recycl 196:107035. https://doi.org/10.1016/j.resconrec.2023.107035
111. Yapicioglu P, Yesilnacar MI (2022) Grey water footprint assessment of groundwater resources in southeastern Turkey: effect of recharge. Water Supply 22:615–627. https://doi.org/10.2166/ws.2021.247
112. Reza AH, Günther B, Taghizadeh TZ (2022) Effectiveness of biochar and zeolite soil amendments in reducing pollution of municipal wastewater from nitrogen and coliforms. Sustainability. https://doi.org/10.3390/su14148880
113. Ghimire U, Gude VG, Magbanua BS (2022) Energy and nutrient recovery from dairy and municipal wastewater sources in a terracotta-biochar bioelectrochemical system. Clean Technol Environ Policy. https://doi.org/10.1007/s10098-022-02361-7
114. Parisa M, Elham GA, Rohollah F, Allah SH, Jalil K (2022) Nitrate removal from agricultural effluent using sugarcane bagasse active nanosorbent. J Appl Water Eng Res. https://doi.org/10.1080/23249676.2021.1982030
115. Hui H, Jiayuan Z, Tian W, Pei W (2022) Adsorption of toxic metal ion in agricultural wastewater by torrefaction biochar from bamboo shoot shell. J Clean Prod. https://doi.org/10.1016/j.jclepro.2022.130558
116. Teixidó M, Charbonnet JA, LeFevre GH, Luthy RG, Sedlak DL (2022) Use of pilot-scale geomedia-amended biofiltration system for removal of polar trace organic and inorganic contaminants from stormwater runoff. Water Res. https://doi.org/10.1016/j.watres.2022.119246

117. Zuo XJ, Xu QQ, Li Y, Zhang KF (2022) Antibiotic resistance genes removals in stormwater bioretention cells with three kinds of environmental conditions. J Hazard Mater 429:9. https://doi.org/10.1016/j.jhazmat.2022.128336
118. Qiu B, Tao X, Wang H, Li W, Ding X, Chu H (2021) Biochar as a low-cost adsorbent for aqueous heavy metal removal: a review. J Anal Appl Pyrolysis 155:105081. https://doi.org/10.1016/j.jaap.2021.105081
119. Zulfiqar M, Rabat NE, Bahadar A, Lashari N, Mahnashi MH, Alqarni AO (2022) Development of *Elaeis guineensis*/polyvinyl alcohol/carbon nanotube composites for efficient adsorption of dye: experimental and theoretical approach. Int J Environ Sci Technol 19:6499–6520. https://doi.org/10.1007/s13762-021-03520-x
120. Zhang J, Shao J, Jin Q, Li Z, Zhang X, Chen Y, Zhang S, Chen H (2019) Sludge-based biochar activation to enhance Pb(II) adsorption. Fuel 252:101–108. https://doi.org/10.1016/j.fuel.2019.04.096
121. Rouibah K, Ferkous H, Delimi A, Himeur T, Benamira M, Zighed M, Darwish AS, Lemaoui T, Yadav KK, Bhutto JK, Ahmad A, Chaiprapat S, Benguerba Y (2023) Biosorption of zinc (II) from synthetic wastewater by using Inula Viscosa leaves as a low-cost biosorbent: experimental and molecular modeling studies. J Environ Manag 326:116742. https://doi.org/10.1016/j.jenvman.2022.116742
122. Zhu ZQ, Wu YQ, Hu CZ, Zhang LH, Ding H, Zhu YN, Fan YM, Deng H, Zhou XB, Tang S (2022) Elimination of zinc ions from aqueous solution by a hydroxylapatite-biochar composite material with the hierarchical porous microstructures of sugarcane waste. J Clean Prod 362:15. https://doi.org/10.1016/j.jclepro.2022.132483
123. Yilmaz C, Guzel F (2022) Performance of wild plants-derived biochar in the remediation of water contaminated with lead: sorption optimization, kinetics, equilibrium, thermodynamics and reusability studies. Int J Phytoremediat 24:177–186. https://doi.org/10.1080/15226514.2021.1931025
124. Yi Y, Wang XY, Zhang YX, Ma J, Ning P (2022) Adsorption properties and mechanism of Cr(VI) by Fe-2(SO_4)(3) modified biochar derived from *Egeria najas*. Colloid Surf A-Physicochem Eng Asp 645:13. https://doi.org/10.1016/j.colsurfa.2022.128938
125. Goala M, Yadav KK, Alam J, Adelodun B, Choi KS, Cabral-Pinto MMS, Hamid AA, Alhoshan M, Ali FAA, Shukla AK (2021) Phytoremediation of dairy wastewater using *Azolla pinnata*: application of image processing technique for leaflet growth simulation. J Water Process Eng 42:102152. https://doi.org/10.1016/j.jwpe.2021.102152
126. Gizaw A, Zewge F, Kumar A, Mekonnen A, Tesfaye M (2021) A comprehensive review on nitrate and phosphate removal and recovery from aqueous solutions by adsorption. J Water Supply Resour Technol-Aqua. https://doi.org/10.2166/aqua.2021.146
127. Zubair M, Manzar MS, Suleiman MA, Fernandes DP, Meili L, Essa WA, Al-Adam H, AlGhamdi JM, Mu'azu ND, Haladu SA, Khan G (2022) Production of magnetic biochar-steel dust composites for enhanced phosphate adsorption. J Water Process Eng 47:11. https://doi.org/10.1016/j.jwpe.2022.102793
128. Zeng Z, Zhang SD, Li TQ, Zhao FL, He ZL, Zhao HP, Yang XE, Wang HL, Zhao J, Rafiq MT (2013) Sorption of ammonium and phosphate from aqueous solution by biochar derived from phytoremediation plants. J Zhejiang Univ Sci B 14:1152–1161. https://doi.org/10.1631/jzus.B1300102
129. Karunanithi R, Ok YS, Dharmarajan R, Ahmad M, Seshadri B, Bolan N, Naidu R (2017) Sorption, kinetics and thermodynamics of phosphate sorption onto soybean stover derived biochar. Environ Technol Innov 8:113–125. https://doi.org/10.1016/j.eti.2017.06.002
130. Krishna Veni D, Kannan P, Jebakumar Immanuel Edison TN, Senthilkumar A (2017) Biochar from green waste for phosphate removal with subsequent disposal. Waste Manag 68:752–759. https://doi.org/10.1016/j.wasman.2017.06.032
131. Kamyab H, Chelliapan S, Hayder G, Yusuf M, Taheri MM, Rezania S, Hasan M, Yadav KK, Khorami M, Farajnezhad M, Nouri J (2023) Exploring the potential of metal and metal oxide nanomaterials for sustainable water and wastewater treatment: a review of their antimicrobial properties. Chemosphere 335:139103. https://doi.org/10.1016/j.chemosphere.2023.139103
132. Park J-H, Wang JJ, Xiao R, Zhou B, Delaune RD, Seo D-C (2018) Effect of pyrolysis temperature on phosphate adsorption characteristics and mechanisms of crawfish char. J Colloid Interface Sci 525:143–151. https://doi.org/10.1016/j.jcis.2018.04.078
133. Utami M, Wang S, Musawwa MM, Purbaningtias TE, Fitri M, Yuspita I, Abd-Elkader OH, Yadav KK, Munusamy-Ramanujam G, Bang D, Chang SW, Ravindran B (2023) Simultaneous photocatalytic removal of organic dye and heavy metal from textile wastewater over N-doped TiO_2 on reduced graphene oxide. Chemosphere 332:138882. https://doi.org/10.1016/j.chemosphere.2023.138882
134. Gao Y, Zhang J, Chen C, Du Y, Teng G, Wu Z (2021) Functional biochar fabricated from waste red mud and corn straw in China for acidic dye wastewater treatment. J Clean Prod 320:128887. https://doi.org/10.1016/j.jclepro.2021.128887
135. Rajarathinam N, Arunachalam T, Raja S, Selvasembian R (2020) Fenalan Yellow G adsorption using surface-functionalized green nanoceria: an insight into mechanism and statistical modelling. Environ Res 181:108920. https://doi.org/10.1016/j.envres.2019.108920
136. Georgin J, Franco DSP, Grassi P, Tonato D, Piccilli DGA, Meili L, Dotto GL (2019) Potential of *Cedrella fissilis* bark as an adsorbent for the removal of red 97 dye from aqueous effluents. Environ Sci Pollut Res 26:19207–19219. https://doi.org/10.1007/s11356-019-05321-9
137. Wathukarage A, Herath I, Iqbal MCM, Vithanage M (2019) Mechanistic understanding of crystal violet dye sorption by woody biochar: implications for wastewater treatment. Environ Geochem Health 41:1647–1661. https://doi.org/10.1007/s10653-017-0013-8
138. Ma J, Zhou B, Zhang H, Zhang W, Wang Z (2019) Activated municipal wasted sludge biochar supported by nanoscale Fe/Cu composites for tetracycline removal from water. Chem Eng Res Des 149:209–219. https://doi.org/10.1016/j.cherd.2019.07.013
139. Zhou YR, Li ZL, Ji LL, Wang Z, Cai L, Guo J, Song WD, Wang YN, Piotrowski AM (2022) Facile preparation of alveolate biochar derived from seaweed biomass with potential removal performance for cationic dye. J Mol Liq 353:11. https://doi.org/10.1016/j.molliq.2022.118623
140. Yavari S, Asadpour R, Kamyab H, Yavari S, Kutty SRM, Baloo L, Abd Manan TSB, Chelliapan S, Sidik AB (2022) Efficiency of carbon sorbents in mitigating polar herbicides leaching from tropical soil. Clean Technol Environ Policy 24:251–260. https://doi.org/10.1007/s10098-021-02113-z
141. Hevira L, Zilfa R, Ighalo JO, Aziz H, Zein R (2021) *Terminalia catappa* shell as low-cost biosorbent for the removal of methylene blue from aqueous solutions. J Ind Eng Chem 97:188–199. https://doi.org/10.1016/j.jiec.2021.01.028
142. Yang Q, Wu P, Liu J, Rehman S, Ahmed Z, Ruan B, Zhu N (2020) Batch interaction of emerging tetracycline contaminant with novel phosphoric acid activated corn straw porous carbon: adsorption rate and nature of mechanism. Environ Res 181:108899. https://doi.org/10.1016/j.envres.2019.108899
143. Yao ZW, Shao PH, Fang DF, Shao JC, Li DW, Liu LL, Huang Y, Yu Z, Yang LM, Yu K, Luo XB (2022) Thiol-rich, porous carbon for the efficient capture of silver: understanding the relationship between the surface groups and transformation pathways of silver. Chem Eng J 427:9. https://doi.org/10.1016/j.cej.2021.131470
144. Yan SW, Yu W, Yang T, Li Q, Guo JH (2022) The adsorption of corn stalk biochar for Pb and Cd: preparation, characterization, and batch adsorption study. Separations 9:13. https://doi.org/10.3390/separations9020022
145. Xiong JQ, Liang LP, Shi WP, Li Z, Zhang ZN, Li XQ, Liu YZ (2022) Application of biochar in modification of fillers in bioretention cells: a review. Ecol Eng 181:10. https://doi.org/10.1016/j.ecoleng.2022.106689
146. Utami M, Wang S, Musawwa MM, Mafruhah L, Fitri M, Wijaya K, Johnravindar D, Abd-Elkader OH, Yadav KK, Ravindran B, Chung WJ, Chang SW, Munusamy-Ramanujam G (2023) Photocatalytic degradation of naphthol blue from Batik wastewater using functionalized TiO_2-based composites. Chemosphere 337:139224. https://doi.org/10.1016/j.chemosphere.2023.139224

Publisher's Note