

REVIEW

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Applications of biochar in medical and related environmental fields: current status and future perspectives

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Abstract

Biochar (BC) is a stable, carbon-rich material produced through biomass pyrolysis in an oxygen-restricted environment. In recent years, BC has gained recognition as an environmentally friendly material and has been extensively researched for its various applications related to human health. However, the medical applications of biochar remain relatively unexplored. This review aims to analyze recent publications from PubMed, focusing on the direct association between biochar and medical science over the past 3 years. The analysis identified five main subjects: contaminant immobilization, medical waste treatment and nutrient recovery, biochar toxicity, electrical sensors and biosensors, and drug delivery. Among these subjects, drug delivery and biosensors demonstrated the most direct relevance to the medical field. To enhance the validity of our findings, a bibliometric analysis was performed using the Web of Science Core Collection to visualize the trends in medical applications of biochar over time. The results further support our analysis. Finally, potential directions for future medical applications of biochar were discussed. This review underscores the necessity for further research on the medical applications of biochar. By exploring its potential in drug delivery, biosensors, and other domains, biochar has the potential to revolutionize medicine.

Highlights

- Current state of biochar research in medicine was categorized into five subjects.
- The utilization of biochar as nanocarriers for medication delivery is a potential research area.
- This study demonstrated the huge potential of biochar for delivering drugs.

Keywords Biochar-medicine, Drug delivery, Nanoparticles, Contaminant immobilization, Bibliometric analysis

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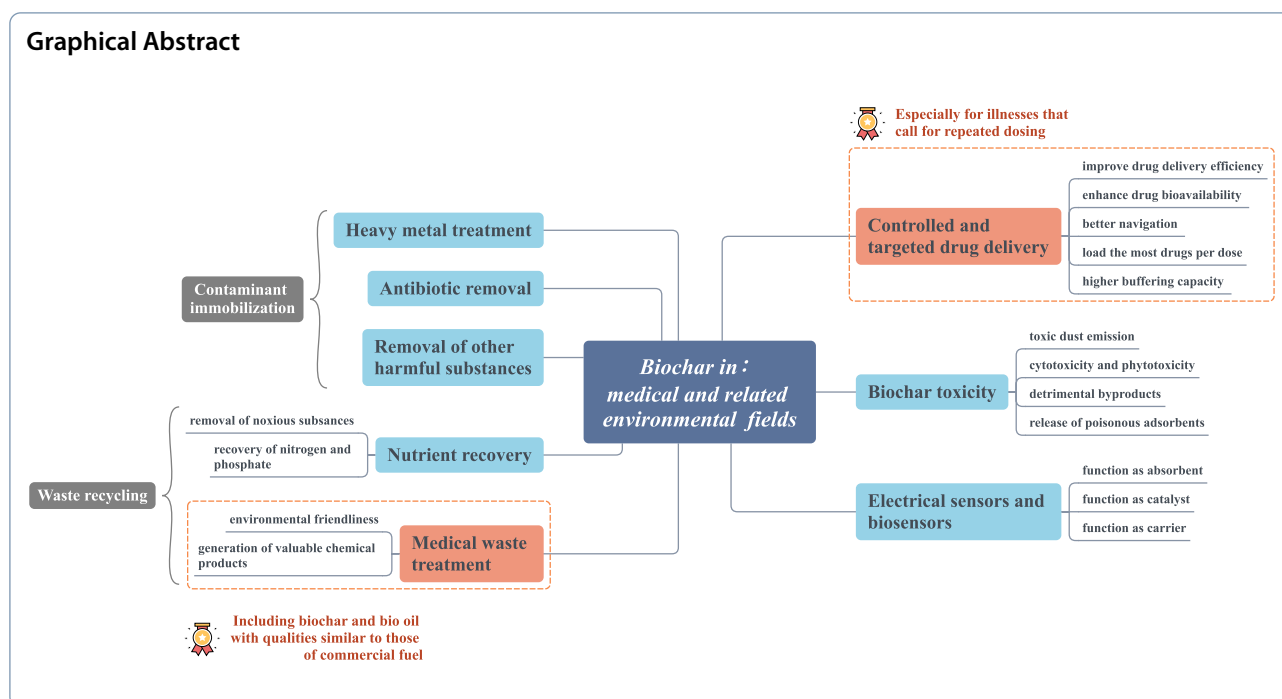
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Graphical Abstract



1 Introduction

Biochar is a carbon-rich and porous material generated through pyrolysis at temperatures ranging from 300 to 900 °C under oxygen-deficient conditions (Liang et al. 2021). It exhibits stability, environmental friendliness, and a straightforward production process, utilizing various feedstock sources such as plant biomass, agricultural residues (e.g., wheat straw, rice husk, and corn), aquatic waste biomass, industrial waste, and animal manure (Patel et al. 2022). The exceptional adsorption capability of biochar is attributed to its extensive surface area and abundant active sites. Furthermore, biochar acts as a catalyst in diverse reactions through the generation of persistent free radicals (PFRs). Its porous structure and large surface area enable the loading of a broad range of functional chemicals, making it an ideal carrier in numerous applications (Shao et al. 2022). Additionally, biochar exhibits ease of modification in terms of species composition, roughness, porosity, functional groups, and specific surface area (Liu et al. 2022a, b), thereby imparting enhanced properties. Modification techniques encompass physical methods for optimizing physical properties such as size and density, chemical activation involving acid, metal-salt, and alkaline modifications, and biological engineering approaches such as microorganism colonization and doping with other materials (Patel et al. 2022). Doping biochar with metals, such as iron and zinc, represents a viable option to enhance its adsorptive capacity, considering the relatively low capacity of raw biochar (Patel et al. 2022).

Biochar's exceptional characteristics have led to its widespread utilization in various fields over the past decade. Researchers have primarily focused on its application in agricultural production, environmental pollution remediation, and climate change adaptation. These applications include nutrient recovery (Xu et al. 2019), wastewater treatment (Liu et al. 2022a, b), contaminant immobilization (Li et al. 2021), soil amendment strategies (Sashidhar et al. 2020), and carbon sequestration in soil (Xiao et al. 2018), all of which have direct or indirect implications for human health. For instance, heavy metal contamination in water has emerged as a significant threat to human health, causing damage to liver, lungs, and stomach functions (Nguyen and Trinh 2020; Ke et al. 2021). The highly absorbent nature of biochar enables effective removal of heavy metals from wastewater (Inyang et al. 2016), as well as other toxic substances such as triclosan (TCS) (Ma et al. 2022), potentially toxic elements (PTEs) (Muhammad et al. 2020), and antibiotics in contaminated soil (Qiao et al. 2018; Patel et al. 2019). However, there are several potential side effects of biochar. It may emit toxic dust and impair the respiratory systems. The process of pollutants adsorption by biochar could also result in possible health damage as well.

From the above, it is clear that biochar and human health have a complicated relationship and there is a lack of thorough and methodical reviews in this field. Additionally, the use of biochar in biology has attracted increasing attention in recent years. In PubMed, a renowned database in medicine and the life sciences, the

number of annual reports on biochar has surged from 3 in 2013 to 2507 in 2022 (Fig. 1, refer to Online Resource 1 for detailed data 1). To learn more about the potential uses and limitations of biochar, we decided to review the utilization of biochar from a brand-new perspective: the employment of biochar in the medical field. It is not just about clarifying the relationship between biochar and human health, but also about expanding the application possibilities and practicality of biochar. To do this, we searched PubMed for the studies revealing a direct connection between medicine and biochar over the past 3 years. Through careful literature review and summarization, five directions of current biochar application in the medical field were clarified and elaborated: *contaminant immobilization, medical waste treatment and nutrient recovery, biochar toxicity, electrical sensors and biosensors, and drug delivery*. According to Fig. 1, it is evident that the number of studies focusing on biochar in the field of life sciences has experienced significant growth in recent years, with a continuing upward trend. Among these studies, the treatment of harmful pollutants has emerged as the most extensively researched area, with a particular emphasis on the absorption of heavy metals and antibiotics. This dominance of pollutant treatment underscores the relevance of biochar in environmental remediation. Based on the data from the past 3 years

(2019–2022), there is a gradual increase in the proportion of studies investigating the removal of other harmful substances using biochar. This includes the treatment of drugs, endocrine pollutants, viruses, and other agents, indicating a growing connection between biochar and medical applications. In addition to pollutant control, there has been a consistent rise in the literature exploring the utilization of biochar in biosensors, thereby directly showcasing its relevance in medical detection technologies. These developments not only shed light on the future trajectory of biochar but also suggest the importance of our review.

Apparently, drug delivery and biosensors most directly reflect the employment of biochar in the medical field. Considering the obvious advantages of biochar in drug delivery, we concentrated on the former that we also discussed in detail. And for the first time we have made a comprehensive comparison between biochar and conventional drug carriers in the medical field. To make our results more credible, we searched through the Web of Science Core Collection, focusing on the subjects of “biochar” and “medicine” from 2013 to 2023 and performed bibliometric analysis on the keywords from the search results (Table 2, Fig. 3a-b). Finally promising directions of biochar utilization in the medical area were also discussed at the end of this review.

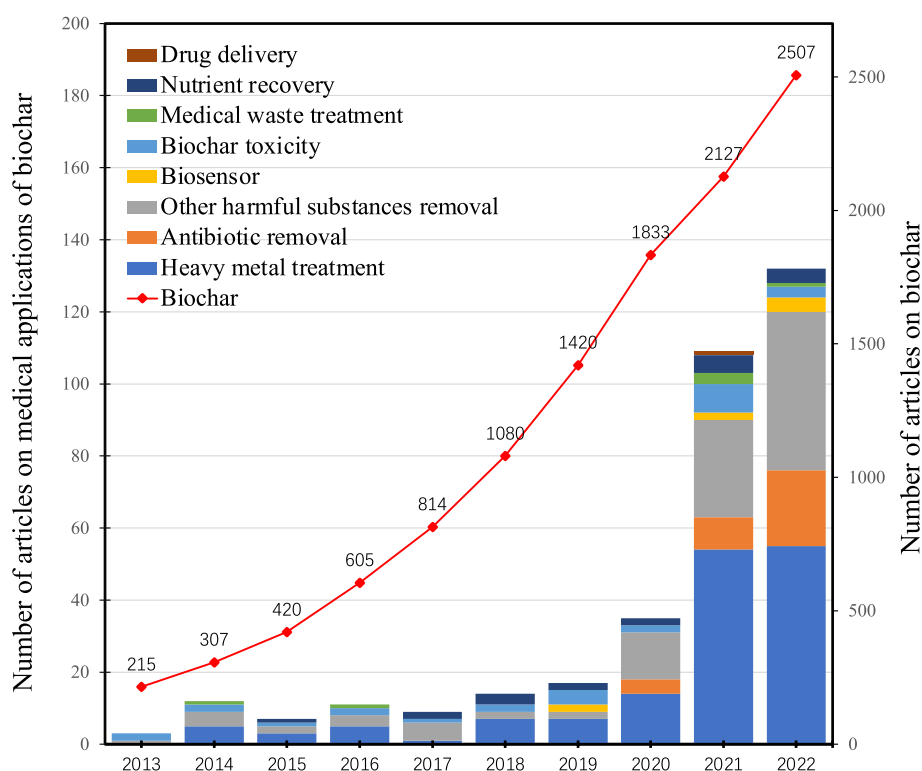


Fig. 1 The numbers of articles on biochar and its medical and related environmental applications in PubMed from 2013 to 2022

2 Literature review approach

In general, there are very few articles that directly discuss the medical applications of biochar. In 2019–2021, a total of 280 articles associated with biochar were found in PubMed. We limited the “species” in PubMed filters to “humans” and performed a manual screening. The inclusion criteria were 1) demonstrating a direct effect on the human body, 2) associated with human excrement, and 3) related to direct application in medicine as a specific material. Finally, a total of 78 papers were obtained and generalized into five categories: 1) *contaminant immobilization* section mainly discussed employing biochar for the remediation of chemicals that are noxious to human body; 2) *medical waste treatment and nutrient recovery* talked about medical waste treatment as well as nitrogen and phosphorus recycling from human excreta;

Table 1 Literature reflecting a direct relationship between biochar and medical science in the last 3 years from PubMed

Medical application	Number	Percentage
Heavy metal treatment	33	42.31%
Antibiotic removal	28	35.90%
Other harmful substances removal	6	7.69%
Biosensor	4	5.13%
Biochar toxicity	4	5.13%
Medical waste treatment	3	3.85%
Nutrient recovery	2	2.56%
Drug delivery	1	1.28%

3) *biochar toxicity* accentuated possible health risks to human body posed by biochar itself; 4) *electrical sensors and biosensors* analyzed biochar utilization technology for medical testing; 5) *drug delivery* section presented the application of biochar as nanocarriers for drugs in the course of disease treatment (Table 1, Figs. 1 and 2, Online Resource 2). Therefore, a thorough overview of the medical employment of biochar was provided and we will next go into more detail on these topics.

By looking at the keywords, we summarized the study topics in a given field and investigated the hotspots and future paths for research. Based on the search terms (subject) “medicine” and “biochar” from 2013 to 2023, 693 papers were retrieved from the Web of Science Core Collection database. The collected data were examined using the keyword co-emergence tool incorporated into VOSviewer, plotted in “Network Visualization”, “Overlay Visualization (year)”, and “Density Visualization”. Each circle represents a different keyword and the size of the circle indicates how often a pair of keywords appears together in a publication.

A total of 3772 keywords were retrieved from the 693 published entries and five clusters were constructed from the network map of the top 100 most frequent keywords (Fig. 3a), which mirrored the fundamental knowledge framework of the relevant study areas. As shown in Fig. 3a, five distinct study trajectories could be discerned, represented by clusters of blue, green, red, purple, and yellow. The red cluster is dominated by keywords like soil, heavy-metals, toxicity, and pyrolysis temperature. It represents solid waste treatment using

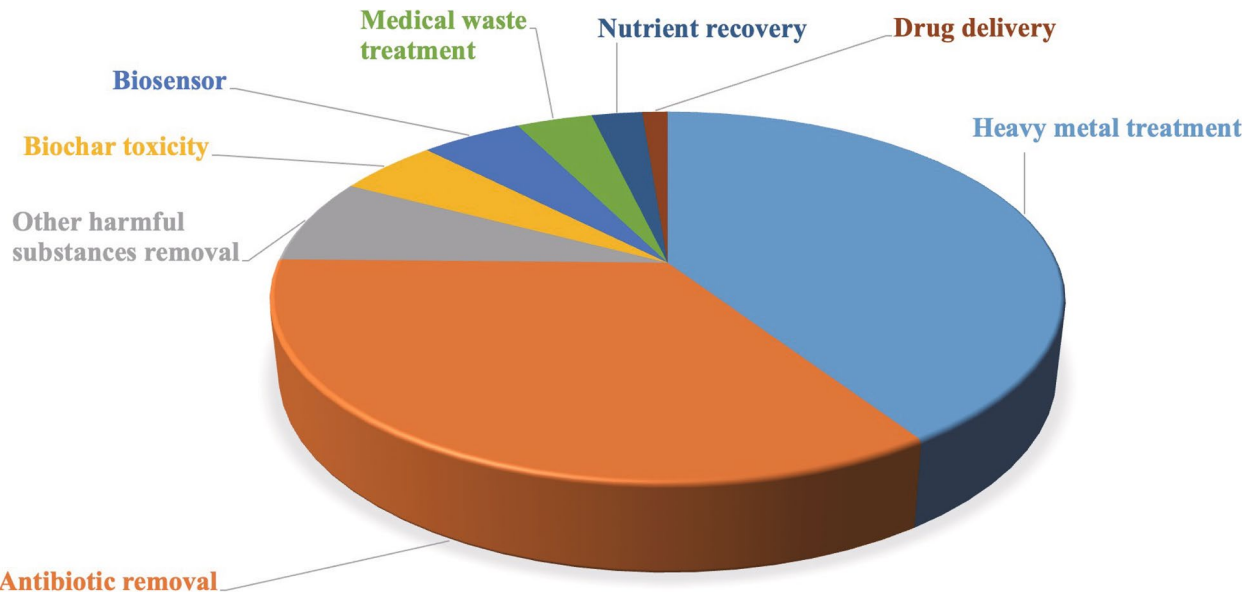


Fig. 2 Overview of biochar’s medical and related environmental applications from PubMed over the previous 3 years

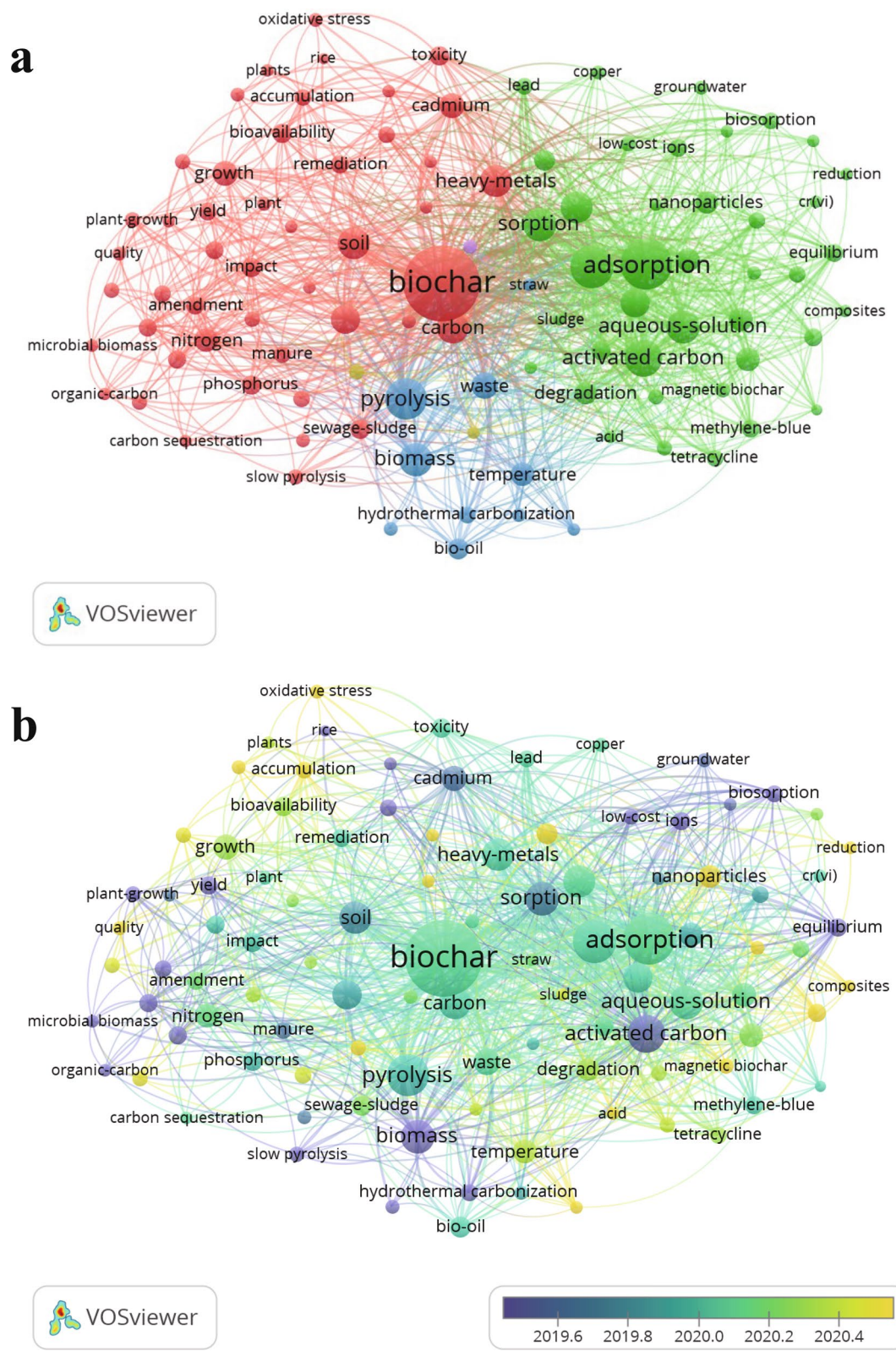


Fig. 3 Distribution of 100 frequency keywords through bibliometric analysis of keywords. **a** A network diagram of the most related keywords (TOP100). **b** Dynamics and historical patterns of the frequency of keywords (2019 to 2021)

biochar in the medical field, such as soil remediation and solid waste toxicity (include biochar itself), which is consistent with the categories of *other harmful substance removal*, *heavy metal treatment*, and *biochar toxicity*. The keywords of green cluster include adsorption, aqueous-solution, biosorption, and nanoparticles, and it was considered as the direction of aqueous-waste management related to medicine. It is also consistent with the summarized topics of *biosensor*, *heavy metal treatment*, *antibiotic removal*, and *drug delivery*. The blue cluster mainly includes pyrolysis, waste, biomass and bio-oil, showing the point for bioenergy production of wastes in line with our summarized topic of *medical waste treatment*. The weights of the remaining two clusters are considerably smaller compared to the three clusters mentioned earlier. The yellow cluster consists of keywords such as phosphate and ammonium, which align with the summarized category of *nutrient recovery*. These keywords highlight the utilization of biochar in the context of waste recycling. The purple cluster, comprising the keyword “biodegradation”, is the sole keyword within the top 100 frequency keywords. This keyword, however, corresponds to the primary research hotspot of biochar in recent years (Wu et al. 2021b). The top 30 keywords are listed in Table 2 along with their frequencies and overall link strengths. Keywords of higher frequencies suggest that waste treatment applications are the main area of research interest, including “adsorption”, “removal”, “soil”, and “waste-water”, which mostly cover the topics of soil remediation and aqueous-waste management. The bioavailability applications, however, continue to be prominent and exhibit a significant total link strength among these 30 keywords (e.g., nanoparticles and activated carbon). Figure 3b displays the keyword overlay visualization for the previous 3 years (2019–2021). The color-coded legend represents the average year in which each keyword appeared. From the overlay visualization, keywords (like nanoparticles, composites, and oxidative stress) related to biological employment of biochar have now become a thriving area for research. This precisely echoes the promising directions (*drug delivery* and *medical waste treatment*) of future medical applications of biochar, which will be proposed after this detailed review.

3 Contaminant immobilization

Biochar has gained significant attention as a promising material for the immobilization of contaminants, primarily due to its abundant active sites, porous structure, and large specific surface area (Shao et al. 2022). Its exceptional adsorption capabilities make it an ideal absorbent for a wide range of organic and inorganic pollutants, resulting in extensive research in recent years. In this chapter, the objective is to comprehensively

Table 2 Top 30 keywords related to employment of biochar in medical field

Rank	Keyword	Occurrences	Total link strength
1	Biochar	382	1676
2	Adsorption	180	969
3	Removal	121	673
4	Pyrolysis	114	528
5	Activated carbon	95	502
6	Sorption	77	485
7	Biomass	75	358
8	Aqueous-solution	73	434
9	Water	72	388
10	Carbon	69	325
11	Soil	69	355
12	Heavy-metals	67	375
13	Waste-water	58	328
14	Pyrolysis temperature	56	318
15	Waste	47	254
16	Cadmium	44	310
17	Growth	43	175
18	Nitrogen	40	188
19	Aqueous-solutions	39	249
20	Kinetics	39	219
21	Temperature	38	191
22	Performance	37	182
23	Degradation	36	160
24	Nanoparticles	35	143
25	Bio-oil	30	123
26	Mechanisms	30	181
27	Impact	28	141
28	Sewage-sludge	28	153
29	Toxicity	28	136
30	Bioavailability	26	123

discuss the immobilization of heavy metals, antibiotics, and other harmful substances that have direct implications for human health. This section will delve into their detrimental effects, conventional management strategies, the advantages associated with the application of biochar, and the intricate interactions between biochar and these pollutants. To enhance clarity and coherence in presenting the subject matter, a formal, logical, and academically rigorous writing style will be applied throughout this chapter. Furthermore, a well-crafted figure (Fig. 4) is also presented to visually depict the interactions between biochar and the targeted pollutants, which aims to facilitate better comprehension and interpretation of the discussed phenomena.

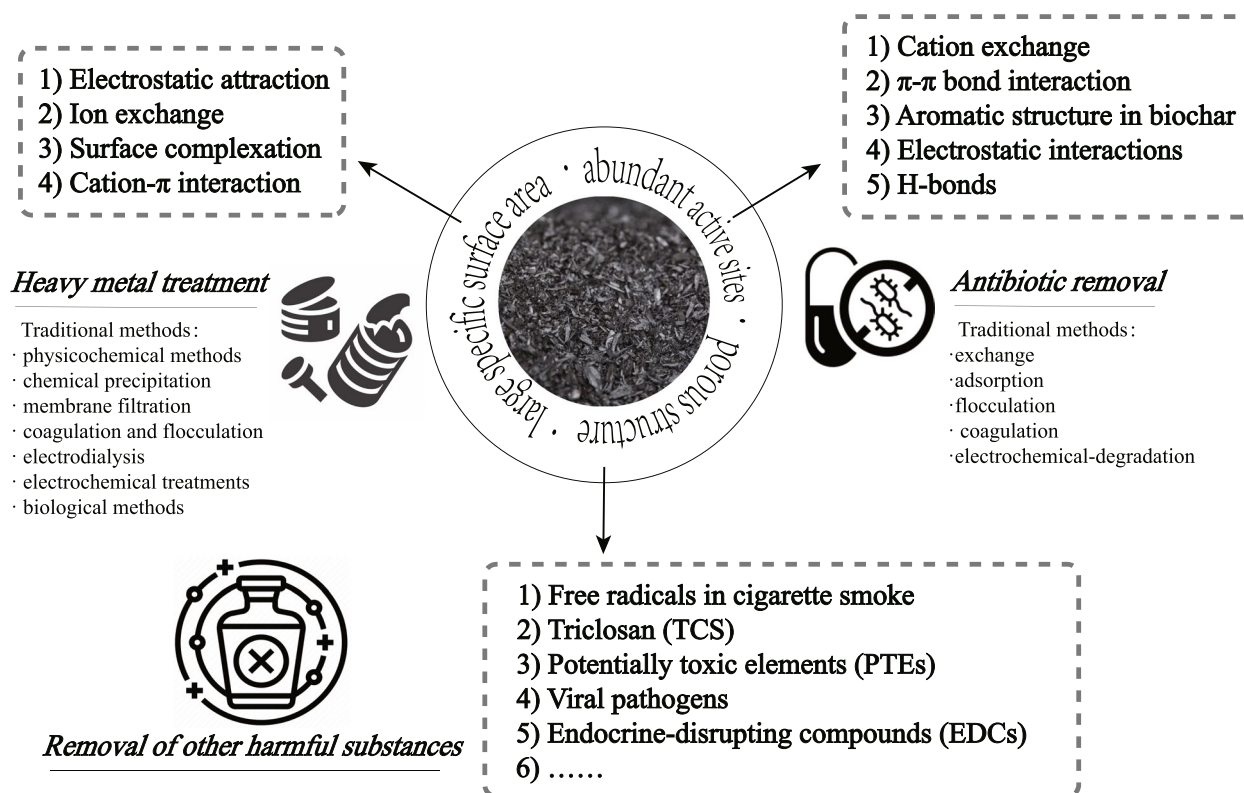


Fig. 4 Medical applications of biochar in contaminant immobilization

3.1 Heavy metal treatment

Heavy metals (HMs) are notorious for being highly poisonous, carcinogenic, and causing organ deposition, all of which have a negative influence on human body (Liu et al. 2022a). According to previous reports, water contaminated with heavy metals, including arsenic, iron, and cadmium has become the most important pollutant posing dangers to human health (e.g., liver, lungs, and stomach) (Nguyen and Trinh 2020; Ke et al. 2021). As demonstrated in a 2014 report from the Chinese Ministry of Ecology and Environment, nickel (Ni), mercury (Hg), cadmium (Cd), arsenic (As), lead (Pb), copper (Cu), chromium (Cr), and zinc (Zn) are the principal HMs found in Chinese soil (Gong et al. 2022). The US Agency for Toxic Substance and Disease Registry (ATSDR) also listed As, Pb, Cd, and Hg as the top 4 heavy metals that require immobilization, followed by Ni, Cr, Cu, and Zn (Gong et al. 2022). Heavy metals are mostly produced by industry, human activity, and natural calamities. These heavy metals are left behind in the soil and water supplies, eventually building up in the food intended for human consumption (Liu et al. 2022a).

Traditional methods for the removal of heavy metals (HMs) encompass a range of approaches, including membrane filtration, physicochemical methods, coagulation

and flocculation, chemical precipitation, electrodialysis, biological methods, and electrochemical treatments (Ke et al. 2021). Extensive evaluations have been conducted to assess the advantages and disadvantages of several soil heavy metal treatment techniques (Gong et al. 2022). However, these methods often face challenges related to technical limitations, theoretical deficiencies, and high costs, impeding their widespread implementation (Wu et al. 2021a). In addressing these concerns, Li et al. (2020) and Xiao et al. (2019) have proposed chemical immobilization as a feasible, cost-effective, and ecologically sustainable approach for neutralizing HMs. Chemical immobilization acts by reducing the biological reactivity and mobility of HMs through mechanisms such as precipitation, adsorption, complexation, and ion exchange (Fan et al. 2020; Khan et al. 2020). Moreover, extensive research has been conducted on various amendments that exhibit efficacy in immobilizing HMs, including different minerals, fly ash, green waste, lime, compost, and red mud (Xiao et al. 2019; Gong et al. 2022).

The specific surface area (SSA) of biochar, in combination with its inorganic mineral species and diverse functional groups, including amide, carbonyl, alkyne, sulfonyl, ether, hydroxyl, carboxyl, and siloxane (Lian and Xing 2017; Liu et al. 2022a), bestows it with a remarkable

capacity to adsorb and immobilize heavy metals (HMs) (Liu et al. 2019). The manufacturing process of biochar is straightforward, and it can be derived from a wide range of feedstock sources, rendering it a reliable and environmentally benign material. Moreover, biochar exhibits favorable modifiability, enabling the incorporation of chemical modifiers to augment its efficacy in remediation, a practice that is gaining increasing attention in recent studies (Liu et al. 2022a). Extensive research has substantiated the profound ability of biochar to effectively sequester significant amounts of heavy metals from water and waste streams by virtue of its robust adsorption capabilities (Inyang et al. 2016). Notably, the adsorption characteristics of biochar have been reported to be comparable to those of activated carbon, a commonly employed adsorbent (Liang et al. 2022). On the other hand, it was discovered that biochar had a lower potential impact on global warming and energy demand than the latter (Alhashimi and Aktas 2017). Statistics showed that the average greenhouse gas emissions and average energy demands of biochar were $-0.9 \text{ kg CO}_2 \text{ eq/kg}$ and 6.1 MJ/kg , respectively, and were $6.6 \text{ kg CO}_2 \text{ eq/kg}$ and 97 MJ/kg , respectively, for activated carbon (Alhashimi and Aktas 2017). Economic performance analysis showed that the average costs by biochar and activated carbon were $\$5/\text{kg}$ and $\$5.6/\text{kg}$, respectively (Alhashimi and Aktas 2017). It is obvious that if designed properly biochar could be at least equally efficient as activated carbon while less expensive (Alhashimi and Aktas 2017). In light of this, numerous studies have investigated the use of biochar in heavy metal absorption. And the mechanism of biochar for eliminating HMs can be summarized as ion exchange, electrostatic attraction, surface complexation, cation- π interaction, and coprecipitation (Pan et al. 2021; Qiu et al. 2022). Biochar possesses an inherent cation exchange capability (CEC) due to the presence of active cations on its surface, which can undergo exchange with metal cations. This property enables biochar to facilitate the absorption of heavy metals through ion exchange mechanisms. Additionally, biochar contains functional groups such as carboxyl groups ($-\text{COOH}$) that possess ion exchange abilities. These functional groups on the biochar surface can also form surface complexes with heavy metals, leading to their adsorption. Furthermore, the carboxylic groups can engage in cation- π interactions, which further contribute to the adsorption of heavy metals. The mineral components present on the surface of biochar can also combine with heavy metals to form insoluble compounds, a process referred to as coprecipitation. Research has demonstrated that biochar exhibits high electronegativity, which is associated with the presence of negatively charged functional groups on its surface. As a result, the negatively charged biochar can

electrostatically attract positively charged metal cations, thereby facilitating their absorption (He et al. 2019).

3.2 Antibiotic removal

In addition to heavy metals, biochar has demonstrated the potential to absorb organic substances, including residual antibiotics, which are closely related to human health and the environment. Antibiotics have been widely used as effective antimicrobial agents in the treatment of various infectious diseases for an extended period. However, overuse of antibiotics has resulted in significant environmental pollution in recent years, leading to the emergence of multi-drug resistant bacteria that pose a threat to human health and disrupt the ecological balance. According to the Chinese Academy of Sciences' 2015 publication, "Antibiotic Pollution Map of Rivers in China", the norfloxacin (NOR) concentration in the Pearl River (Guangdong province) was even higher than 1000 ng/L , while the average antibiotic concentration in China's major rivers was approximately 303 ng/L (Zhang et al. 2015; Liang et al. 2022). Besides contaminating soil and water supply, genes that are resistant to antibiotics are also produced when antibiotics are left in the environment, which are widely distributed in food chain and damage the ecosystem (Qiao et al. 2018; Patel et al. 2019). Apart from drug-resistant issues, antibiotic leftovers in the environment may also cause direct health problems including impaired immunity, noxious damage, and allergic reactions (Fang et al. 2021; Liang et al. 2022). Therefore, it is of utmost importance to address these issues by properly handling residual antibiotics as soon as possible.

Currently, several strategies are employed to address the issue of antibiotic pollution, including ion exchange, adsorption, flocculation, coagulation, electrochemical degradation, ozonation, and membrane filtration (Du et al. 2021; Langbehn et al. 2021; Wu and Hu 2021). Among these approaches, the adsorption method presents numerous advantages, such as simplicity of operation, low energy consumption, high removal efficiency, and environmental friendliness (Liang et al. 2022). However, similar to other techniques, conventional adsorbents suffer from drawbacks in terms of sustainability and cost-effectiveness. In response to growing environmental concerns, bioremediation or biodegradation has emerged as a promising method for the elimination of such organic pollutants (Patel et al. 2022).

Considering the aforementioned concerns regarding antibiotic pollution, biochar has garnered significant attention as a promising candidate for remediation due to its remarkable adsorption capacity, long-term stability, and environmentally friendly characteristics. In recent years, substantial advancements have been made in the application of biochar to alleviate the direct effects

of antibiotics on bacteria, thereby facilitating the direct or indirect removal of antibiotic contaminants from the environment (Patel et al. 2022). Prior to the use in soil-plant systems, researchers thoroughly assessed the degradation effects of bacteria in biochar pores on antibiotics (Fiaz et al. 2021; Katiyar et al. 2022). Zhang et al. (2022) recently found that biochar exhibited high immobilizations of heavy metals (64.4% of Zn and 85.5% of Cu) and significant eliminations of veterinary antibiotics (40.7% of enrofloxacin and 41.9% of oxytetracycline) after combining *Herbaspirillum huttiense* (HHS1) with waste fungus chaff-based biochar (WFCB). Moreover, biochar was effective in minimizing the spread of genes associated with antibiotic resistance (ARGs) (Zhang et al. 2022). It was able to lower the abundance of prospective ARG hosts (the genera *Brevundimonas* and *Rhodanobacter* and phylum Proteobacteria) and several resistance genes, such as *aacA/aphD*, *tetR*, *tetM*, *tetH*, *aadA9*, *tet(PB)*, *tetS*, *czcA*, *aacC*, and *tetT* (Zhang et al. 2022).

In addition to biodegradable routes, non-biodegradable pathways, including Photolysis, Ozonation, advanced oxidation processes, and Fenton processes, have been explored for antibiotic degradation (Kraemer et al. 2019; Katiyar et al. 2022). In the context of biochar application, non-biodegradable routes also demonstrate significant potential. Extensive literature has investigated the utilization of biochar for antibiotic removal through non-biodegradable pathways, revealing various interactions between biochar and adsorbed antibiotics, such as cation exchange, π - π bond interactions, the presence of aromatic structures in biochar, hydrogen bonding, and electrostatic interactions (An et al. 2021; Zhou et al. 2021). However, unmodified biochars exhibit relatively limited adsorption capacities, and their small particle size and low density pose challenges for their removal from treated solutions (Liang et al. 2022). To address this issue, the combination of biochar with magnetic media has been proposed, as it not only enhances the efficiency of pollutant adsorption but also enables the rapid isolation of pollutants using external magnets (Hosny et al. 2022; Liang et al. 2022). Inspired by this concept, Liang et al. (2022) successfully prepared magnetic biochar through the co-pyrolysis of $\text{FeCl}_3/\text{CaCl}_2$ and poplar wood chips in a molten-salt medium. The modified approach employed in this study resulted in a higher proportion of micropores in Fe_2O_3 /biochar during the carbonization process, which likely contributed to the enhanced removal efficiency of norfloxacin (NOR) (Liang et al. 2022). Under pH 6.0 conditions, the magnetic biochar exhibited a maximum norfloxacin adsorption capacity of 38.77 mg/g. Additionally, the Fe_2O_3 -modified biochar demonstrated superparamagnetic characteristics, enabling its potential for recycling and offering economic benefits (Liang

et al. 2022). Although significant advancements had been made in biochar engineering, the production of biochar on an economical scale remains a challenge (Liang et al. 2022). Regarding magnetic biochar, Liang et al. (2022) proposed that their designed reusable magnetic biochar had the potential to remove antibiotics effectively and economically from aquatic environments.

3.3 Removal of other harmful substance

Besides antibiotics and heavy metals, removal of other harmful substances by biochar has also been investigated, where biochar could act as either a nanozyme/catalyst or an absorbent.

For instance, Liu and colleagues (Liu et al. 2022b) reported that the biochar derived from silkworm excrement could serve as nanozyme. They established that the biochar nanozyme had the ability to scavenge excess free radicals, such as ROS and RNS from cigarette smoke (Liu et al. 2022b). Additionally, when placed in a cigarette filter, the biochar nanozyme could successfully shield mouse lung tissue from exposure to cigarette smoke (Liu et al. 2022b). Environmental pollutants like triclosan (TCS) potentially do harm to both human and animal health (Ma et al. 2022). For this, Ma et al. (2022) developed a novel biochar/ Ag_3PO_4 /polyaniline (PANI) photocatalyst that showed remarkable photocatalytic properties for the elimination of TCS. The ideal photocatalyst (1.0% T-Bio/AP/1.0% PANI) showed exceptional photocatalytic activity when exposed to visible light, with a TCS elimination rate of 85.21% within 10 min (Ma et al. 2022). The apparent rate constant K' was 2.38 times that of Ag_3PO_4 (Ma et al. 2022). They continued to examine 11 key TCS breakdown intermediates and discovered that the photocatalyst significantly reduced each of them as well (Ma et al. 2022).

As an absorbent, biochars (BCs) demonstrated noteworthy abilities in the removal of potentially toxic elements (PTEs) (Muhammad et al. 2020), viral pathogens in urban stormwater runoff (Graham et al. 2021; Yao et al. 2021), endocrine-disrupting compounds (EDCs) in water bodies (Nasir et al. 2022), and toxic trace elements in the ecosystem (Naeem et al. 2022). However, when it comes to a high concentration of contaminants, biochar is relatively insufficient in adsorbing these pollutants, so modification of BC is also highly advocated.

4 Medical waste treatment and nutrient recovery

In addition to remediation of environmental pollutants and toxic substances, biochar also shows considerable application potential in the thermochemical conversion of medical waste and harmless treatment of human excreta (Fig. 5).

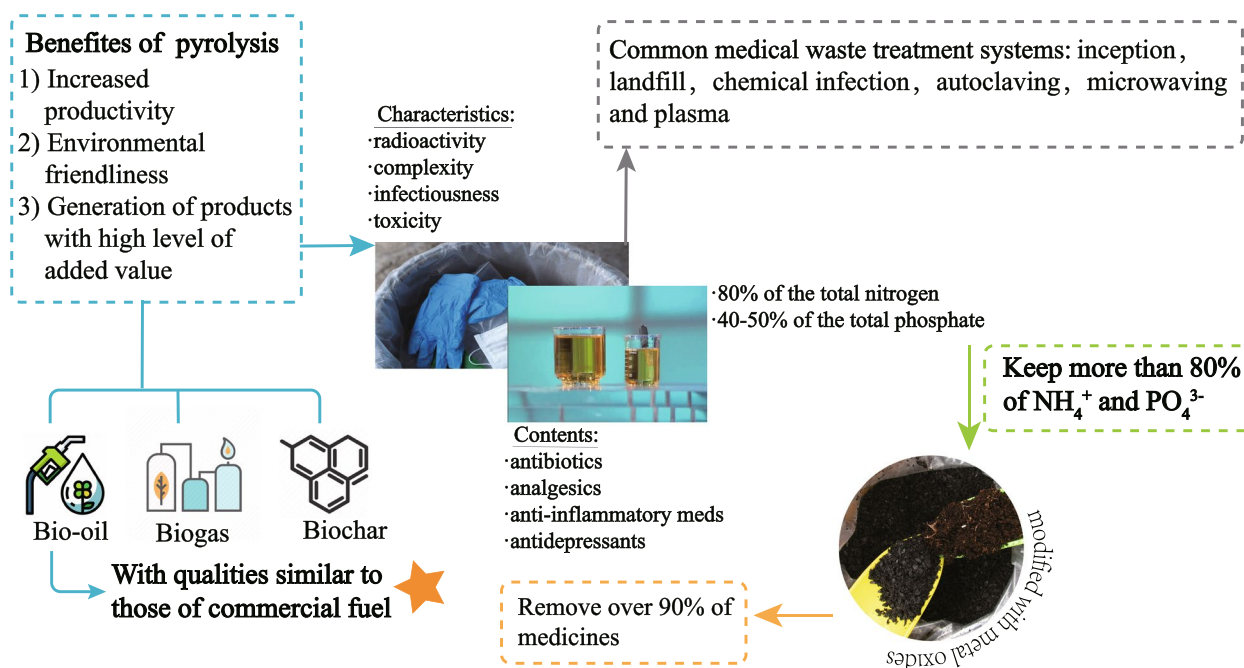


Fig. 5 Applications of biochar in nutrient recovery and the harmless treatment of medical wastes

4.1 Nutrient recovery

Human urine is a distinctive waste stream characterized by elevated levels of nutrients and toxic compounds, including heavy metals and unmetabolized antibiotics. Compared to other municipal effluents, human urine contains significantly higher concentrations of medications, exceeding those by 2–3 orders of magnitude (Sun et al. 2018). Antibiotics are widely present in urine, with more than 75% of the discharged antibiotics remaining unprocessed (Katsikaros and Chrysikopoulos 2020). In a study by Ramanayaka et al. (2020), the adsorptive removal of co-occurring nutrients and oxytetracycline (OTC) in hydrolyzed synthetic human urine was investigated using biochar of different particle sizes, including macro biochar (BC), nanobiochar (NBC), and colloidal biochar (CBC). The results showed that CBC exhibited the highest adsorption capacity for NH_4^+ , PO_4^{3-} , SO_4^{2-} , and OTC (up to 136.7 mg/g) in hydrolyzed human urine (Ramanayaka et al. 2020). The authors suggested that the treated urine could potentially be used as a safe fertilizer, as the remaining nutrients are abundant while the antibiotics have been effectively eliminated. In another study by Solanki and Boyer (2017), the removal of several medications, including diclofenac, paracetamol, acetylsalicylic acid, ibuprofen, citalopram, naproxen, and carbamazepine, was investigated. Biochars derived from southern yellow pine, activated coconut carbon, and bamboo were compared to activated carbon for pharmaceutical removal from urine compositions with a

concentration of 40 g/L. The findings demonstrated that the tested biochars exhibited superior pharmaceutical removal, adsorbing more than 90% of each pharmaceutical compound (Solanki and Boyer 2017). Furthermore, these biochars demonstrated the ability to retain over 80% of NH_4^+ and PO_4^{3-} in urine while effectively removing over 90% of medications, making them potentially advantageous for future utilization as a nutrient product (Solanki and Boyer 2017).

Human urine, in addition to containing potentially harmful substances, also contains a range of essential nutrients. Studies have shown that although human urine constitutes only about 1% of the total volume of municipal wastewater, it contributes significantly to the overall nitrogen and phosphate content, accounting for approximately 80% of the total nitrogen and 40%–50% of the total phosphate (Wilsenach et al. 2007). Various methods have been employed to recover ammonium (NH_4^+) and phosphate (PO_4^{3-}) from wastewater, including artificial wetlands, chemical precipitation, biochemical degradation, and flocculation/coagulation (Marciniczyk et al. 2022). However, they are all short for massive waste production with expensive operational and maintenance cost (Shakoor et al. 2021). As of now, employing biochar to extract nutrients from urine has grown to be an important part of wastewater management (Xu et al. 2019) for the following reasons: 1) biochar is cost-effective with a wide range of feedstock type and simple synthesis method; 2) biochar can be modified with magnetic substance and

recycled easily without extra waste production; 3) biochar has huge surface area with abundant functional group enabling its excellent adsorption performance for phosphate (PO_4^{3-}) and ammonium (NH_4^+); 4) biochar contains high carbon contents, stable structure, and high cation exchange capacity (CEC) that are beneficial in sustainable adsorption (Shakoor et al. 2021). Numerous studies have indicated that natural biochar has limited capacity to absorb nutrients from urine. However, research has shown that the absorption efficiency can be significantly improved by doping biochar with minerals such as Mg, Fe, Al, and Ca (Park et al. 2015; Xu et al. 2019; Shakoor et al. 2021). Xu et al. (2019) conducted a study in which they investigated the effectiveness of metal ion-modified wood waste biochars for phosphate recovery from human urine. The findings demonstrated that the phosphate adsorption performance of the modified biochars, particularly Mg-biochar, was superior to that of natural biochar. Mg-biochar exhibited an exceptional adsorption capacity of up to 118 mgP/g when the concentration of MgCl_2 reached 2.3 M (Xu et al. 2019).

In addition to the adsorption phase, desorption processes play a crucial role in nutrient recovery. Several factors have been identified as significant determinants of the desorption processes, including the type of biochar, pH conditions, and the nature of the desorbing fluid (Marcinićzyk et al. 2022). Research indicates that the release of inorganic phosphorus is influenced by the pyrolysis temperature of biochar. A study conducted by Trazzi et al. (2016) revealed that biochar produced at higher pyrolysis temperatures, specifically 700 °C, exhibited enhanced phosphorus absorption but also higher levels of phosphorus desorption. Furthermore, Shin et al. (2020) discovered that a solution containing 2% citric acid facilitated greater phosphorus desorption compared to a regular solution. The desorption percentages observed were 70% and 90% respectively. This effect could be attributed to the increased solubility of phosphorus at lower pH levels, as the 2% citric acid solution had a pH of 2.5.

The primary mechanisms that influence the desorption processes are ion exchange and electrostatic interaction (Marcinićzyk et al. 2022).

4.2 Medical waste treatment

Following the COVID-19 outbreak, there has been a notable escalation in the utilization of packaging materials and personal protective equipment (PPE), leading to a significant upsurge in medical waste generation (Igalavithana et al. 2022). According to reports, medical waste has increased explosively from 3.64 kg/day per 1000 persons to 27.32 kg/day (Di Maria et al. 2020; Singh et al. 2020; Yang et al. 2021) since the

outbreak started. Most medical wastes are made of plastic, which has long been known for endangering marine life and generating an adverse environmental impact (Igalavithana et al. 2022) with low degradability. Medical waste also demonstrates traits of radioactivity, complexity, infectiousness, and toxicity (Su et al. 2021) making it even more difficult to manage this type of trash and placing an immense pressure on the current waste management system (Klemeš et al. 2020; Purnomo et al. 2021). Therefore, it is now crucial to manage these wastes safely and effectively.

Conventional medical waste treatment systems encompass various methods, including incineration, landfilling, chemical disinfection, autoclaving, microwaving, and plasma treatment (Su et al. 2021). Purnomo, Kurniawan, and their colleagues (Purnomo et al. 2021) have highlighted that chemical and thermal procedures, which ensure effective disinfection, may be the most suitable approaches for the management of such waste. Additionally, they have presented detailed information as shown in Table 3, elucidating the distinctive characteristics of different medical waste treatment methods (Purnomo et al. 2021). Thermal conversion technologies such as pyrolysis, high temperature incineration and gasification are preferred because the high temperature process is beneficial for both disinfection and garbage management (Purnomo et al. 2021). The infectivity of the virus was reported to be reduced by at least 4 $\log_{10}$ after thermal treatment at 80 °C for just 1 min (Saknimit et al. 1988). Currently, high temperature inception is widely applied for processing medical waste, but like other technologies, it has drawbacks such as hazardous gas production, significant land occupation, and unsustainability.

So, there is still a lack of effective and ecofriendly technology for medical waste treatment. The primary technique used to produce biochar is pyrolysis. Due to its advantageous environmental and financial properties, pyrolysis has recently grown in popularity in the garbage processing industry. Currently, it is regarded as a novel approach of managing medical waste. Its benefits manifest in increased productivity, environmental friendliness, and the generation of products with a high level of added value (including biochar, bio-oil, biogas, and other valuable chemical products). In general, the pyrolysis process is divided into two steps. In the first step, at high temperature, chemical bonds in the biomass are broken, prompting the formation of biochar. During this process, fragmentation and depolymerization also occur and lead to the production of biogas and bio-oil, respectively. Following the first step, the second step mainly includes subsequent reactions of the above products, including re-polymerization and cracking. There will also be biochar formation during the re-polymerization process.

Table 3 Characteristics of different medical-waste treatment methods (Purnomo, Kurniawan et al. 2021)

Treatment methods	Advantages	Disadvantages	Challenges
RDF (without further processing)	• High recovery and low rejection rate (due to high plastic and paper contents of CMW) • Low drying cost (due to low moisture content of CMW)	• Risk of infection for operator • Requirement for disinfection stage	• Suitable disinfection method
Incineration	• Simple process and mature technology • High material flexibility • No requirement for disinfection stage • Low fuel requirement (due to high calorific value of CMW)	• High carbon emission • Possibility of producing harmful or corrosive gasses • Only able to recover heat	• Flue gas treatment technology • CO₂ capture and storage technology
Dry carbonization	• Higher energy density product • No requirement for disinfection stage • Suitable moisture content for CMW • Low ash and sulfur content • Low carbon emission	• Insufficient operating conditions to facilitate further degradation • Possibility of producing harmful or corrosive gasses	• Gas treatment technology
Wet carbonization	• Higher energy density product • No requirement for disinfection stage • Low carbon emission • Low ash product • Able to remove chlorine content from PVC efficiently	• Requires addition of water to CMW • Requires washing and drying of product • The energy for pressurization and heating is considered high • Requires high-pressure reactor • Difficulty for continuous process	• Development of continuous process to increase efficiency
Pyrolysis	• Possibility to produce chemical feed-stock • Flexibility of product based on condition • Low carbon emission • Suitable for PE and PP, which is the major constituent of CMW • No requirement for disinfection stage	• Need further research (developing technology) • Not suitable for PVC, PET, and rubber	• Development of technology to maturity
Air gasification	• Simple process • Suitable for PE and PP, which is the major constituent of CMW • No requirement for disinfection stage	• Not suitable for PVC, PET and rubber	• Tar removal technology
Steam gasification	• Suitable for PE and PP, which is the major constituent of CMW • High hydrogen yield, suitable for syn-gas generation • Able to treat PVC (Able to recover chlorine from PVC) • No requirement for disinfection stage	• Not suitable for PET and rubber • Requires high amount of energy • High tar formation	• Heat integration system to increase energy efficiency of the process • Tar removal technology

From "Technological review on thermochemical conversion of COVID-19-related medical wastes" by Purnomo, C. W., Kurniawan, W. & Aziz, M. (2021). *Resources, Conservation and Recycling* 167, p.10 (<https://doi.org/10.1016/j.resconrec.2021.105429>). Copyright 2021 by Elsevier. Reprinted with permission

Cracking refers to the process in which components continue to decompose to form smaller molecules. Temperature and humidity are two important factors affecting the pyrolysis process. High raw material humidity will promote generation of liquid by-products, while low raw material humidity will generate more biochar. In terms of temperature, when it is below 450 °C, coupled with slower heating rates, it is more conducive to biochar production. Relatively, fast pyrolysis is more conducive to the formation of bio oil. Based on this, the pyrolysis conditions can be changed as needed to achieve the desired product (Osman et al. 2023).

It is important to note that bio oil created during pyrolysis process was found to have qualities similar to those of commercial fuel and hold the potential to replace regular fossil fuels, which is also the primary characteristic that sets it apart from other technologies (Su et al. 2021). Som et al. (2018) looked into the features of the bio-oil made by pyrolyzing plastic medical waste (PWM). They identified that it has an calorific value of 41.31 MJ/kg, a pour point of 14 °C, a flash point of 39 °C, and a density of 840 kg/m³, performing similar properties as commercial fuels (such as gasoline and diesel). In addition to bio-oil, Paraschiv et al. (2015) tested the properties of

medical waste-derived biogas, which also displayed great quality and a high calorific value ranging from 27.17 to 46.80 MJ/kg, 11.00 to 21.00 wt%. They found that the main constituents of the biogas were CH_4 , C_2H_4 , C_2H_6 , C_3H_6 , and C_3H_8 . And the LHV (lower heating values) of those biogas ranged from 39.16 to 69.22 MJ/Nm³, meaning it was comparable to natural gas and might replace it in industrial and urban settings (Paraschiv et al. 2015). Recently, Ullah et al. (2022) conducted a study where they developed activated biochar (ABC600) by pyrolyzing medical waste and applying KOH activation. The researchers investigated the adsorption capacity of ABC600 for the removal of methylene blue (MB) and reactive yellow (RYD-145), which are commonly used cationic dyes (Ullah et al. 2022). Their findings revealed that ABC600 exhibited exceptional adsorption capabilities, removing up to 922.2 mg/g and 343.4 mg/g of MB and RYD-145, respectively (Ullah et al. 2022). Moreover, the maximum removal efficiencies for MB and RYD-145 were determined to be 99.9% and 92.5%, respectively (Ullah et al. 2022). Based on these results, the researchers concluded that biochar derived from the pyrolysis of medical waste could serve as a highly effective adsorbent for treating contaminated wastewater and mitigating the environmental risks associated with toxic substances (Ullah et al. 2022).

The economical production of biochar has posed a significant challenge, impeding its widespread adoption. In order to determine the most effective approach for managing medical waste, Hong et al. (2018) conducted an assessment of three treatment methods: steam sterilization, chemical disinfection, and pyrolysis. Through their analysis, the authors established that pyrolysis emerged as the most financially viable option, yielding a net profit of \$189.96 per ton. Moreover, the pyrolysis process was regarded as a win-win strategy for both the environment and the economy due to its electricity and sodium hydroxide generation processes (Hong et al. 2018). In the pursuit of effective remediation techniques for solid plastic waste, Al-Salem et al. (2017) investigated four distinct approaches: burning, landfilling, gasification, and pyrolysis. The results indicated that microwave-assisted pyrolysis offered notable environmental advantages by reducing harmful gas emissions, lowering operational costs, and minimizing heating time. Consequently, pyrolysis demonstrated promising economic feasibility alongside the production of valuable byproducts. Furthermore, catalytic pyrolysis proved to be even more advantageous by facilitating higher reaction rates at lower temperatures, thereby influencing product selectivity and enhancing overall efficiency (Al-Salem et al. 2017; Purnomo et al. 2021). However, it should be noted that catalysts can entail substantial costs. An analysis of biochar

investments from plant root sources showed that when the total amount of pyrolysis reached 20 tons per day, the energy requirement of pyrolysis was lower than that contained in the product biochar. The return on investment (ROI) and internal rate of return (IRR) of biochar production reached 17.58% and 8.96%, respectively, which was moderately economically viable, with a payback period of 10 years (Harsono et al. 2013).

However, the release of dangerous gases continues to be the biggest issue with pyrolysis, including PAHs, HCl, SO_2 , and NO_x . Additionally, the expensive nature of the catalytic process limits its further utilization. In the future, it may be helpful to construct large-scale pyrolysis to lower costs. Ooi et al. (2019) have demonstrated that the addition of catalysts can reduce toxic gas emissions such as nitrogenous and oxygenates compounds. Studies have shown that through the application of new catalysts, improved equipment and the development of new processes to construct an advanced gas cleaning system, the emission of toxic gases can be reduced and the production of valuable products can be promoted to maximize economic and environmental benefits (Goh et al. 2019). Thus, advanced gas cleaning system is needed to address these pollution problems (Su et al. 2021).

5 Biochar toxicity

Although biochar has many benefits, its detrimental impacts on the environment and general health cannot be ignored. Gelardi et al. (2019) thoroughly reviewed the toxicity of biochar although there is still a lack of in-depth literature elucidating on biochar's toxicity. They mentioned that biochar typically involved the four types of toxicity listed below:

First, biochar has a low density with porous structure. When applied to remediate soil, it can be disturbed by soil and other environmental factors (such as the wind and soil microorganisms) and emits toxic dust from its porous structure. According to previous reports, biochar-repaired soil is more likely to produce PM_{10} (Ravi et al. 2016), a class of harmful airborne particles with a diameter of less than 10 μm and the inhalation of which has been associated with respiratory illnesses, chronic heart disease, and renal disease (Gelardi et al. 2019).

In the process of adsorption, many harmful substances (such as heavy metals, pesticides, polychlorinated dibenzo-p-dioxins and polychlorinated biphenyls (PCBs), dibenzofurans (PCDD/DFS), and PAH (Gelardi et al. 2019)) adsorbed by biochar may also cause damage to human body due to biochar's dust emissions.

Moreover, research has demonstrated that direct contact with biochar may be detrimental, including cytotoxicity and phytotoxicity (Gelardi et al. 2019). Studies have shown that biochar contains high concentrations

of polycyclic aromatic hydrocarbons, which can have adverse effects if not applied properly. Moreover, many harmful substances, such as heavy metals and polychlorinated pollutants, are easily combined on the skeleton of polycyclic aromatic hydrocarbons, showing hydrophobicity and not easy to be degraded (Khan et al. 2021).

In addition to inhalation and direct contact, the production process of biochar also causes the emission of some noxious substances, including furans, dioxins, volatile organic compounds (VOCs), heavy metals, PCBs, and PAHs, among which PAHs have been linked to *Salmonella*/microbial mutagenicity (Anjum et al. 2014) and suppression of urease enzyme activity (Liu et al. 2018).

In short, the drawbacks of biochar cannot be ignored. However, there are currently few publications focusing on optimizing the production technology of biochar to minimize its toxicity, while many papers have placed an emphasis on choosing the optimal plan and following an agreement during the application of biochar to reduce its toxicity. Xiang et al. (2021) also conducted a systematic review on the potential toxicity of biochar. Although there is currently a lack of techniques to systematically reduce biochar toxicity, they offer constructive suggestions for this. The toxicity of biochar largely comes from the interaction with the environment, so further research on the interaction mechanism of biochar in the environment may help increase the safety of biochar application. Secondly, biochar contains a wealth of functional groups and active molecules, these molecules may have potential toxicity by themselves or interact, so ascertaining the mechanism of action of related molecules will help understand the biological toxicity of biochar.

6 Electrical sensors and biosensors

The detection of biomarkers in blood is an important content in the field of medical analysis. However, due to the relatively low concentration of biomarkers in blood, current bioassay technologies primarily focus on achieving high sensitivity and accuracy. Consequently, most existing detection methods are time-consuming, labor-intensive, and require large sample sizes (Cancelliere et al. 2022). In recent years, there has been a growing interest in the development of simple, convenient, and efficient biological detection technologies to address these limitations. One such technology gaining attention is electrochemical immunosensors, facilitated by advancements in nanotechnology. Electrochemical immunosensors based on nanomaterials offer excellent sensitivity, reproducibility, and convenience (Li et al. 2022).

However, the application requirements for electrical sensors have expanded beyond sensitivity and accuracy, encompassing efficacy, stability, and reproducibility. Biochar, characterized by its high porosity, electrical charge,

diverse chemical composition, and elevated carbon content, possesses the potential to serve as a catalyst, carrier, and absorbent. These inherent functional properties position biochar as a promising candidate for utilization in electrochemical and biosensing applications. Notwithstanding its potential, the exploration of biochar's capabilities as a biological and electrochemical sensor remains in its nascent stages. A recent study by Li et al. (2022) provides a comprehensive analysis of the use of biochar as sensors. Literature that is now available mainly describes the utilization of biochar for the detection of heavy metals, pesticide and veterinary medication residues, environmental estrogens, and organic polysaccharides.

In medical field, the implementation of biochar as a biosensor has already been documented. Basically, the compounds to be detected first bond to biochar. Then electronic signals are sent to the computer where the accurate measurement is made. Dong et al. (2018) developed a highly conductive and absorbable biochar nanoparticles (BCNPs) for the detection of 17 β -estradiol in water. They revealed that BCNP800 (BCNPs produced under the temperature of 800 °C) displayed the best absorption and conductivity and its detection limit reached 11.30 nM. Its accuracy and reliability were proved to be close to that of conventional high-performance liquid chromatography analysis. In addition to adsorbent, biochar also acts as a catalyst though the precise mechanism is unknown. The morphology of biochar may be a crucial element in enhancing the catalytic performance (Li et al. 2022). Utilizing the catalytic property of biochar, Kalinke et al. (2019) devised a non-enzymatic biosensor capable of detecting glucose levels in human saliva. This innovative design demonstrated a remarkable limit of quantification (LOQ) of 0.457 μ M. In addition to serving as catalysts and absorbents, biochar has also been effectively employed as carriers to facilitate the loading of specific functional molecules, including nickel hydroxide (Kalinke et al. 2019) and antibodies (Cancelliere et al. 2022), in order to enhance detection capabilities. For example, Cancelliere et al. (2022) loaded IL-6 antibodies onto biochar for IL-6 detection in human blood which realized a LOD of 4.8 pg/ml and showed a better sensitivity and reproducibility than ELISA kit, a conventional detection method.

Nevertheless, there are still some obstacles to the application of biochar in sensors. First, the porous structure of biochar is beneficial for sensor applications. In the production process, high pyrolysis temperature is conducive to the generation of porous structure, but excessively high temperature will lead to its destruction. Moreover, the energy consumption and pollution of the pyrolysis process have always been the problems that hinder the

wide application of biochar. Therefore, how to optimize the production conditions is a problem that needs to be considered in the further application of biochar. Secondly, there are abundant functional groups on the surface of biochar. When biochar is used in biosensors, it needs high sensitivity and repeatability. How to avoid the non-specific reaction of functional groups is a problem that needs to be overcome in the application of biochar (Li et al. 2022).

7 Drug delivery

Among all the aspects mentioned above, drug delivery is unquestionably one of the most relevant medical applications of biochar (Fig. 6).

When it comes to drug delivery, nanoparticle is undoubtedly the most popular material in the past 10 years (Park 2014), and the employment of nanoparticles as drug carriers is the focus of recent research. Nanomaterials that can react to certain stimuli and achieve regulated drug release are ideal drug delivery carriers. Thus, using nanocarriers for controlled and targeted drug delivery has gained increasing attention. The reasons are that 1) nanocarriers can improve drug delivery efficiency, 2) nanocarriers help enhance the bioavailability of drugs, 3) nanocarriers show better navigation

in targeted delivery, and 4) nanocarriers can load the most drugs per dose. At present, common nanocarriers in controlled drug delivery include: liposomes, dendrimers, nanosphere or nanocapsule, solid lipid nanoparticles, nanofibers, polymers, self-assembled polymeric micelles, exosomes and carbon nanotube, etc. (Adepu and Ramakrishna 2021).

Biochar can be used as absorbent, catalyst, and carrier. Application of the former two have been reported detailly in many studies. However, there are relatively little research on the utilization of biochar as a carrier for molecular delivery even though biochar has a large surface area, a variety of functional molecules, easy tailorability and cost-effective properties, all of which indicate that it is an excellent carrier. Sashidhar et al. (2020) have thoroughly reviewed the application of biochar as a carrier in soil remediation. They emphasized that biochar has distinctive advantages over other carrier materials due to the natural presence of multiple functional groups in it. Also, it is reported that as a carrier, biochar shows a higher buffering capacity (Mukherjee et al. 2011), which is undoubtedly beneficial for the controlled release of substances. Therefore, it is conceivable that biochar has great potential in drug delivery when used as nanocarriers. Furthermore,

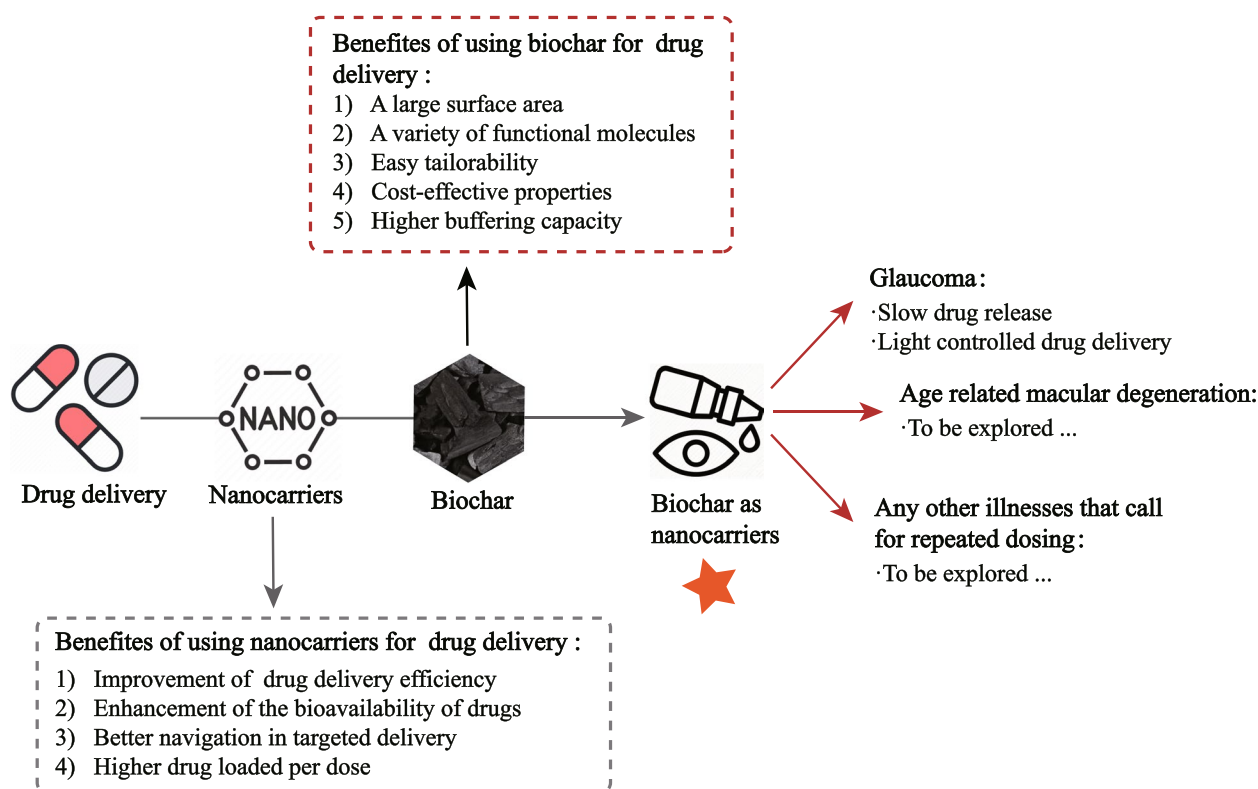


Fig. 6 Medical applications of biochar in drug delivery

biochar possesses inherent characteristics that make it highly adaptable, allowing for specific modifications to be made and enabling the attainment of various advanced drug delivery functionalities, including targeted delivery and stimulus-responsive release. In comparison to extensively studied nanocarriers utilized in drug delivery systems, biochar offers numerous advantages. Drawing upon the comprehensive review by Adepu and Ramakrishna (2021), a detailed list of the advantages of biochar over commonly employed nanocarriers was compiled, which is presented in Table 4 (Adepu and Ramakrishna 2021). Among these nanocarriers, biochar stands out for its simple synthesis process, low cost, long-term stability and easy tailorability of various properties. To our knowledge, this is the first time that biochar has been compared with these common nanocarriers in drug delivery.

It is worth noting that in the current body of literature from PubMed, there is only one study using biochar as nanocarriers for drug delivery. Wang et al. (2021) generated a hydrogel balls (HBS) based drug delivery system that contained hydrogel balls as basic structure, two drugs for glaucoma treatment and ZnO modified biochar. With the addition of ZnO modified biochar, this drug delivery system realized slow drug release, light controlled drug delivery, and possible antibacterial effect. In a safety test, this composite material did not exhibit any overt toxicity, either in vitro or in vivo, indicating the usability of this method. As a novel drug delivery scheme, this kind of material was designed to be embedded under the conjunctiva and was able to achieve stable and long-term (up to 17 days) drug release without frequent drug delivery, which has long been a problem of glaucoma treatment. This study not only suggests that biochar may be used to cure glaucoma, but also indicates its huge application potential in treating any other illnesses that call for repeated dosing such as diabetes and hypertension.

Age related macular degeneration is another blinding disease that contributes most of the blindness among the elderly. It is primarily caused by choroidal neovascularization, which develops into the retina followed by rupture and bleeding and finally obstructs the vision. Choroidal neovascularization is mainly mediated by vascular endothelial growth factor. For a long period of time, patients with age-related macular degeneration rely on regular administration of vascular endothelial growth factor antibody. It shares many similarities to glaucoma treatment in terms of tissue specificity and mode of administration. Therefore, it is convincible that biochar also holds great potential in the management of age-related macular degeneration. So, utilizing biochar-based

drug carriers to treat age-related macular degeneration is one of the areas worth exploring in the future.

8 Conclusion and perspectives

In summary, this overview highlights the various applications of biochar in the medical field. Biochar has demonstrated considerable potential due to its exceptional adsorption properties and cost-effectiveness. Predominant areas of investigation include the immobilization of contaminants, such as heavy metals, and the removal of organic pollutants including antibiotics and other harmful substances, aligning with the current research boundaries and development trends of biochar (Wu et al. 2021b). Biochar also has a lot of promising applications in the sustainable treatment and reuse of human excrement and medical waste (Fang et al. 2022; Solanki and Boyer 2017; Wei et al. 2022). According to previous reports, MgO hybrid biochar held excellent adsorption potential for phosphorus recovery (523.9 mg/g) and was able to recycle >98% of P from bio-liquid wastewater and aqueous environment (Fang et al. 2022). Furthermore, by-products derived from the pyrolysis of medical waste have been reported to possess high commercial value (Su et al. 2021). Additionally, the toxicity of biochar itself has been categorized into four types and extensively examined in other articles (Gelardi et al. 2019). Biosensing and drug delivery are direct applications of biochar in the medical field. Although the literature on biosensors has received increasing attention, with studies by Li et al. (2022), Kalinke et al. (2019), and Cancelliere et al. (2022), there appears to be limited research specifically exploring the potential of biochar as a drug carrier. Our search results yielded only one essay investigating this aspect.

Studies have shown that biochar is a viable material for medicine delivery system. It exhibits greater qualities than other drug carriers. And for the first time, a thorough comparison between biochar and other nanocarriers that have been studied in drug delivery system has been deeply discussed. Moreover, literature have demonstrated that biochar is feasible to be used in the treatment of illnesses requiring regular, long-term dosing (such as diabetes and age-related macular degeneration) (Wang et al. 2021). Considering the tremendous potential of applying biochar as a nanocarrier and the developmental trends demonstrated in the overlay visualization from Bibliometric Analysis, we proposed that employing biochar in drug delivery system is a promising field in medical world. In addition, we discovered that pyrolysis, the method of biochar production, is appropriate for treating medical waste in the context of COVID-19 pandemic, which has created massive amounts of medical waste generation. Significantly,

Table 4 Advantages of biochar over other nanocarriers in drug delivery (Adepu and Ramakrishna 2021)

Material	Advantages of the material	Disadvantages of the material	Advantages of biochar over the material
Dendrimers	• Uniformity in molecular weight, size, shape, and branch length • A high degree of branching results in a high surface area • Availability of internal cavities with Polyvalency offers high load and targeting • High water solubility • Biocompatibility and absence of immunogenicity	• Complex synthesis process • Possibility of incomplete reactions with terminal groups • Steric hindrance to the core molecule and dendrons obstructs the formation of high generation dendrimer	• Simple synthesis process • Cross-linked microporous structure and highly graphitized carbon structures
Nanofibers	• High specific surface area • Multiple drugs with high load capacity • Tunable physicochemical properties • Good Spatio-temporal distribution of drugs • Great choice of polymers that are biodegradable and biocompatible • Designed for various routes of administration for both hydrophilic and hydrophobic drugs	• Scalability is an issue • Poor control over nanofiber dimensions • Need to optimize the solvent system for each polymer in the electrospinning process	• Feasible and low-cost synthesis methods • Easy tailorability of its various properties
Metal nanoparticles	• Tunable sizes and shapes (spherical, triangular, cubic, rods, stars, etc.) • Possibilities of easy functionalization • Size-dependent activity	• RES uptake might result in low biocompatibility and cytotoxicity • Instability of nanoparticles	• Long-term stability
Mesoporous silica nanoparticles	• Ordered porous structure • High surface area • Tunable pore size and functionalization • Poorly water-soluble drugs and gene delivery	• More studies are needed on cytotoxicity • The presence of high surface silanol groups interacts with the phospholipids of the red blood cell membranes leads to hemolysis	• Various functional groups on the surface • Modified to be biocompatible
Carbon nanotubes	• High surface area, enhanced conductivity and strength • Vast functionalization sites • Optical properties • For targeted delivery	• High immunogenicity, carcinogenicity, and cytotoxicity • Non-biodegradable • Poor aqueous solubility and poor absorption	• Can be modified to be hydrophilic or hydrophobic
Nanocapsules /nanospheres	• Efficient drug accumulation at the target site • Controlled release of drug over weeks	• Non-degradable polymers accumulate in tissues • In vivo metabolism and elimination, routes are not elucidated • High production cost	• Low-cost • Feasible synthesis methods
Quantum dots	• Semiconductor nanocrystals with broad excitation spectra, narrow emission spectra and tunable emission peaks • Possess long fluorescence lifetimes and negligible photobleaching • Ability to conjugate with proteins and multiple molecular targets simultaneously	• Quantum dot degradation results in the leaching of heavy metals such as Cadmium which generates reactive oxygen species (ROS) • High cytotoxicity	• Long-term stability

Table 4 (continued)

Material	Advantages of the material	Disadvantages of the material	Advantages of biochar over the material
Exosomes	• Cell targeting and gene delivery • Ability to loading both hydrophilic and lipophilic drugs • Exosomes membranes possess many proteins thus show very high organotropism • Immunocompatible if derived autologous	• Rapid clearance from the blood • Current methods available suffer low drug load and retention • Purification and large scale extraction is a hassle	• Non-degradable property • Great load potential • Feasible and low-cost synthesis methods
Liposomes	• Less cytotoxic • Amphiphilic and Self-assembly capability • Can load both hydrophilic and lipophilic drugs • High payload • Longer duration of action	• Could crystallize during long term storage • Poor control over the drug release rate • Lack of means to prevail biological barriers • Sufficient load of drugs for which pH and ion gradients do not apply • Leakage and fusion of loaded drug Phospholipids may undergo oxidation and hydrolysis	• Long-term stability • Well-controlled drug release • Good retention of loaded drugs with little leakage

Adapted from "Controlled Drug Delivery Systems: Current Status and Future Directions": Adepu, S. and S. Ramakrishna (2021),Molecules 26(19), p.31 (<https://doi.org/10.3390/molecules26195905>). CC-BY-NC

the by-products generated in the pyrolysis process of medical waste are proved to reach the same quality as commercial products (Su et al. 2021). Aligned with the overlay visualization from Bibliometric Analysis, we believe that this is another promising direction for the future development of biochar.

The application of biochar in medicine is a new field to be developed. Through the above review, we know that the application of biochar in the medical field includes many aspects, some of which are still in their infancy and show great application prospects. Nevertheless, the use of biochar presents potential health risks. The application of biochar in the medical field

still requires caution. Therefore, before applying biochar to actual medical practice, it is necessary to conduct a comprehensive and systematic inspection and generalization, which is also the original intention of this article. In order to make the results of our review more understandable and to increase our practicability, we compared various categories of medical materials/methods involved in this article that use biochar. And we summarized them into main bullets with certain ideas and presented them in the form of a table (see Table 5 for details). It can be seen from Table 5 that most of the common materials and methods used in the medical field have the following three problems: 1) high

Table 5 Comparison of biochar with other materials in the medical field

Categories	Traditional methods/materials	Drawbacks of traditional methods/materials	Advantages of biochar application	Disadvantages of biochar application
Heavy metal treatment	• Membrane filtration • Physicochemical methods • Coagulation and flocculation • Chemical precipitation • Electrodialysis, biological methods • Electrochemical treatments	• Technical limitations • Theoretical deficiencies • High costs	• Specific surface area • Inorganic mineral species • Diverse functional groups • Easy tailorability • Simple synthesis process	• Production of biochar on an economical scale remains a challenge • Release of dangerous gases in biochar production • Emission of toxic dust from its porous structure • Possible detrimental effect from direct contacting • Potential release of contaminants absorbed within biochar • Challenge to optimize the synthesis process for a mild and low-energy-consuming condition
Antibiotic removal	• Ion exchange • Adsorption • Flocculation, coagulation • Electrochemical degradation • Ozonation • Membrane filtration	• Unsustainability • Unfavorable cost-effectiveness	• Remarkable adsorption capacity • Long-term stability • Environmentally friendly characteristics	
Nutrient recovery	• Artificial wetlands • Chemical precipitation • Biochemical degradation • Flocculation/coagulation	• Massive waste production • Unfavorable cost-effectiveness	• Cost-effective properties • Easy tailorability • Specific surface area • Diverse functional groups • Stable structure • High cation exchange capacity	
Medical waste treatment	• Incineration • Landfilling • Chemical disinfection • Autoclaving • Microwaving • Plasma treatment	• Hazardous gas production • Significant land occupation • Unsustainability	• Increased productivity • Environmental friendliness • Generation of products with a high level of added value	
Electrical sensors and biosensors	• Microfluidic techniques • Fluorescence techniques • Surface plasmon resonance techniques • Enzyme-linked immunosorbent assay • Western blot	• Times consuming • Unfavorable cost-effectiveness • Relatively large quantities of samples required	• Cost-effectiveness • Environmental friendliness	
Drug delivery	• Liposomes • Dendrimers • Nanosphere • Solid lipid nanoparticles • Nanofibers • Polymers • Self-assembled polymeric micelles • Exosomes • Carbon nanotube	• Complex synthesis process • High production cost • Non-biodegradable	• Simple synthesis process • Modified to be biocompatible • Cost-effectiveness	

production costs, especially in the field of direct use in the human body, such as for molecular detection and drug delivery system. The content of biomarkers in the human body is mostly low, so most biosensors require high sensitivity. On the one hand, it is necessary to hire more professional technicians to process samples, and on the other hand, it also leads to higher requirements on the microstructure of the sensor to detect these molecules, which all increase the development cost of biosensors. Because the drug delivery system is in direct contact with the human body, it is necessary to consider many aspects such as the safety, toxicity, immunogenicity and degradation products of the delivery material. Therefore, it needs to be applied cautiously, and the development cost is relatively high; 2) it pollutes the environment, mainly reflected in the treatment of some medical waste. Due to the large amount of production, most of the medical waste is disposed of by some simple and quick disposal methods, such as landfill or incineration. These processing methods do not fully consider the impact on the environment and cannot be sustainable. It is urgent to develop new medical waste treatment methods; 3) it has low persistence, which is mostly reflected in waste treatment systems that need to be reused, such as the absorption and treatment of toxic substances. When it comes to the decontamination of some special wastes, recycling of useful substances is also required. This puts higher demands on the absorbing materials. Most of the current waste treatment systems lack this durability, and frequent replacement will inevitably bring about low-cost performance.

Interestingly, the characteristics of biochar can meet the above-mentioned deficiencies. Biochar is a well-known environment-friendly material in the 21st century. It shows great potential in atmospheric environment governance, soil modification and pollutant governance. Due to the wide source of raw materials and simple production process, the production cost of biochar is generally low. A lot of waste can also be used to make biochar through processing. The most outstanding property of biochar is its high absorbency, due to its porous structure and large surface area. It has unique advantages in the field of pollutant absorption. And because biochar is easily modified, some advanced pollutant treatment requirements become possible, such as the reabsorption of nitrogen and phosphorus in sewage. Despite the numerous advantages attributed to biochar, it is important to acknowledge certain limitations, including the potential toxicity associated with biochar itself and the potential release of contaminants absorbed within biochar. These factors can pose significant obstacles to the effective utilization of biochar as a carrier for medicinal applications,

necessitating further investigation and research. Additionally, it is crucial to emphasize the need for optimizing the production process and refining the modification techniques employed for biochar, with the goal of minimizing any pollution resulting from its production process while fully capitalizing on the material's desirable performance characteristics.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1007/s44246-023-00066-0>.

Additional file 1. Number of annual reports on biochar from 2013 to 2021 in PubMed (Supplementary Information for Fig. 2).

Additional file 2. Reference list of literature reflecting a direct relationship between biochar and medical science in the last 3 years from PubMed (Supplementary Information for Table 1).

Additional file 3.

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Not applicable.

Permission note

Table 3 in this article is from "Technological review on thermochemical conversion of COVID-19-related medical wastes" by Purnomo, C. W., Kurniawan, W. & Aziz, M. (2021). *Resour Conserv Recycl* 167, p.10 (<https://doi.org/10.1016/j.resconrec.2021.105429>). Copyright 2021 by Elsevier. We have obtained permission from the publisher for reuse of Table 3 with a RightsLink Printable License that is provided in Supplementary Material (Online Resource 3). Table 4 in this article is adapted from "Controlled Drug Delivery Systems: Current Status and Future Directions", by Adepu, S. and S. Ramakrishna (2021). *Molecules* 26(19), p.31 (<https://doi.org/10.3390/molecules26195905>), which is an open access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>) that allows unrestricted use, distribution, and reproduction in any medium so long as the original author and source are acknowledged.

Authors' contributions

Shujie Zhang provided idea for the article. Qiao Zhuo performed the literature search and data analysis. Shujie Zhang and Chen Zhao revised the manuscript. Shujie Zhang and Chen Zhao supervised the progress of the whole project. All writers provided feedback on earlier drafts of the manuscript after Qiao Zhuo wrote the original draft. All authors have read and approved the final draft.

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Availability of data and materials

The data generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

All individuals taking part in the study have given their informed consent.

Consent for publication

The correctness of the statements made in the manuscript is verified by the authors. All co-authors have given their consent for the publishing.

Competing interests

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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