Water Research X 18 (2023) 100167

Contents lists available at ScienceDirect

Water Research X

journal homepage: www.sciencedirect.com/journal/water-research-x

Review

# Sewage sludge derived biochar for environmental improvement: Advances, challenges, and solutions

Lei Zhao [a,*,1], Zhong-Fang Sun [a,1], Xiao-Wen Pan [b], Jing-Yan Tan [a], Shan-Shan Yang [a], Jie-Ting Wu [d], Chuan Chen [a,*], Yuan Yuan [c], Nan-Qi Ren [a]

[a] State Key Laboratory of Urban Water Resources and Environment, School of Environment, Harbin Institute of Technology, Harbin 150090, China
[b] Power China Huadong Engineering Corporation Limited, China
[c] College of Biological Engineering, Beijing Polytechnic, Beijing 10076, China
[d] School of Environment, Liaoning University, Shenyang, China

ARTICLE INFO

*Keywords:*
Sludge biochar
Environmental improvement
Application barriers
Strategies and prospects

ABSTRACT

With the rapid growth yield of global sewage sludge, rational and effective treatment and disposal methods are becoming increasingly needed. Biochar preparation is an attractive option for sewage sludge treatment, the excellent physical and chemical properties of sludge derived biochar make it an attractive option for environmental improvement. Here, the current application state of sludge derived biochar was comprehensively reviewed, and the advances in the mechanism and capacity of sludge biochar in water contaminant removal, soil remediation, and carbon emission reduction were described, with particular attention to the key challenges involved, e.g., possible environmental risks and low efficiency. Several new strategies for overcoming sludge biochar application barriers to realize highly efficient environmental improvement were highlighted, including biochar modification, co-pyrolysis, feedstock selection and pretreatment. The insights offered in this review will facilitate further development of sewage sludge derived biochar, towards addressing the obstacles in its application in environmental improvement and global environmental crisis.

## 1. Introduction

With the advancement in the world's economy and urbanization, sewage sludge as the main solid waste of urban sewage treatment plants has been increasing on a yearly basis. For example, in 2021 alone, the total amount of sludge in China reached 80.6 million tons (China, 2021). It is estimated that the annual amount of sludge may be higher than 90 million tons by 2025 (Zhang et al., 2020d). According to the definition of the U.S. Environmental Protection Agency (EPA) (USEPA, 2007), sewage sludge is reusable as it is rich in organic matter, nutrients, and various waste biomass materials containing trace elements. Yet, on the other hand, sewage sludge contains pathogens and heavy metal pollutants, as well as a large multitude of toxic organic chemicals that are harmful to humans and the ecological system. If treated improperly, it can cause serious secondary pollution to the environment. Presently, the most widely used sludge treatment methods include biological technologies (anaerobic digestion, aerobic composting), dewatering, and drying. The final destinations of disposed sludge were agricultural use, landfill, and construction materials. Table 1 shows how sewage sludge is disposed of in Europe, America, and Japan. As can be seen, turning sludge into resources is a future trend in these areas and all over the world.

Biochar is an easy-to-prepare porous material with an aromatic compound structure. Compared to traditional incineration/combustion, which requires higher temperature (300°C–1000°C) and significant energy input, hydrothermally treated sludge is preferable due to the lower energy consumption, higher yield, and oxygen-containing functional group content (Chen et al., 2021). Previous studies have also found that sludge pyrolysis has great advantages over incineration in reducing heavy metal pollution at a pyrolysis temperature lower than 600°C (Chen et al., 2020).

The properties of sludge-derived biochar are usually affected by factors such as moisture content, pyrolysis temperature, residence time, heating rate, etc. (Han et al., 2022; Hu et al., 2022; Sun et al., 2022b). Gaur et al. (2020) observed the carbon content decreased significantly with the increase of retention time at each tested temperature. Zheng

* Corresponding authors.
*E-mail addresses:* lzhao@hit.edu.cn (L. Zhao), cchen@hit.edu.cn (C. Chen).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.wroa.2023.100167
Received 16 September 2022; Received in revised form 6 January 2023; Accepted 15 January 2023
Available online 17 January 2023

et al. (2019a) showed that with the increase in reaction temperature, volatile matter decreased obviously. For example, when the pyrolysis temperature increased from 300°C to 700°C, the yield of sludge biochar decreased from 91.1% to 81.2% (Zhang et al., 2022b). In addition, recent researches reveal that improving pyrolysis temperature usually results in a larger biochar surface area. When the pyrolysis temperature rises from 500°C to 900°C, the porosity of the biochar increases from 0.056 $cm^3/g$ to 0.099 $cm^3/g$, while the specific surface area increases from 25.4 $cm^2/g$ to 67.6 $cm^2/g$ (Patel et al., 2020). This phenomenon should be attributed to that the tar produced at low temperatures adheres to the surface of biochar and blocks the pores, while the tar gradually decomposes when the temperature rises, thus accelerating the formation speed of pores and increasing the specific surface area (Zhang et al., 2022a). While in some cases, the specific surface area and porosity decrease when the pyrolysis temperature rises. It may be due to the melting and collapse of the pore wall at excessively high temperatures. Similar to specific surface area and porosity, the pH of biochar also changes with variations in pyrolysis temperature and materials. The pH value of biochar has a significant effect on its function as an adsorbent to remove pollutants. When biochar is used to remove pollutants from water, the pH value of the solution significantly affects the surface charges of biochar. At higher pyrolysis temperatures, the alkali in sewage sludges is released from the structure, and the oxygen-containing functional groups decompose, resulting in a decrease in the number of acidic functional groups (Wang et al., 2019). It is also reported that the pH value of biochar is more significantly affected by its aromatization degree (Khan et al., 2020). With a rise in pyrolysis temperature, the alkalinity of organic anions in biochar also increases. The above changes in the properties of biochar also affect the high adsorption of biochar. For example, He et al. (2022) found that fine biochar (with a large specific surface area) has significantly higher $NH_4^+$-N adsorption capacity than medium and coarse biochar. However, Lee et al. (2022) found that the adsorption capacity of anions decreases with the increase of pH, while the adsorption capacity of cations increases with the increase of pH.

With the advantages of high absorbability, stable chemical properties, large specific surface area, rich porous structure, and numerous surface functional groups, sludge derived biochar has a wide prospect of application. Despite numerous studies published on the production and properties of biochar, to the best of our knowledge, no extensive review is available on the application of sludge derived biochar on environmental improvement. Therefore, the objective of this paper is aimed to, in brief, provide a state-of-the-art review of current and emerging sludge biochar application fields that were effective in water pollution control, soil remediation, carbon sink and carbon emission reduction as shown in Fig. 1. Emphasis is put on the key challenges and new strategies for overcoming sludge biochar application barriers to realizing highly efficient pollutants removal, soil conditioning, and carbon dioxide mitigation.

## 2. Application of sludge biochar in water contaminants removal

The multifunctional characteristics of biochar show a very effective potential in the field of water environment remediation (Ahmad et al., 2014). Recent studies showed that biochar can be used as an adsorbent to remove a number of organic pollutants in water (Table 2). Generally, the absorption process and types of pollutants that can be absorbed by biochar depend on the physical and chemical structures of the biochar surface. The absorption mechanisms mainly include hydrophobic interaction, pore filling, electrostatic adsorption, and hydrogen bond (Qiu et al., 2022), as provided in Fig. 2.

### 2.1. Hydrophobic interaction

Relevant studies show that if a pollutant has hydrophobic functional groups such as the methyl group, then it can be removed by biochar through hydrophobic interaction (Dai et al., 2019). Theoretically, the higher the pyrolysis temperature (> 500°C), the higher the hydrophobicity and aromaticity of biochar, the larger the specific surface area, and thus the easier it is to absorb hydrophobic and nonpolar organic pollutants. For example, when the pyrolysis temperature is increased from 350°C to 750°C, the surface functional groups, hydrophobicity, and crystallinity of biochar are increased, making it more effective to remove tetracycline (Choi et al., 2020). Compared with low-temperature pyrolyzed biochar, high-temperature biochar (700°C) with high aromaticity enhanced its antibiotic adsorption capacity (Premarathna et al., 2019). In particular, a high dose of biochar will produce more active sites, which will further enhance the adsorption of tetracycline (Kang et al., 2023), but excessive active substances may also cause self-quenching, leading to the removal rate of tetracycline decreases (Zhu et al., 2019).

### 2.2. Pore filling

Pore filling is considered another main mechanism by which biochar absorbs organic matter. Based on pore sizes, pores can be structurally divided into micropores (< 2 nm), medium pores (2–50 nm), and large pores (> 50 nm). Studies found that pore structures have a significant effect on pollutant absorption in water. Generally, biochar with medium pores is more effective in absorbing organic matter, while larger pores help increase water permeability. The pore size increases with the increase of pyrolysis temperature, and the pores are easily filled with organic pollutants to achieve a high removal rate. Xu et al. (2022) found that the larger the void volume of biochar, the larger the specific surface area, the smaller the average pore diameter, the stronger the pore-filling effect, and thus the better the removal of organic pollutants. During the pollutant removal in the liquid phase, the absorption of organic pollutants is related to the micro and medium pores on biochar. When removing microplastics, larger microplastics are stuck in the gap of biochar, and others are trapped in the pore of biochar. The colloidal

**Table 1**
Treatment and disposal of sewage sludge in different countries.

| Countries | Disposal status | Impact conditions | Refs. |
|---|---|---|---|
| The European Union | The main treatment methods used in the EU are biostabilisation techniques, dewatering, and drying. Over 50% of sludge is stabilized by anaerobic digestion, with the UK achieving 66% digestion and Germany achieving 100% sludge stabilization. The final sludge disposal is dominated by land use and resource use after incineration, with the proportion of landfill continuing to decline. | Promote the agricultural use of sludge to prevent the impact of sludge on soil, flora and fauna, and public health. | (Levidow and Raman 2019) |
| The U.S. | Nearly 60% of the sludge is stabilised by aerobic composting or anaerobic fermentation techniques and used to make biomass fertiliser, with the remainder being incinerated and landfilled, and a small amount used for mine rehabilitation. | Sludge production is high, regulations generally encourage agricultural use and pollutant concentrations are strictly controlled. | (Steele et al. 2022) |
| Japan | Sludge treatment is based on anaerobic digestion, composting and melting, and in recent years disposal has been based on harmless use in gardens or green spaces, with the ash from incineration made into solid bricks or building materials. | Land resources are scarce and heavy metal limit standards are strict. | (Wang and Nakakubo 2022) |

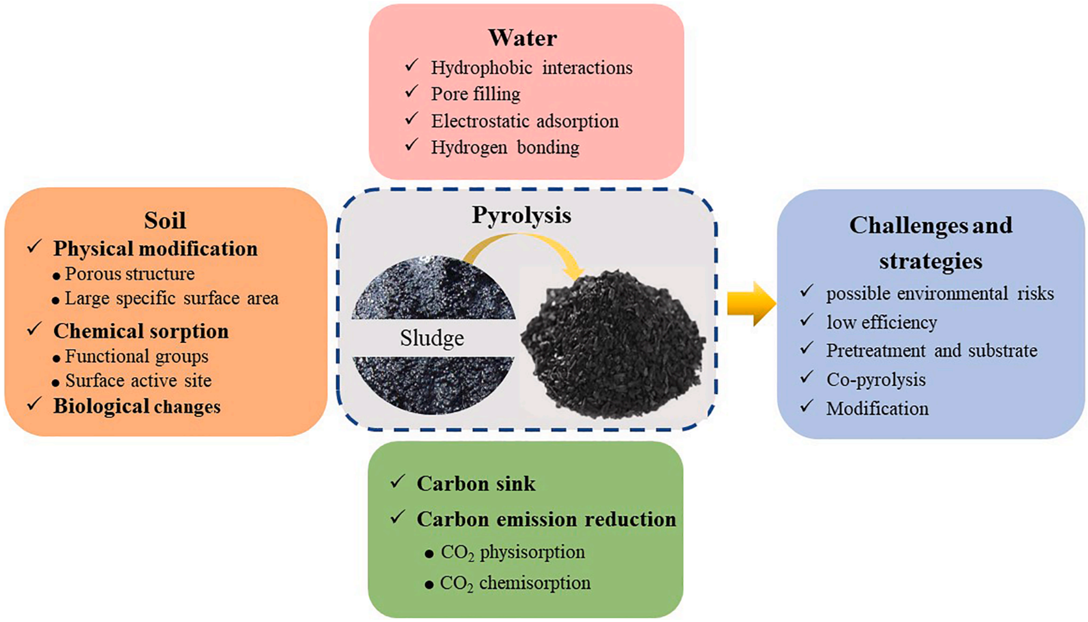


**Fig. 1.** Organizational venation diagram of the review.

**Table 2**
Application of sludge biochar in water contaminants removal.

| Materials | Specific Surface Area ($m^2$/g) | Contaminants | Efficiency | Refs. |
|---|---|---|---|---|
| Sewage sludge | 63.0 | Fulvic acids | 93.0–96.0 mg/g | Konczak et al. (2021) |
| Sewage sludge | 89.2 | Phosphate ions | 88.1 mg/g | Kończak and Huber (2022) |
| Sewage sludge and willow | 74.6 | Ammonium ions | 36.0 mg/g | Kończak and Huber (2022) |
| Nano-zero-valent iron and sewage sludge | - | Cr (VI) | 11.6 mg/g | Liu et al. (2020) |
| Pharmaceutical sludge activated by NaOH | 756.4 | Tetracycline | 379.8 mg/g | Liu et al. (2021) |
| Sewage sludge | 12.4 | Remazol Brilliant Blue R dye | 80.6 mg/g | Raj et al. (2021) |
| Sewage sludge | 30.6 | Pb, Cu, and Zn | 21.3%, 72.1% and 30.3%, | Wang et al. (2021b) |
| Sewage sludge/ cotton stalks | 78.6 | Pb, Cu, and Zn | 19.0%, 34.9% and 18.2% | Wang et al. (2021b) |
| Waterworks sludge | - | Methylene blue | 300.4 mg/g | Xi et al. (2022) |
| Sewage sludge | 36.5 | Cr, Cu and Zn | 77.0%, 97.4% and 99.7% | Zhang et al. (2022) |
| Sewage sludge | 47.4 | Cr (VI) | 16.6 mg/g | Zhu et al. (2022) |
| Sewage sludge | 76.4 | Cr (VI) | 22.9 mg/g | Zhu et al. (2022) |
| Sewage sludge containing Fe | - | Tetracycline | 90.3% | Kang et al. (2023) |
| Ferromanganese-bearing sludge | 43.1 | Phthalate esters | 65.0% | Hung et al. (2022) |

property of biochar winds the microplastics to increase their size, so as to fix the microplastics for removal (Wang et al., 2020d). Moreover, the interaction between medium pores and hydrophobic pore walls also plays a significant role in removing pollutants.

### 2.3. Electrostatic adsorption

Electrostatic adsorption is also one of the mechanisms for pollutant removal, which mainly rely on charges of the biochar surface and the electrical property of pollutants. There are clay minerals with high ion exchange capacity on the surface of biochar, which stimulate the adsorption of organic dyes, antibiotics, and other pollutants through the ion exchange (Premarathna et al., 2019). Recent studies showed that the functional groups on the surface of sludge biochar could affect the removal rate of anionic and cationic dyes. Wang et al. (2020a) demonstrated that electrostatic adsorption was the main driving force for the adsorption of acridine orange (AO) by biochar. Wang et al. (2021a) also concluded that the electrostatic interaction between biochar and microplastics dominates the removal of microplastics. To improve the removal of organic pollutants, the surface of biochar needs to be modified by functional groups with different electrical properties. In addition, given the charges on biochar surface are significantly affected by pH, the absorption of organic pollutants is also related to variations in pH. When pH $< 7.95$, the surface of sludge biochar activated by peroxydisulfate (PDS) is negatively charged, resulting in electrostatic repulsion between PDS and tetracycline, which reduces the removal rate of tetracycline. The degradation rate of tetracycline is the highest when pH is 5 (Kang et al., 2023). It is generally believed that low pH (i.e. $< 3$) is essential for the dissolution of heavy metals (Yu et al., 2022). Moreover, it should be noted that the electrostatic adsorption effect is mainly related to charges on the biochar surface and the electrical properties of heavy metal ions. As the biochar surface is largely negatively charged, positively charged ions such as $Pb^{2+}$, $Cd^{2+}$, and $Cu^{2+}$ can be easily absorbed onto biochar due to electrostatic interaction. Lima et al. (2022) found that the maximum absorption of $Cd^{2+}$ and $Zn^{2+}$ by sludge biochar was 56.9 mg/g and 26.1 mg/g, respectively.

### 2.4. Hydrogen bonding

Hydrogen bonding represents another mechanism by which biochar

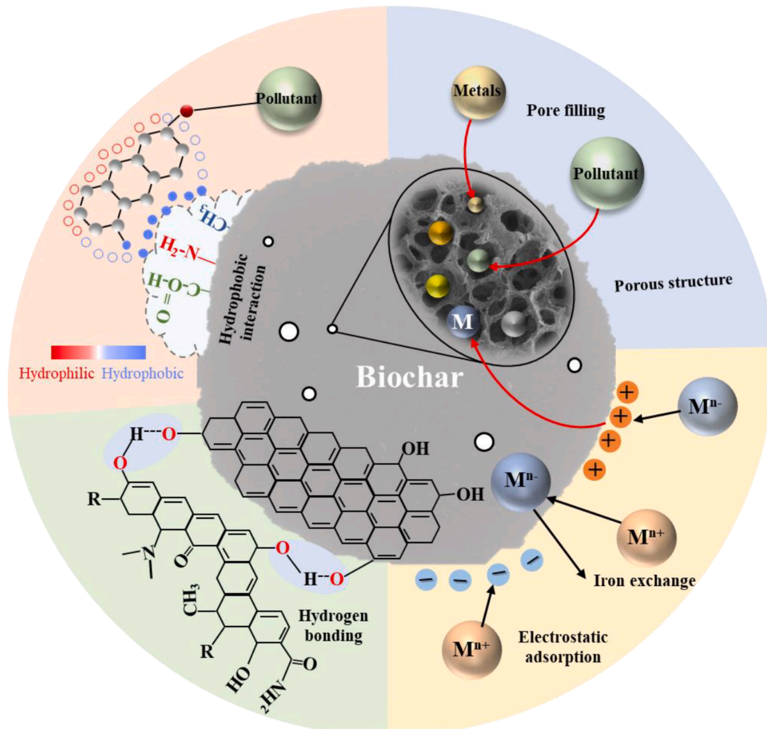


**Fig. 2.** Adsorption mechanism diagram of biochar in water treatment.

absorbs organic matter. The ability of biochar to form hydrogen bonds with hydrogen atoms on pollutants (except heavy metals) is related to the existence of functional groups in biochar (Rangabhashiyam et al., 2022). Zhang et al. (2022b) found that when the pyrolysis temperature of biochar is lower than 350°C, more hydrogen bonds on the material surface can effectively interact with polar organic pollutants. Similarly, biochar prepared at a temperature lower than 500°C has more -C=O groups, leading to a higher degradation of sulfamethoxazole (Wang and Wang, 2021). In addition, the removal performance of biochar against organic pollutants can also be improved by modification. Xu et al. (2022) prepared biochar from sludge and modified sludge biochar with montmorillonite and nano zero-valent iron (nZVI), which produced more effective and stable functional groups on the surface of biochar, promoted the aggregation of free radical cations and improved the adsorption capacity of nitrogen and phosphorus to 34.8 mg/g and 294.1 mg/g, respectively. The adsorption mechanism is related to ligand exchange, electrostatic attraction, and ionic bonds. In addition, phosphorus (P) can be removed by chemical precipitation and co-precipitation of iron corrosion products by nZVI modification. Liu et al. (2021) activated sludge with sodium hydroxide and prepared sludge biochar by dry mixing method. The results showed that the biochar has good tetracycline adsorption performance and the maximum adsorption capacity can reach 379.8 mg/g. Further, the biochar prepared from Fe-Mn activated sludge has good absorptivity and biodegradability for Orange G (75.2%) (Hao et al., 2020). For example, Zhang et al. (2021b) formed Fe0/$Fe_3O_4$/biochar composite by pyrolysis of sludge and walnut shell. The composite has a porous structure and a large specific surface area (109.9 $m^2$/g), and more -OH is produced on the surface, which can promote the degradation of methylene blue. Hung et al. (2022) also found that the oxidation of electron transfer, hydroxyl addition, free radicals (HO·), and non-free radicals in the system was enhanced after the use of biochar, which improved the degradation rate of phthalate esters (90%), indicating that the redox property of biochar and chemical structures of pollutants have a certain effect on the redox process of organic pollutants. Mian et al. (2020) found that N-doped sludge biochar can be used as a non-metal activator to effectively activate peroxymonosulfate (PMS) and thus oxidize and remove organic matter.

Further, given the complicated composition of biochar, biochar materials may contain redox-active metals (e.g., Cu, Fe, and Mn), which can experience certain morphological changes in the biomass pyrolysis process and participate in the reaction in the activation of oxidant, thereby promoting degradation of organic matters. Therefore, biochar is a superior absorbent for organic pollutants and can effectively activate a number of oxidants to oxidize and decompose organic pollutants. In view of the influence of the synthesis method and substrates of biochar on its application, we summarized the elemental composition and characteristics of biochar in order to analyze its application value. It can be seen from Table 3 that sludge biochar produces more ash, which can be used as a biostimulator to remediate the environment (Zhang et al., 2020a). Therefore, sludge biochar has advantages in promoting pollutant remediation.

## 3. Application of sludge biochar in soil remediation

From the analysis of heavy metal content and leachable amount in biochar, it is believed that sewage sludge biochar might be also suitable for soil improvement (Phoungthong et al., 2016).Biochar can be stored in the soil for a long time due to its chemical and thermal stability (Shen et al., 2021). The inherent characteristics of biochar have a positive impact on the physical, chemical, and biological characteristics of the soil amendments, including soil aggregation, pH regulation, nutrient retention, etc., and lead to changes in microbial community structure (He et al., 2021). Its adsorption mechanism diagram is shown in Fig. 3. Meanwhile, by virtue of more adsorption active sites and functional groups of biochar itself, it can be used to remove and immobilize pollutants in the soil to achieve the purpose of soil remediation.

### 3.1. Physical modification

The improvement of soil by adding biochar is mainly reflected in the following aspects. Generally, the porous structure and large specific

**Table 3**
Main characteristics of biochar obtained under different substrates and preparation methods.

| | Substrate | Ash (%) | Volatile matter (%) | Moisture (%) | C (%) | H (%) | N (%) | S (%) | HHV (M/Kg) | Refs. |
|---|---|---|---|---|---|---|---|---|---|---|
| Hydrothermal | Pine | 0.10 | 80.28 | 7.51 | 48.10 | 6.57 | 0.10 | 0.01 | 23.88 | (Wilk et al. 2019) |
| | Acacia | 0.16 | 76.58 | 7.22 | 47.00 | 5.76 | 0.11 | 0.01 | 18.08 | (Wilk et al. 2019) |
| | Beech wood | 1 | 79 | 7 | 48.1 | 6.5 | 0.1 | 0.1 | 19.2 | (Tremel et al. 2012) |
| | Mrine plastic debris | 6.95 | - | 24.5 | 79.0 | 11.9 | 0.60 | - | 38.3 | (Iniguez et al. 2019) |
| | Microalgal biomass | 24.7 | 29.0 | 2.5 | 27.4 | 7.0 | 5.5 | 0.4 | 12.58 | (Khoo et al. 2020) |
| | Banana leaves | 8.4 | 23.3 | - | 49.1 | 4.11 | 1.73 | 1.36 | - | (Mosqueda et al. 2019) |
| | Sewage sludge | 40.06 | 50.45 | 1.33 | 29.60 | 4.30 | 4.35 | 1.58 | 14.34 | (Wilk et al. 2019) |
| Pyrolysis | Corn stalk | 9.6 | 15.4 | - | 73.4 | 1.7 | 1.3 | 0.1 | - | (Wang et al. 2022) |
| | Corn cob | 12.4 | 18.3 | - | 79.5 | 2.2 | 0.8 | 0.1 | - | (Wang et al. 2022) |
| | Rice straw | 13.07 | 76.87 | - | 40.06 | 5.47 | 0.69 | 0.48 | 13 | (Hong et al. 2020) |
| | Flax straw | 2.9 | 81.3 | - | 44.4 | 6.7 | 1.4 | 1.2 | 18.2 | (Mukhambet et al. 2022) |
| | Wheat straw | 14.61 | 65.78 | 7.27 | 38.3 | 6.1 | 2.0 | 0.3 | - | (Ma et al. 2022) |
| | Oat straw | 6.9 | 66.7 | 7.6 | 43.97 | 6.16 | 0.66 | - | - | (Mlonka-Medrala et al. 2021) |
| | Canola straw | 20.4 | - | - | 66.8 | 2.2 | 1.6 | - | 24.6 | (Nzediegwu et al. 2021) |
| | Sawdust | 0.7 | - | - | 85.9 | 2.9 | 0.4 | - | 32.3 | (Nzediegwu et al. 2021) |
| | Sewage sludge | 45.38 | 43.97 | 1.49 | 29.29 | 3.84 | 5.63 | 0.99 | - | (Zhu et al. 2022) |

HHV: Higher heating values

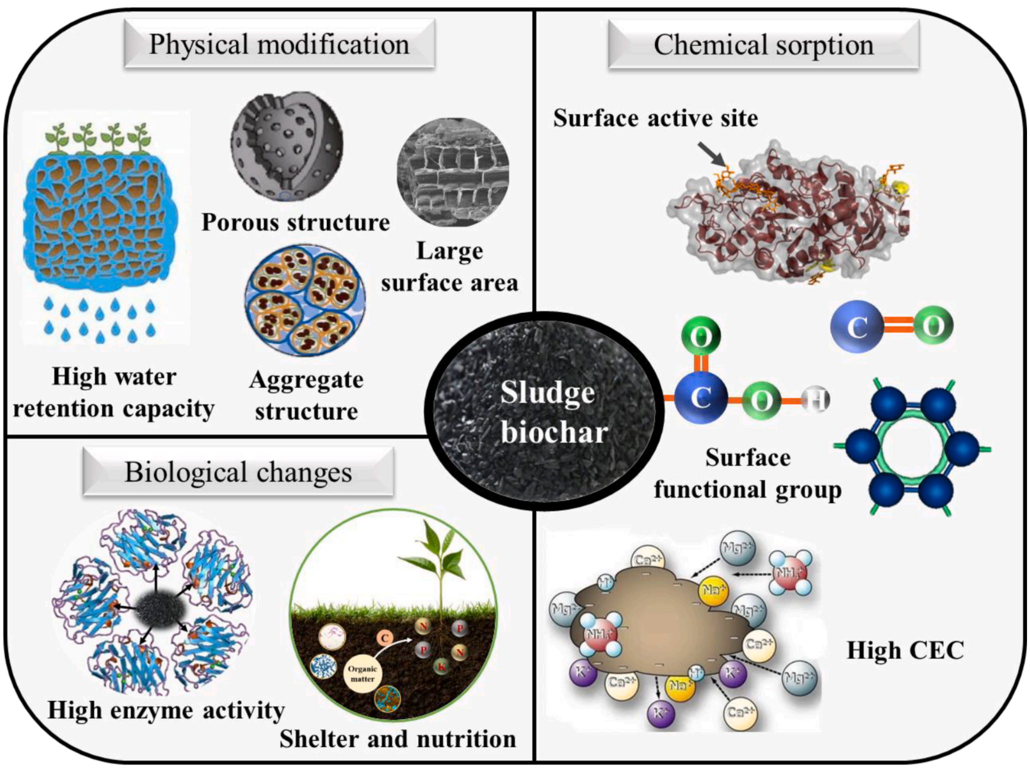


**Fig. 3.** Adsorption mechanism diagram of biochar in soil remediation.

surface area of biochar reduce the soil bulk density, increase the porosity and aggregate structure, and improve the water-retention and supply capacities and hydrophobicity (Adhikari et al., 2022; Zheng et al., 2022). Tokova et al. (2020) added 20 t/ha biochar to a silver loam haplic luvisol, which significantly reduced the bulk density to 12% and increased the soil porosity to 12%. Zhang et al. (2020c) showed that biochar improved the soil aggregates, the micro aggregates and large aggregates in the soil increased by 65–86% and 67–89%, respectively, compared with the control. This led to an increase in soil physical structure, accelerated the growth of crop roots, and increased the total crop yield (10–16%). Recent studies have shown that the effect of biochar on improving water retention capacity is related to the biochar particle size and concentration. Mao et al. (2019) showed that adding 5% biochar can significantly improve the water-holding capacity and hydrophobicity of red and yellow soils. Vilas-Boas et al. (2021) added 10% biochar to sandy soil to achieve 345 g/kg water retention capacity.

As a carbon-rich material, biochar can improve the organic carbon content in the soil. Additionally, the mineral elements rich in biochar can improve the soil nutrient content and effectively regulate the circulation of nutrients in the soil. Zhang et al. (2020c) added 20–40 t/ha biochar in the rice-wheat rotation field, the organic carbon content in the soil increased by 26–53%, and the content of other nutrients in the soil such as total nitrogen and phosphorus increased by 14–16% and 6–19%, respectively. Fang et al. (2020) used Mg/Ca modified biochar to absorb phosphorus in the acid extract of incineration sewage sludge ash for fertilization. Further research suggested that the modified biochar enhanced soil nutrient circulation and organic matter decomposition, improved the germination index of plant seeds, and promoted plant growth and development (Ahmad et al., 2022). It was found that the presence of mineral elements and functional groups in biochar promotes the alkali exchange capacity, thereby increasing the pH of the soil (Wu et al., 2020). In addition, the presence of a large number of hydroxyl and carboxyl groups and aromatic ring structures provides exchange sites for ions on biochar, thus improving the cation exchange capacity (CEC) of soil and affecting the absorption of nutrients by crops. Alves et al. (2021) added sludge biochar to the sandy loam and increased the CEC value from 3.04 to 6.34. Finally, a beet yield of 7.17 times higher than that without biochar was obtained.

Biochar can be used as a slow nutrient release fertilizer for soil remediation and crop growth, because biochar can reduce the migration of water-soluble ions, nutrient loss through leaching, and use of soluble mineral sources (Luo et al., 2021). Therefore, the nutrient can be slowly released into the soil for a long time, thus contributing to improving nutrient absorption and crop productivity. Fachini et al. (2022) studied the release of potassium (K) from the sewage sludge biochar-based fertilizer rich in potassium chloride to the natural silica sand. The biochar reduced the potassium release rate by 77%, improved the potassium utilization efficiency, reduced the leaching amount of potassium, and reduced the risk of this nutrient polluting the groundwater.

### 3.2. Chemical sorption

In recent years, the application of biochar to remove various pollutants from soil has received extensive attention and has been considered an environmentally friendly and cost-effective curing agent, which can directly remove pollutants from the soil by adsorption of available active sites on the surface of materials (El-Naggar et al., 2021; El-Naggar et al., 2020). Wang et al. (2021b) studied the use of Pb adsorption sites composed of phosphorus compounds on the surface of sewage sludge/cotton straw biochar to fix the Pb in the soil. In addition, biochar increased the content of total organic carbon in the soil and formed more Pb complexes, thus further improving the stabilization efficiency of Pb. The application of biochar can also reduce the content of exchangeable heavy metals and their biological effects, improve nutrient utilization, and promote crop growth. Hale et al. (2020) reduced the content of $Al^{3+}$ significantly after adding biochar to aluminum-rich soil. Furthermore, it is worth noting that the metal is concentrated during the preparation of biochar. The number of metals in biochar introduced into the soil is therefore presumed to be much more than that in the original sludge. However, in the study of Zhang et al. (2021a), the use of biochar can significantly reduce the accumulation of metals in the edible part of crops (corn and radish), making it meet the edible content standard (hazard index $< 1$). The formation of oxygen-containing functional groups (C-O/C-OH and C=O) and the change of pH in the soil after adding biochar can realize the adsorption and removal of heavy metals. Aihemaiti et al. (2022) used ferrous sulfate modified sludge biochar to migrate vanadium (V) in the contaminated soil of the mining area. The iron modified biochar provides an amorphous iron oxide with high adsorption capacity, thus further fixing V in the soil. The results showed that the water extractability and acid solubility of vanadium in the contaminated soil was reduced by 99% and 95%, respectively, and the concentration of vanadium was reduced from 340 mg/kg to 14.2 mg/kg. For the degradation of PPCPs in soil, the effect of biochar has also been studied. Chang et al. (2021) used iron manganese oxide modified biochar to increase the residual amount of phthalate in the soil, which is related to the improvement of bacterial community structure by biochar. It has also been confirmed that the removal of polyfluoroalkyl substances (PFAS) from the soil by sewage sludge biochar is also an economic and environmentally sustainable waste management option (Krahn et al., 2022).

### 3.3. Biological changes

Biochar can provide shelter, nutrition, and a comfortable living environment for soil microorganisms (Zheng et al., 2022). The porous structure and high specific surface area of biochar can protect the attachment, and growth of soil microorganisms from the impact of external adverse conditions such as soil pollutants. In addition, nutrient elements (C, N, P, K), ash, and minerals are additional nutrient sources to promote microbial growth. The addition of sludge biochar can improve the state of microorganisms to achieve the degradation and fixation of pollutants in soil. For example, Aihemaiti et al. (2022) have proved that adding biochar can promote the abundance of *Preoteobacteria* and significantly reduce the migration of V (V(V) and V(IV)) in soil. Diao et al. (2022) added sludge biochar to paddy soil, which affected the diversity and species of soil microorganisms (*Actinobacteriota, Pontibacter*, and *Alkaliphilus*), and reduced the bioavailability of Cd and Pb. Ali et al. (2019)found that the addition of sludge biochar to the soil had a strong impact on the accessibility of organochlorine pesticides (OCPs) (8–69%), and enriched the soil microbial community (*Proteobateria, Firmitutes, Gemmatimonades*, and *Actinobacia*). The improvement of enzyme activity also proves the efficiency of biochar. Paz-Ferreiro et al. (2012) monitored the activity of several enzymes that can reflect the soil quality index, such as dehydrogenase, beta-glucosidase, phytoestrase, and arylsulphatase, and found that the enzyme activity was promoted after the addition of sludge biochar. Du et al. (2019) also confirmed that the addition of sludge biochar can improve the activity of aryl sulfase, beta-glucosidase, and dehydrogenase enzymes, thereby improving the removal efficiency of total carbon, N, and S.

In addition to improving microbial activity and enzyme activity, biochar, with its redox-active functional groups, graphitized structure, and redox-active metals, can also be used as an electronic medium to promote the electron transfer process, so as to achieve microbial degradation of pollutants in soil. An et al. (2022) found that the addition of biochar improved the electron transfer ability of microorganisms, and concluded that the electrochemical properties of biochar were important factors affecting the microbial community structure. Tan et al. (2019) used iron-containing biochar to significantly accelerate the electron transfer from microbial cells to Orange G, thereby increasing the reduction removal rate (72–97%). It is proposed that the conductive domain and the charge discharge of surface functional groups in the biochar are the key points for microorganisms to reduce Orange G.

## 4. Application of sludge biochar in carbon dioxide mitigation

### 4.1. Carbon sink

With increasing greenhouse gas emissions and climate change, the question of how to control the emissions of greenhouse gases has been a worldwide crucial problem. Research shows that the continuously increasing carbon content in the atmosphere is mainly caused by the loss of soil carbon sink during large scale land use (Wani et al., 2022). As a stable carbon-rich substance, biochar can fix carbon elements in both preparation and storage processes to prevent carbon from entering the atmosphere, thereby effectively improving soil carbon sink. Adding biochar to the soil will reduce methane and carbon dioxide emissions and fix carbon in the soil, but this is limited to soil with only low organic carbon (Schimmelpfennig et al., 2014). In the study of Hu et al. (2023), the fixed amount of $CO_2$ in soil increased by 50% after adding biochar, because the carbon in biochar is difficult to be degraded, the mechanism behind the carbon change remains to be solved. Meanwhile, adding biochar to soil has a significant impact on the decomposition of organic matter in the soil, and further improves the storage of soil organic carbon. This can be confirmed by several aspects: (1) Compared with organic carbon in natural soil, unstable carbon remaining in biochar obtained under incomplete pyrolysis is preferentially used; (2) Biochar induced the change of microbial community related to soil organic carbon degradation (Yang et al., 2022); (3) Biochar promotes soil aggregation and reduces enzyme activities related to carbon degradation (Gross et al., 2022).

### 4.2. Carbon emission reduction

$CO_2$ capture is considered a potential strategy to reduce the amount of $CO_2$ released into the atmosphere (Guo et al., 2022). Sludge is converted into biochar through pyrolysis, rather than being directly burned or mineralized, which also substantially reduces carbon dioxide emissions. Additionally, biochar is a kind of renewable resource with favorable adsorption performance. As an efficient and environment-friendly $CO_2$ adsorbent, it has many advantages such as low energy demand, low cost, multi-porous structure, and high wide availability (Qiao and Wu, 2022). Compared with other adsorbents such as amine-supported silica, carbonaceous materials, zeolites, and metal-organic frameworks, biochar is more stable, highly aromatized, and carbon-rich (Lee et al., 2020), and is expected to become an economically and environmentally friendly substitute (Guo et al., 2022). The adsorption of carbon dioxide ($CO_2$) by biochar is classified as physical adsorption and chemical adsorption. The adsorption mechanism diagram of biochar in $CO_2$ mitigation is shown in Fig. 4.

(1) $CO_2$ physisorption

The excellent pore structure of biochar play an important role in the physical adsorption of $CO_2$. The pore structure, especially the micropores with a diameter of less than 1 nm, is closer to the dynamic diameter of $CO_2$ molecules. Moreover, because of the overlapping adsorption force and potential field of adjacent pore walls, it has a stronger attraction to $CO_2$ (Guo et al., 2016). Therefore, the physical adsorption can be enhanced by adjusting the pore distribution of biochar (Guo et al., 2022). Serafin et al. (2017) found that by adjusting the pyrolysis temperature and pressure, the biochar showed different micropore sizes, resulting in different sensitivity of carbon dioxide adsorption. At 0°C and 1 atm, only the micropores within the range of 0.30–0.86 nm are most effective for carbon dioxide capture. When the temperature rises to 25°C, the optimum pore size is 0.30–0.33 nm. In the study of Igalavithana et al. (2020b), the sludge posed a more microporous structure of 0.5 nm after pyrolysis at 550°C and steam activation for 45 min, achieving a $CO_2$ adsorption capacity of 2.5 mol/kg. According to the adsorption kinetics test, the $CO_2$ adsorption is finally in equilibrium, indicating that the physical adsorption of biochar is stable. Liu et al. (2022) prepared sludge biochar at the pyrolysis temperature of 600°C. The micropore volume was 0.019 $cm^3$/g, respectively, and the $CO_2$ adsorption capacity reached 28.4 mg/g. Proper adjustment of sewage sludge can promote biochar utilization as an adsorbent. Liu et al. (2022) selected two commonly used dehydration regulators (cationic polyacrylamide and polymer aluminum chloride) to treat raw sludge. The results showed that the micropore volume and micropore surface area of biochar were significantly increased, reaching 0.025 $cm^3$/g and 41.2 $m^2$/g, 0.022 $cm^3$/g and 40.1 $m^2$/g, respectively. Meanwhile, the $CO_2$ adsorption capacity of 48.5 mg/g and 31.9 mg/g were achieved. The $CO_2$ absorbed into the pores of biochar can be released through desorption for further utilization, such as direct utilization (fire extinguishing, cooling), indirect utilization (carbonation, curing of cement), and conversion into value-added compounds. In addition, the recyclability of carbon dioxide can be improved through multiple adsorption-desorption cycles (> 99%) (Igalavithana et al., 2020a).

(2) $CO_2$ chemisorption

The $CO_2$ chemisorption depends on the surface chemical properties of biochar, such as alkaline earth metals, surface functional groups, alkalinity, hydrophobicity, non-polarity, and aromaticity (Igalavithana et al. 2020b; Shafawi et al., 2021), and $CO_2$ is adsorbed by the heterogeneous interaction between $CO_2$ and the biochar surface. However, it is worth noting that the interaction between $CO_2$ and adsorbent decreases with the increase of $CO_2$ load. Therefore, the adsorption capacity of biochar for $CO_2$ will get a discount when over $CO_2$ volume is loaded (Serafin et al., 2017). Increasing the surface alkalinity will change the surface functional groups to improve the interaction with $CO_2$. The $CO_2$ can be converted into carbonaceous compounds, while reducing the oxygen and hydrogen content, the hydrophobicity and low polarity of biochar were greatly improved, which in turn improved the $CO_2$ adsorption capacity of biochar. In addition, the larger specific surface area provides more active sites for $CO_2$ adsorption, which is conducive to $CO_2$ reduction.

The Lewis acid-base interaction and condensation between nitrogen-containing and oxygen-containing functional groups on biochar and $CO_2$ is the most important chemisorption interaction (Shafawi et al., 2021). Alkali elements and alkaline earth metals (Ca, Mg, K, Na, etc.) can improve the alkalinity of biochar, thereby improving the affinity for acidic $CO_2$ and enhancing the adsorption capacity for $CO_2$. Xu et al. (2016) pyrolyzed sludge to produce alkaline biochar, in which Fe, K, Na and other mineral components can induce chemical adsorption of $CO_2$ through mineral reaction. For example, FeOOH in biochar adsorbs $CO_2$

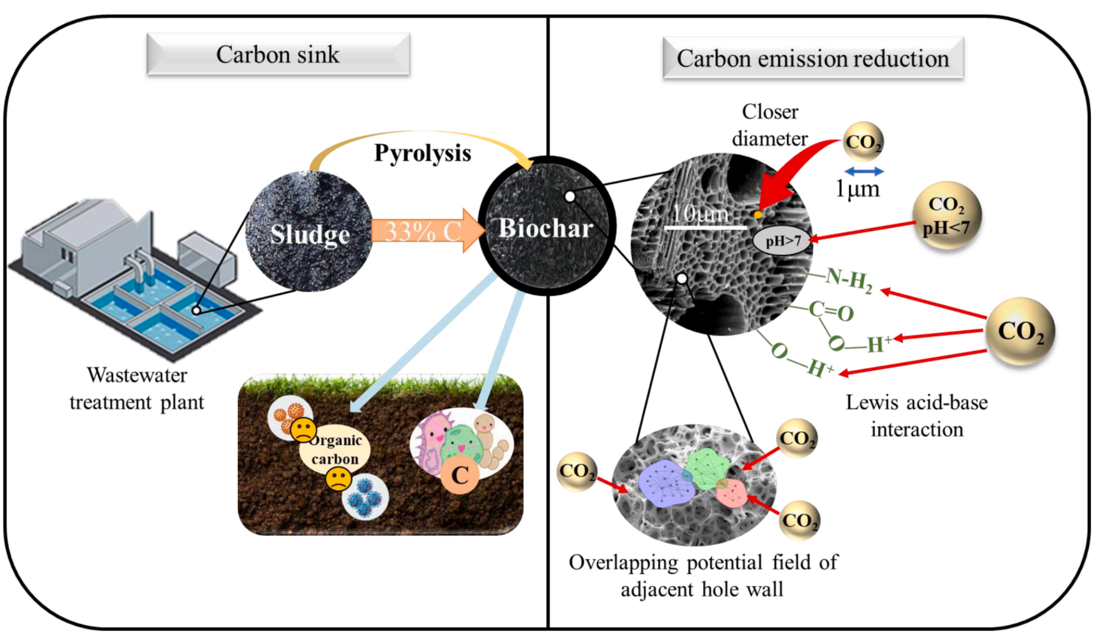


**Fig. 4.** Adsorption mechanism diagram of biochar in carbon dioxide mitigation.

and converts it into $Fe(OH)_2CO_3$, and its adsorption capacity can reach 18.2–34.4 mg/g. Different materials and pyrolysis conditions determine the existence or types of functional groups in biochar. Basic functional groups and oxygen-rich functional groups play a role in promoting the $CO_2$ adsorption capacity of biochar. In addition, common nitrogen-containing functional groups (amide, imine, pyridine, pyrrole, and lactam groups) in biochar can also be used to improve its $CO_2$ adsorption capacity. Li et al. (2022a) reported that more nitrogen content was detected on the surface of biochar produced by sludge pyrolyzed at 700°C, forming more nitrogen-containing functional groups and strengthening its adsorption of $CO_2$. After KOH modification, the adsorption rate of biochar on $CO_2$ is faster, and the adsorption capacity almost increases vertically with time, finally reaching a plateau. Xu et al. (2020) found the maximum $CO_2$ adsorption capacity of N-doped biochar was 49.2 mg/g, which was 55.2% higher than that of original biochar. The presence of heteroatoms (O, K, N, and S) in biochar also plays a positive role in $CO_2$ adsorption (Li et al., 2022b), in which the presence of N and S on the surface of the biochar plays a greater role (Igalavithana et al., 2020a). This is mainly because heteroatoms can further modify the surface area and pore structure of biochar, enhance the hydrophobicity of biochar and improve the electron transfer rate (Ochedi et al., 2020; Petrovic et al., 2022).

## 5. Key barriers of sludge-derived biochar on environmental improvement

### 5.1. Limited adsorption capacity of sludge-derived biochar

The pollutants in soil and water, and the $CO_2$ emissions are typically in the range of 791.71–2071.31 kg/ha, 7.27–42.76 t/day, 13.3–16.2 kt (Song and Pang, 2021; Tian et al., 2022; Yirong, 2022), respectively, while the adsorption capacity of sludge-derived biochar, is generally less than 379.8 mg/g (Table 2). A higher adsorption rate is required to make the industrial application of sludge-derived biochar more economically viable and technically feasible. Therefore, one of the major challenges for sludge-derived biochar on environmental improvement is the poor adsorption performance from the target compounds to the biochar, caused by the limited adsorption capacity. This issue is particularly serious for a large number of pollutants due to the limited biochar preparation. Even massive sludge-derived biochar is introduced into systems, biochar is only available to superficial margins of the target compounds due to limited binding sites in the biochar matrix

The typical equation for describing the rate of biochar adsorption is shown in Eq. (1):

$$Q_e = (C_0 - C_e)\frac{V}{m} \tag{1}$$

where $Q_e$ represents the equilibrium adsorption capacity, mg/g, $C_0$ and $C_e$ represent the initial and equilibrium pollutant concentrations respectively, mg/L, $V$ represents the solution volume, mL; $m$ represents the mass of the added biochar, g (Chen et al., 2022). Moreover, proper biochar recycling equipment is needed, since unused biochar is easily left in the system. The resultant low biochar adsorption capacity will significantly increase the cost of biochar supply, therefore decreasing the economic benefits.

### 5.2. Application restrictions in sludge-derived biochar on environmental improvement

The sludge-derived biochar on environmental improvement has the advantage of simplicity. However, restrictions associated with possible toxicity, energy consumption, and cost input are big issues in sludge-derived biochar applications. The possible toxicity of biochar on the environment and human health is necessary to determine whether biochar can be applied on a large scale. As given in Table 4, the presence of pollutants and toxic substances in biochar, such as volatile organic compounds (VOCs), heavy metals, potentially toxic elements (PTEs), environmentally persistent free radicals (EPFRs), polycyclic aromatic hydrocarbons (PAHs), and dioxins depend on the source of raw sludge and pyrolysis conditions (Zheng et al., 2019b). In particular, the biochar pyrolyzed from sludge also contains heavy metals, toxic substances, and a large amount of nitrogen and phosphorus, which is easy to cause water eutrophication and soil contamination, resulting in threats to the safety of animals, plants, or human beings (He et al., 2019; Hu et al., 2022; Qian et al., 2022). Therefore, when using sludge biochar for pollutant removal, soil remediation, or carbon emission reduction, the composition and quantity of pollutants should be thoroughly determined.

**Table 4**
Main pollutants in sludge biochar obtained under different preparation conditions.

| Feedstock | Pyrolysis Temperature (°C) | Heating rate (°C/min) | Retention time (h) | Pollutants | Refs. |
|---|---|---|---|---|---|
| Sewage sludge | 200–360 | - | 1 | PAHs | Chang et al. (2021) |
| Sewage sludge | 500 | 25 | 5 | PAHs | Tomczyk et al. (2020) |
| Sewage sludge | 550–850 | 25 | 2 | Heavy metals (Zn, Cu, Pb) | Chen et al. (2018) |
| Sewage sludge | 300–700 | 10 | 3 | PAHs | Chen et al. (2019) |

The cost and energy consumption of sludge biochar pyrolysis is a significant part of the application. The preparation of biochar from sludge pyrolysis are multiple processes, such as feedstock supply, biochar pyrolysis, transportation, maintenance, storage, and even regeneration. For instance, it was found that the lower raw material input is beneficial for transportation and storage, and is more conducive to achieving higher pyrolysis energy efficiency (Li et al., 2023). Moreover, the pyrolysis temperature largely determines the output of biochar (Zhang et al., 2020e). This phenomenon means how to balance energy consumption, biochar output, and biochar application efficiency is also an issue that needs to be considered in the biochar application.

## 6. Potential solutions for overcoming barriers

### 6.1. Strategies for enhanced sludge-derived biochar adsorption capacity

(1) Biochar modification

Original biochar can be directly used to adsorb pollutants, heavy metals, and $CO_2$, but it usually shows poor adsorption performance, which limits the large-scale application of biochar for adsorption. Therefore, in practical application, it is necessary to modify biochar to improve its physical and chemical properties, such as improving the specific surface area, increasing pore structure, and embellishing surface functional groups (Serafin et al., 2021; Shafawi et al., 2021). At present, biochar modification includes physical modification, acid modification, alkali modification, mineral modification, nitrogen doping modification, etc. (Hu et al., 2022). In the study of Beckinghausen et al. (2020), the sludge biochar was steam activated, and the results showed that the specific surface area increased by nearly 2.5 times. Ma et al. (2020) modified sludge biochar with phosphoric acid, its specific surface area increased from 14.0 $m^2$/g to 41.6 $m^2$/g, and its adsorption capacity for ciprofloxacin increased from 11.2 mg/g to 15.0 mg/g. KOH modification could increase the porous characteristics of biochar, including both surface area and porosity. It was found by (Li et al., 2022b) that the $CO_2$

adsorption capacity of the original biochar is 35.5–42.9 mg/g, while the value increased to 136.7–182.0 mg/g after KOH activation. The specific surface area of the biochar is 3.9–14.5 times increased, and the micropores formed also assist in enhancing the adsorption capacity of $CO_2$. Another study used 4 mol/L NaOH solution to modify sludge biochar, the specific surface area was increased from 10.9 $m^2$/g to 135.6 $m^2$/g, and its maximum $Cd^{2+}$ adsorption capacity reached to 5.8 mg/g. Wang et al. (2020b) demonstrated that sulfur doping can promote the formation of metastable biochar persulfate complex and enhance the degradation of bisphenol A.

(2) Co-pyrolysis

The effect of biochar is dependent on the type of contaminants. Therefore, it is also worth mixing the sludge with other catalysts or co-pyrolysis with multiple substrates to produce biochar. For example, zero-valent iron (ZVI) can be used as a filler to eliminate heavy metals due to its excellent reduction and adsorption properties (Song et al., 2021). Studies have shown that mixing biochar with ZVI can remediate polluted paddy soil mildly and moderately (Qiao et al., 2019). The combination of composite materials can change biochar into different shapes such as porous biochar, biochar-based beads, and biochar-based hydrogels, so as to adapt to special environments that may lead to the loss of biochar (Sun et al., 2022b).

The separate pyrolysis of sewage sludge has the disadvantages of low energy efficiency and high nitrogen content. While the co-pyrolysis of sewage sludge and biomass can eliminate these problems by virtue of the synergy effect (Qiu et al., 2020). In the study of Naqvi et al. (2019), the co-pyrolysis of sewage sludge and rice husk showed lower activation energy (45.1 kJ/mol–65.8 kJ/mol), that is, the biochar can be synthesized faster with lower energy consumption. Additionally, synergistic pyrolysis could also recover organic components more effectively. Zhang et al. (2020b) found that the co-pyrolysis of sludge and rice husk is more suitable for immobilization with metals, and the co-pyrolysis of sludge and bamboo sawdust is conducive to the increase of the aromatization of biochar. Furthermore, the co-pyrolysis of sewage sludge and other biomass can achieve more carbon fixation, improve carbon storage, and reduce carbon emissions into the environment (Sun et al., 2022a). Igalavithana et al. (2020b) co-pyrolyzed the sludge and pine sawdust at 550°C gave the pore diameter of 0.4–0.5 nm and surface area of 581.7 $m^2$/g, which resulted in the $CO_2$ adsorption capacity increased to 0.7 mmol/g. Konczak et al. (2020) produced biochar by co-pyrolysis of sludge and $CO_2$, which can effectively reduce the toxicity of biochar and alleviate the greenhouse effect caused by $CO_2$.Although modification methods can greatly improve the feasibility and effectiveness of biochar application, these strategies mean additional process and resource consumption. Therefore, developing more economical and feasible sludge biochar modification methods is an important development direction in the future.

### 6.2. *Relieve sludge biochar application restrictions on environmental improvement*

The major challenge for the application of sludge-derived biochar is the generation of toxic compounds. The toxic compounds are generally produced through the following two pathways. Surface reactions that occur between biochar and the target compounds may lead to the release of harmful substances (Xiang et al., 2021), which further cause potential risks to the ecological environment. The free radicals of biochar itself may also induce reactive $O_2$ species that are toxic to aquatic plants released into the water. To solve the above issues, several strategies can be addressed: (I) Pretreatment of sludge prior to pyrolysis (such as acid-elutriation (Yu et al., 2022), advanced oxidation (Wen et al., 2022), hydroxylamine enhanced Fenton oxidation (Yu et al., 2020) (Sun et al., 2022b). (II) Using aging and thermal post-treated biochar to remove polycyclic aromatic hydrocarbons and volatile organic compounds (Han et al., 2022). (III) Choosing precursors with fewer pollutants for pyrolysis. In general, proper pyrolysis unit design can also reduce the content of PAHs, VOCs, dioxins, and persistent free radicals (PFRs), so as to produce biochar safely (Guo et al. 2022; Han et al. 2022).

The key factors to evaluate the feasibility of biochar application are the environmental impact, energy consumption, and economic analysis involved in the sludge derived biochar pyrolysis. With the characteristics of no gas turbine and no reagent cleaning, sludge biochar greatly reduces the emissions of greenhouse gases, ozone, and high concentrations of Zn and Cl, thus showing lower environmental impact than most traditional sewage sludge treatments (Huang et al., 2022). It should be noteworthy that the market price of biochar is still not comparable to the production price (0.78 CAD/kg biochar) (Huang et al., 2022). Therefore, the economic benefits and energy recovery benefits of biochar production from sewage sludge can be improved by introducing bio-oil, natural gas and other sewage sludge by-products into the pyrolysis process (You et al., 2020).

## 7. Conclusion and prospects

Pyrolyzing sewage sludge to biochar improves the physicochemical properties of sewage sludge and broadens the range of applications. Compared to the challenges of traditional methods that need expensive catalysts or intensive energy, sewage sludge derived biochar is promising particularly from a long-term perspective, considering that the input-to-output ratio is continuing to decline. Technical bottlenecks for implementing large-scale sewage-derived biochar for environmental improvement include adsorption capacity and application limitations. In order to address these issues, improved biochar modification and appropriate co-pyrolysis are necessary to enable biochar adsorption capacity improvement and pollutants removal selectivity. Moreover, integrating pretreatments and post-treatments with biochar preparation is a promising strategy to avoid toxic compound contamination during environmental improvement. Finally, the whole life cycle assessment of the aforementioned biochar preparation and application process is required to further evaluate its economics and environmental feasibility.

This review summarizes recent trends in the research on sewage sludge biochar. It is concluded that sludge biochar has high efficiency, strong applicability, and environment-friendly significance in the field of environmental improvements such as water pollution control, soil remediation, and carbon emission reduction. In view of the challenges in applying biochar, new strategies such as feedstock selection and pretreatment, co-pyrolysis, and biochar modification are proposed. It is expected that the insights given in this review will promote more efforts contributed to sludge biochar preparation and modification, thus boosting its application in environmental improvement.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgments

This study was supported by the National Natural Science Foundation of China (No. 31800115, No. 52076063); the Fundamental Research Funds for the Central Universities (Grant No.HIT. OCEF.2021031); the China Postdoctoral Science Foundation (No. 2018M640299); the Heilongjiang Postdoctoral Foundation (No. LBH-Z18091), China; the State Key Laboratory of Urban Water Resource and

Environment, Harbin Institute of Technology (No. 2021TS21), China; Open Project of Key Laboratory of Environmental Biotechnology, CAS (Grant No kf2020009); Foundation from National Engineering Research Center for Bioenergy (Grant No 2021B008); 201 Major Key Projects from Power China Huadong Engineering Corporation Limited (KY2018-ZD-04), and Heilongjiang Touyan Innovation Team Program.

## References

Adhikari, S., Timms, W., Mahmud, M.A.P., 2022. Optimising water holding capacity and hydrophobicity of biochar for soil amendment - a review. Sci. Total Environ. 851 (1), 158043.
Ahmad, A., Chowdhary, P., Khan, N., Chaurasia, D., Varjani, S., Pandey, A., Chaturvedi, P., 2022. Effect of sewage sludge biochar on the soil nutrient, microbial abundance, and plant biomass: a sustainable approach towards mitigation of solid waste. Chemosphere 287 (1), 132112.
Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S., Ok, Y.S., 2014. Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99, 19–33.
Aihemaiti, A., Chen, J., Hua, Y., Dong, C., Wei, X., Yan, F., Zhang, Z., 2022. Effect of ferrous sulfate modified sludge biochar on the mobility, speciation, fractionation and bioaccumulation of vanadium in contaminated soil from a mining area. J. Hazard. Mater. 437, 129405.
Ali, N., Khan, S., Li, Y., Zheng, N., Yao, H., 2019. Influence of biochars on the accessibility of organochlorine pesticides and microbial community in contaminated soils. Sci. Total Environ. 647, 551–560.
Alves, B.S.Q., Zelaya, K.P.S., Colen, F., Frazao, L.A., Napoli, A., Parikh, S.J., Fernandes, L. A., 2021. Effect of sewage sludge and sugarcane bagasse biochar on soil properties and sugar beet production. Pedosphere 31 (4), 572–582.
An, T., Chang, Y., Xie, J., Cao, Q., Liu, Y., Chen, C., 2022. Deciphering physicochemical properties and enhanced microbial electron transfer capacity by magnetic biochar. Bioresour. Technol. 363, 127894.
Beckinghausen, A., Reynders, J., Merckel, R., Wu, Y.W., Marais, H., Schwede, S., 2020. Post-pyrolysis treatments of biochars from sewage sludge and a. mearnsii for ammonia (NH4-n) recovery. Appl. Energy 271.
Chang, X., Song, Z., Xu, Y., Gao, M., 2021. Response of soil characteristics to biochar and Fe-Mn oxide-modified biochar application in phthalate-contaminated fluvo-aquic soils. Ecotoxicol. Environ. Saf. 225, 112755.
Chang, Y.C., Xiao, X.F., Huang, H.J., Xiao, Y.D., Fang, H.S., He, J.B., Zhou, C.H., 2021. Transformation characteristics of polycyclic aromatic hydrocarbons during hydrothermal liquefaction of sewage sludge. J. Supercrit. Fluids 170.
Chen, H.M., Zhou, Y.L., Zhao, H.H., Li, Q., 2018. A comparative study on behavior of heavy metals in pyrochar and hydrochar from sewage sludge. Energy Sources Part A Recovery Util. Environ. Eff. 40 (5), 565–571.
Chen, L.M., Liao, Y.F., Ma, X.Q., Niu, Y.D., 2020. Effect of co-combusted sludge in waste incinerator on heavy metals chemical speciation and environmental risk of horizontal flue ash. Waste Manag. 102, 645–654.
Chen, X.Y., Yang, L.S.T., Myneni, S.T., Deng, Y., 2019. Leaching of polycyclic aromatic hydrocarbons (PAHs) from sewage sludge-derived biochar. Chem. Eng. J. 373, 840–845.
Chen, Y.N., Xu, F.T., Li, H., Li, Y.P., Liu, Y.H., Chen, Y.R., Li, M.L., Li, L.S.Z., Jiang, H.J., Chen, L., 2021. Simple hydrothermal synthesis of magnetic MnFe2O4-sludge biochar composites for removal of aqueous Pb2+. J. Anal. Appl. Pyrol. 156.
Chen, Z., Wu, Y., Huang, Y., Song, L., Chen, H., Zhu, S., Tang, C., 2022. Enhanced adsorption of phosphate on orange peel-based biochar activated by Ca/Zn composite: Adsorption efficiency and mechanisms. Colloids Surf. A 651, 129728.
China 2021 Analysis report on in-depth investigation and investment strategic planning of sludge treatment and disposal in China.
Choi, Y.K., Choi, T.R., Gurav, R., Bhatia, S.K., Park, Y.L., Kim, H.J., Kan, E., Yang, Y.H., 2020. Adsorption behavior of tetracycline onto Spirulina sp. (microalgae)-derived biochars produced at different temperatures. Sci. Total Environ. 710.
Dai, Y.J., Zhang, N.X., Xing, C.M., Cui, Q.X., Sun, Q.Y., 2019. The adsorption, regeneration and engineering applications of biochar for removal organic pollutants: a review. Chemosphere 223, 12–27.
Diao, Y., Zhou, L., Ji, M., Wang, X., Dan, Y., Sang, W., 2022. Immobilization of Cd and Pb in soil facilitated by magnetic biochar: metal speciation and microbial community evolution. Environ. Sci. Pollut. Res. Int. 29 (47), 71871–71881.
Du, J., Zhang, Y., Hu, B., Qv, M., Ma, C., Wei, M., Zhang, H., 2019. Insight into the potentiality of big biochar particle as an amendment in aerobic composting of sewage sludge. Bioresour. Technol. 288, 121469.
El-Naggar, A., Chang, S.X., Cai, Y.J., Lee, Y.H., Wang, J.X., Wang, S.L., Ryu, C., Rinklebe, J., Ok, Y.S., 2021. Mechanistic insights into the (im)mobilization of arsenic, cadmium, lead, and zinc in a multi-contaminated soil treated with different biochars. Environ. Int. 156.
El-Naggar, A., Lee, M.H., Hur, J., Lee, Y.H., Igalavithana, A.D., Shaheen, S.M., Ryu, C., Rinklebe, J., Tsang, D.C.W., Ok, Y.S., 2020. Biochar-induced metal immobilization and soil biogeochemical process: an integrated mechanistic approach. Sci. Total Environ. 698.
Fachini, J., Figueiredo, C.C., Vale, A.T.D., 2022. Assessing potassium release in natural silica sand from novel K-enriched sewage sludge biochar fertilizers. J. Environ. Manag. 314, 115080.
Fang, L., Li, J.S., Donatello, S., Cheeseman, C.R., Poon, C.S., Tsang, D.C.W., 2020. Use of Mg/Ca modified biochars to take up phosphorus from acid-extract of incinerated sewage sludge ash (ISSA) for fertilizer application. J. Clean. Prod. 244.
Gaur, R.Z., Khoury, O., Zohar, M., Poverenov, E., Darzi, R., Laor, Y., Posmanik, R., 2020. Hydrothermal carbonization of sewage sludge coupled with anaerobic digestion: Integrated approach for sludge management and energy recycling. Energy Convers. Manag. 224.
Gross, C.D., Bork, E.W., Carlyle, C.N., Chang, S.X., 2022. Biochar and its manure-based feedstock have divergent effects on soil organic carbon and greenhouse gas emissions in croplands. Sci. Total Environ. 806 (Pt 3), 151337.
Guo, L., Yang, J., Hu, G., Hu, X., Wang, L., Dong, Y., DaCosta, H., Fan, M., 2016. Role of hydrogen peroxide preoxidizing on CO2 adsorption of nitrogen-doped carbons produced from coconut shell. ACS Sustain. Chem. Eng. 4 (5), 2806–2813.
Guo, S., Li, Y., Wang, Y., Wang, L., Sun, Y., Liu, L., 2022. Recent advances in biochar-based adsorbents for CO2 capture. Carbon Capture Sci. Technol. 4, 100059.
Hale, S.E., Nurida, N.L., Jubaedah, Mulder, J., Sormo, E., Silvani, L., Abiven, S., Joseph, S., Taherymoosavi, S., Cornelissen, G., 2020. The effect of biochar, lime and ash on maize yield in a long-term field trial in a Ultisol in the humid tropics. Sci. Total Environ. 719.
Han, H., Buss, W., Zheng, Y., Song, P., Khalid Rafiq, M., Liu, P., Mašek, O., Li, X., 2022a. Contaminants in biochar and suggested mitigation measures – a review. Chem. Eng. J. 429, 132287.
Hao, H.R., Zhang, Q., Qiu, Y., Meng, L., Wei, X.N., Sang, W.J., Tao, J.W., 2020. Insight into the degradation of Orange G by persulfate activated with biochar modified by iron and manganese oxides: Synergism between Fe and Mn. J. Water Process Eng. 37.
He, L.Z., Zhong, H., Liu, G.X., Dai, Z.M., Brookes, P.C., Xu, J., 2019. Remediation of heavy metal contaminated soils by biochar: mechanisms, potential risks and applications in China. Environ. Pollut. 252, 846–855.
He, M., Xiong, X., Wang, L., Hou, D., Bolan, N.S., Ok, Y.S., Rinklebe, J., Tsang, D.C.W., 2021. A critical review on performance indicators for evaluating soil biota and soil health of biochar-amended soils. J. Hazard. Mater. 414, 125378.
He, Z., Cao, H., Liang, J., Hu, Q., Zhang, Y., Nan, X., Li, Z., 2022. Effects of biochar particle size on sorption and desorption behavior of NH4+-N. Ind. Crops Prod. 189, 115837.
Hong, Z.Y., Zhong, F., Niu, W.J., Zhang, K., Su, J., Liu, J.Z., Li, L.J., Wu, F.R., 2020. Effects of temperature and particle size on the compositions, energy conversions and structural characteristics of pyrolysis products from different crop residues. Energy 190.
Hu, J., Zhao, L., Luo, J., Gong, H., Zhu, N., 2022. A sustainable reuse strategy of converting waste activated sludge into biochar for contaminants removal from water: modifications, applications and perspectives. J. Hazard. Mater. 438, 129437.
Hu, Y., Thomsen, T.P., Fenton, O., Sommer, S.G., Shi, W., Cui, W., 2023. Effects of dairy processing sludge and derived biochar on greenhouse gas emissions from Danish and Irish soils. Environ. Res. 216 (Pt 2), 114543.
Huang, C., Mohamed, B.A., Li, L.Y., 2022. Comparative life-cycle assessment of pyrolysis processes for producing bio-oil, biochar, and activated carbon from sewage sludge. Resour. Conserv. Recycl. 181, 106273.
Hung, C.M., Chen, C.W., Huang, C.P., Tsai, M.L., Wu, C.H., Lin, Y.L., Cheng, Y.R., Dong, C.D., 2022. Efficacy and cytotoxicity of engineered ferromanganese-bearing sludge-derived biochar for percarbonate-induced phthalate ester degradation. J. Hazard. Mater. 422, 126922.
Igalavithana, A.D., Choi, S.W., Dissanayake, P.D., Shang, J., Wang, C.H., Yang, X., Kim, S., Tsang, D.C.W., Lee, K.B., Ok, Y.S., 2020a. Gasification biochar from biowaste (food waste and wood waste) for effective CO(2) adsorption. J. Hazard. Mater. 391, 121147.
Igalavithana, A.D., Choi, S.W., Shang, J., Hanif, A., Dissanayake, P.D., Tsang, D.C.W., Kwon, J.H., Lee, K.B., Ok, Y.S., 2020b. Carbon dioxide capture in biochar produced from pine sawdust and paper mill sludge: Effect of porous structure and surface chemistry. Sci. Total Environ. 739, 139845.
Iniguez, M.E., Conesa, J.A., Fullana, A., 2019. Hydrothermal carbonization (HTC) of marine plastic debris. Fuel 257.
Kang, X., Zhang, Q., Liu, X., Song, J., Guo, H., Wang, L., 2023. The interface mechanism of sludge biochar activating persulfate to remove tetracycline: the role of the C-O-Fe bridge at the carbon surface. J. Clean. Prod. 384, 135514.
Khan, A., Khan, S., Lei, M., Alam, M., Khan, M.A., Khan, A., 2020. Biochar characteristics, applications and importance in health risk reduction through metal immobilization. Environ. Technol. Innov. 20.
Khoo, C.G., Lam, M.K., Mohamed, A.R., Lee, K.T., 2020. Hydrochar production from high-ash low-lipid microalgal biomass via hydrothermal carbonization: effects of operational parameters and products characterization. Environ. Res. 188.
Kończak, M., Huber, M., 2022. Application of the engineered sewage sludge-derived biochar to minimize water eutrophication by removal of ammonium and phosphate ions from water. J. Clean. Prod. 331, 129994.
Konczak, M., Pan, B., Ok, Y.S., Oleszczuk, P., 2020. Carbon dioxide as a carrier gas and mixed feedstock pyrolysis decreased toxicity of sewage sludge biochar. Sci. Total Environ. 723, 137796.
Konczak, M., Siatecka, A., Nazarkovsky, M.A., Czech, B., Oleszczuk, P., 2021. Sewage sludge and solid residues from biogas production derived biochar as an effective bio-waste adsorbent of fulvic acids from water or wastewater. Chemosphere 278, 130447.
Krahn, K.M., Cornelissen, G., Castro, G., Arp, H.P.H., Asimakopoulos, A.G., Wolf, R., Holmstad, R., Zimmerman, A.R., Sormo, E., 2022. Sewage sludge biochars as effective PFAS-sorbents. J. Hazard. Mater. 445, 130449.

Lee, S., Han, J., Ro, H.M., 2022. Mechanistic insights into Cd(II) and As(V) sorption on miscanthus biochar at different pH values and pyrolysis temperatures. Chemosphere 287 (Pt 2), 132179.

Lee, Y., Kim, Y.T., Kwon, E.E., Lee, J., 2020. Biochar as a catalytic material for the production of 1,4-butanediol and tetrahydrofuran from furan. Environ. Res. 184.

Levidow, L., Raman, S., 2019. Metamorphosing waste as a resource: Scaling waste management by ecomodernist means. Geoforum 98, 108–122.

Li, K., Niu, X., Zhang, D., Guo, H., Zhu, X., Yin, H., Lin, Z., Fu, M., 2022a. Renewable biochar derived from mixed sewage sludge and pine sawdust for carbon dioxide capture. Environ. Pollut. 306, 119399.

Li, K., Zhang, D., Niu, X., Guo, H., Yu, Y., Tang, Z., Lin, Z., Fu, M., 2022b. Insights into CO2 adsorption on KOH-activated biochars derived from the mixed sewage sludge and pine sawdust. Sci. Total Environ. 826, 154133.

Li, Y., Gupta, R., Zhang, Q., You, S., 2023. Review of biochar production via crop residue pyrolysis: development and perspectives. Bioresour. Technol. 369, 128423.

Lima, J.Z., Ferreira da Silva, E., Patinha, C., Rodrigues, V.G.S., 2022. Sorption and post-sorption performances of Cd, Pb and Zn onto peat, compost and biochar. J. Environ. Manag. 321, 115968.

Liu, C., Wu, Y., Lan, G., Ji, X., Xia, Y., Fu, C., Shen, J., Gui, J., Liu, Y., Qu, Y., Peng, H., 2022. CO2 capture performance of biochar prepared from sewage sludge after conditioning with different dewatering agents. J. Environ. Chem. Eng. 10 (5), 108318.

Liu, H., Xu, G., Li, G., 2021. Preparation of porous biochar based on pharmaceutical sludge activated by NaOH and its application in the adsorption of tetracycline. J. Colloid Interface Sci. 587, 271–278.

Liu, L., Liu, X., Wang, D., Lin, H., Huang, L., 2020. Removal and reduction of Cr(VI) in simulated wastewater using magnetic biochar prepared by co-pyrolysis of nano-zero-valent iron and sewage sludge. J. Clean. Prod. 257, 120562.

Luo, W.C., Qian, L., Liu, W.W., Zhang, X., Wang, Q., Jiang, H.Y., Cheng, B.J., Ma, H., Wu, Z.Y., 2021. A potential Mg-enriched biochar fertilizer: Excellent slow-release performance and release mechanism of nutrients. Sci. Total Environ. 768.

Ma, Y.F., Li, P., Yang, L., Wu, L., He, L.Y., Gao, F., Qi, X.B., Zhang, Z.L., 2020. Iron/zinc and phosphoric acid modified sludge biochar as an efficient adsorbent for fluoroquinolones antibiotics removal. Ecotoxicol. Environ. Saf. 196.

Ma, Y.Y., Li, H.J., Yang, H.Q., Zhu, Y.D., Zhao, L.J., Li, M.Y., 2022. Effects of solid acid and base catalysts on pyrolysis of rice straw and wheat straw biomass for hydrocarbon production. J. Energy Inst. 101, 140–148.

Mao, J.F., Zhang, K., Chen, B.L., 2019. Linking hydrophobicity of biochar to the water repellency and water holding capacity of biochar-amended soil. Environ. Pollut. 253, 779–789.

Mian, M.M., Liu, G.J., Zhou, H.H., 2020. Preparation of N-doped biochar from sewage sludge and melamine for peroxymonosulfate activation: N-functionality and catalytic mechanisms. Sci. Total Environ. 744.

Mlonka-Medrala, A., Evangelopoulos, P., Sieradzka, M., Zajemska, M., Magdziarz, A., 2021. Pyrolysis of agricultural waste biomass towards production of gas fuel and high-quality char: experimental and numerical investigations. Fuel 296.

Mosqueda, A., Medrano, K., Gonzales, H., Yoshikawa, K., 2019. Effect of hydrothermal and washing treatment of banana leaves on co-gasification reactivity with coal. Energy Procedia 158, 785–791.

Mukhambet, Y., Shah, D., Tatkeyeva, G., Sarbassov, Y., 2022. Slow pyrolysis of flax straw biomass produced in Kazakhstan: characterization of enhanced tar and high-quality biochar. Fuel 324.

Naqvi, S.R., Hameed, Z., Tariq, R., Taqvi, S.A., Ali, I., Niazi, M.B.K., Noor, T., Hussain, A., Iqbal, N., Shahbaz, M., 2019. Synergistic effect on co-pyrolysis of rice husk and sewage sludge by thermal behavior, kinetics, thermodynamic parameters and artificial neural network. Waste Manag. 85, 131–140.

Nzediegwu, C., Arshad, M., Ulah, A., Naeth, M.A., Chang, S.X., 2021. Fuel, thermal and surface properties of microwave-pyrolyzed biochars depend on feedstock type and pyrolysis temperature. Bioresour. Technol. 320.

Ochedi, F.O., Liu, Y.X., Adewuyi, Y.G., 2020. State-of-the-art review on capture of CO2 using adsorbents prepared from waste materials. Process Saf. Environ. 139, 1–25.

Patel, S., Kundu, S., Halder, P., Ratnnayake, N., Marzbali, M.H., Aktar, S., Selezneva, E., Paz-Ferreiro, J., Surapaneni, A., de Figueiredo, C.C., Sharma, A., Megharaj, M., Shah, K., 2020. A critical literature review on biosolids to biochar: an alternative biosolids management option. Rev. Environ. Sci. Biotechnol. 19 (4), 807–841.

Paz-Ferreiro, J., Gascó, G., Gutiérrez, B., Méndez, A., 2012. Soil biochemical activities and the geometric mean of enzyme activities after application of sewage sludge and sewage sludge biochar to soil. Biol. Fertil. Soils 48, 511–517.

Petrovic, B., Gorbounov, M., Masoudi Soltani, S., 2022. Impact of surface functional groups and their introduction methods on the mechanisms of CO2 adsorption on porous carbonaceous adsorbents. Carbon Capture Sci. Technol. 3, 100045.

Phoungthong, K., Zhang, H., Shao, L.M., He, P.J., 2016. Variation of the phytotoxicity of municipal solid waste incinerator bottom ash on wheat (Triticum aestivum L.) seed germination with leaching conditions. Chemosphere 146, 547–554.

Premarathna, K.S.D., Rajapaksha, A.U., Sarkar, B., Kwon, E.E., Bhatnagar, A., Ok, Y.S., Vithanage, M., 2019. Biochar-based engineered composites for sorptive decontamination of water: a review. Chem. Eng. J. 372, 536–550.

Qian, T., Ong, W.S., Lu, D., Zhou, Y., 2022. A potential phosphorus fertilizer to alleviate the oming "phosphorus crisis"-biochar derived from enhanced biological phosphorus removal sludge. Sci. Total Environ. 838 (Pt 4), 156559.

Qiao, J.T., Yu, H.Y., Wang, X.Q., Li, F.B., Wang, Q., Yuan, Y.Z., Liu, C.P., 2019. The applicability of biochar and zero-valent iron for the mitigation of arsenic and cadmium contamination in an alkaline paddy soil. Biochar 1 (2), 203–212.

Qiao, Y., Wu, C., 2022. Nitrogen enriched biochar used as CO2 adsorbents: a brief review. Carbon Capture Sci. Technol. 2, 100018.

Qiu, B., Shao, Q., Shi, J., Yang, C., Chu, H., 2022. Application of biochar for the adsorption of organic pollutants from wastewater: modification strategies, mechanisms and challenges. Sep. Purif. Technol. 300, 121925.

Qiu, Z.Z., Zhai, Y.B., Li, S.H., Liu, X.M., Liu, X.P., Wang, B., Liu, Y.L., Li, C.T., Hu, Y.J., 2020. Catalytic co-pyrolysis of sewage sludge and rice husk over biochar catalyst: Bio-oil upgrading and catalytic mechanism. Waste Manag. 114, 225–233.

Rangabhashiyam, S., Lins, P., Oliveira, L., Sepulveda, P., Ighalo, J.O., Rajapaksha, A.U., Meili, L., 2022. Sewage sludge-derived biochar for the adsorptive removal of wastewater pollutants: a critical review. Environ. Pollut. 293, 118581.

Raj, A., Yadav, A., Rawat, A.P., Singh, A.K., Kumar, S., Pandey, A.K., Sirohi, R., Pandey, A., 2021. Kinetic and thermodynamic investigations of sewage sludge biochar in removal of Remazol Brilliant Blue R dye from aqueous solution and evaluation of residual dyes cytotoxicity. Environ. Technol. Innov. 23, 101556.

Schimmelpfennig, S., Müller, C., Grünhage, L., Koch, C., Kammann, C., 2014. Biochar, hydrochar and uncarbonized feedstock application to permanent grassland—effects on greenhouse gas emissions and plant growth. Agric. Ecosyst. Environ. 191, 39–52.

Serafin, J., Narkiewicz, U., Morawski, A.W., Wróbel, R.J., Michalkiewicz, B., 2017. Highly microporous activated carbons from biomass for $CO_2$ capture and effective micropores at different conditions. J. $CO_2$ Util. 18, 73–79.

Serafin, J., Ouzzine, M., Cruz, O.F., Srenscek-Nazzal, J., 2021. Preparation of low-cost activated carbons from amazonian nutshells for CO2 storage. Biomass Bioenergy 144.

Shafawi, A.N., Mohamed, A.R., Lahijani, P., Mohammadi, M., 2021. Recent advances in developing engineered biochar for CO2 capture: An insight into the biochar modification approaches. J. Environ. Chem. Eng. 9 (6).

Shen, H., Zhang, Q., Zhang, X., Jiang, X., Zhu, S., Chen, A., Wu, Z., Xiong, Z., 2021. *In situ* effects of biochar field-aged for six years on net N mineralization in paddy soil. Soil Tillage Res. 205, 104766.

Song, J.M., Huang, G.X., Han, D.Y., Hou, Q.X., Gan, L., Zhang, M., 2021. A review of reactive media within permeable reactive barriers for the removal of heavy metal (loid)s in groundwater: current status and future prospects. J. Clean. Prod. 319.

Song, W., Pang, Y., 2021. Research on narrow and generalized water environment carrying capacity, economic benefit of Lake Okeechobee, USA. Ecol. Eng. 173, 106420.

Steele, J.C., Meng, X.Z., Venkatesan, A.K., Halden, R.U., 2022. Comparative meta-analysis of organic contaminants in sewage sludge from the United States and China. Sci. Total Environ. 821, 153423.

Sun, H., Luo, L., Wang, D., Liu, W., Lan, Y., Yang, T., Gai, C., Liu, Z., 2022a. Carbon balance analysis of sewage sludge biochar-to-soil system. J. Clean. Prod. 358, 132057.

Sun, Y., Wang, T., Bai, L., Han, C., Sun, X., 2022b. Application of biochar-based materials for remediation of arsenic contaminated soil and water: preparation, modification, and mechanisms. J. Environ. Chem. Eng. 10 (5), 108292.

Tan, W., Wang, L., Yu, H., Zhang, H., Zhang, X., Jia, Y., Li, T., Dang, Q., Cui, D., Xi, B., 2019. Accelerated microbial reduction of azo dye by using biochar from iron-rich-biomass pyrolysis. Materials 12 (7), 1079.

Tian, K., Li, M., Hu, W., Fan, Y., Huang, B., Zhao, Y., 2022. Environmental capacity of heavy metals in intensive agricultural soils: Insights from geochemical baselines and source apportionment. Sci. Total Environ. 819, 153078.

Tokova, L., Igaz, D., Horak, J., Aydin, E., 2020. Effect of biochar application and re-application on soil bulk density, porosity, saturated hydraulic conductivity, water content and soil water availability in a silty loam haplic luvisol. Agronomy 10 (7). Basel.

Tomczyk, B., Siatecka, A., Jedruchniewicz, K., Sochacka, A., Bogusz, A., Oleszczuk, P., 2020. Polycyclic aromatic hydrocarbons (PAHs) persistence, bioavailability and toxicity in sewage sludge- or sewage sludge-derived biochar-amended soil. Sci. Total Environ. 747.

Tremel, A., Stemann, J., Herrmann, M., Erlach, B., Spliethoff, H., 2012. Entrained flow gasification of biocoal from hydrothermal carbonization. Fuel 102, 396–403.

USEPA, 2007. National Sewage Sludge Survey Report. USEPA, Washington D.C.

Vilas-Boas, A.C.M., Tarelho, L.A.C., Kamali, M., Hauschild, T., Pio, D.T., Jahanianfard, D., Gomes, A.P.D., Matos, M.A.A., 2021. Biochar from slow pyrolysis of biological sludge from wastewater treatment: characteristics and effect as soil amendment. Biofuels Bioprod. Biorefining 15 (4), 1054–1072.

Wang, H., Zhao, W., Chen, Y.N., Li, Y.H., 2020a. Nickel aluminum layered double oxides modified magnetic biochar from waste corncob for efficient removal of acridine orange. Bioresour. Technol. 315.

Wang, H.Z., Guo, W.Q., Liu, B.H., Si, Q.S., Luo, H.C., Zhao, Q., Ren, N.Q., 2020b. Sludge-derived biochar as efficient persulfate activators: sulfurization-induced electronic structure modulation and disparate nonradical mechanisms. Appl. Catal. B Environ. 279.

Wang, J., Sun, C., Huang, Q.X., Chi, Y., Yan, J.H., 2021a. Adsorption and thermal degradation of microplastics from aqueous solutions by Mg/Zn modified magnetic biochars. J. Hazard. Mater. 419, 126486.

Wang, K., Nakakubo, T., 2022. Design of a sewage sludge energy conversion technology introduction scenario for large city sewage treatment plants in Japan: focusing on zero fuel consumption. J. Clean. Prod. 379, 134794.

Wang, L., Olsen, M.N.P., Moni, C., Dieguez-Alonso, A., de la Rosa, J.M., Stenrød, M., Liu, X., Mao, L., 2022. Comparison of properties of biochar produced from different types of lignocellulosic biomass by slow pyrolysis at 600°C. Appl. Energy Combust. Sci. 12, 100090.

Wang, S.Z., Wang, J.L., 2021. Nitrogen doping sludge-derived biochar to activate peroxymonosulfate for degradation of sulfamethoxazole: modulation of degradation mechanism by calcination temperature. J. Hazard. Mater. 418.

Wang, X.D., Li, C.X., Li, Z.W., Yu, G.W., Wang, Y., 2019. Effect of pyrolysis temperature on characteristics, chemical speciation and risk evaluation of heavy metals in biochar derived from textile dyeing sludge. Ecotoxicol. Environ. Saf. 168, 45–52.

Wang, Z., Sedighi, M., Lea-Langton, A., 2020d. Filtration of microplastic spheres by biochar: removal efficiency and immobilisation mechanisms. Water Res. 184, 116165.

Wang, Z., Shen, R., Ji, S., Xie, L., Zhang, H., 2021b. Effects of biochar derived from sewage sludge and sewage sludge/cotton stalks on the immobilization and phytoavailability of Pb, Cu, and Zn in sandy loam soil. J. Hazard. Mater. 419, 126468.

Wani, O.A., Kumar, S., Hussain, N., Wani, A.I.A., Babu, S., Alam, P., Rashid, M., Popescu, S.M., Mansoor, S., 2022. Multi-scale processes influencing global carbon storage and land-carbon-climate nexus: a critical review. Pedosphere.

Wen, Q., Ma, M., Hou, H., Yu, W., Gui, G., Wu, Q., Xiao, K., Zhu, Y., Tao, S., Liang, S., Liu, B., Hu, J., Yang, J., 2022. Recirculation of reject water in deep-dewatering process to influent of wastewater treatment plant and dewaterability of sludge conditioned with Fe(2+)/H(2)O(2), Fe(2+)/Ca(ClO)(2), and Fe(2+)/Na(2)S(2)O(8): From bench to pilot-scale study. Environ. Res. 203, 111825.

Wilk, M., Magdziarz, A., Jayaraman, K., Szymanska-Chargot, M., Gokalp, I., 2019. Hydrothermal carbonization characteristics of sewage sludge and lignocellulosic biomass. A comparative study. Biomass Bioenergy 120, 166–175.

Wu, S.W., Zhang, Y., Tan, Q.L., Sun, X.C., Wei, W.H., Hu, C.X., 2020. Biochar is superior to lime in improving acidic soil properties and fruit quality of Satsuma mandarin. Sci. Total Environ. 714.

Xi, J., Zhang, R., Ye, L., Du, X., Lu, X., 2022. Multi-step preparation of Fe and Si modified biochar derived from waterworks sludge towards methylene blue adsorption. J. Environ. Manag. 304, 114297.

Xiang, L., Liu, S.H., Ye, S.J., Yang, H.L., Song, B., Qin, F.Z., Shen, M.C., Tan, C., Zeng, G. M., Tan, X.F., 2021. Potential hazards of biochar: The negative environmental impacts of biochar applications. J. Hazard. Mater. 420.

Xu, D., Fan, X., Chen, Q., Qiao, S., Zhang, J., Yang, Y., Wang, H., Zhang, L., Hou, J., 2022. Removal of nitrogen and phosphorus from water by sludge-based biochar modified by montmorillonite coupled with nano zero-valent iron. Water Sci. Technol. 85 (7), 2114–2128.

Xu, X.Y., Kan, Y., Zhao, L., Cao, X.D., 2016. Chemical transformation of CO2 during its capture by waste biomass derived biochars. Environ. Pollut. 213, 533–540.

Xu, X.Y., Xu, Z.B., Gao, B., Zhao, L., Zheng, Y.L., Huang, J.S., Tsang, D.C.W., Ok, Y.S., Cao, X.D., 2020. New insights into CO2 sorption on biochar/Fe oxyhydroxide composites: kinetics, mechanisms, and *in situ* characterization. Chem. Eng. J. 384.

Yang, Y., Sun, K., Han, L., Chen, Y., Liu, J., Xing, B., 2022. Biochar stability and impact on soil organic carbon mineralization depend on biochar processing, aging and soil clay content. Soil Biol. Biochem. 169, 108657.

Yirong, Q., 2022. Does environmental policy stringency reduce CO2 emissions? Evidence from high-polluted economies. J. Clean. Prod. 341, 130648.

You, S., Li, W., Zhang, W., Lim, H., Kua, H.W., Park, Y.K., Igalavithana, A.D., Ok, Y.S., 2020. Energy, economic, and environmental impacts of sustainable biochar systems in rural China. Crit. Rev. Environ. Sci. Technol. 52 (7), 1063–1091.

Yu, W., Duan, H., Wang, Z., Yang, J., Yuan, Z., Zheng, M., 2022. Transforming anaerobically digested sludge into high-quality biosolids with an integrated physiochemical approach. Resour. Conserv. Recycl. 184, 106416.

Yu, W., Wen, Q., Yang, J., Xiao, K., Zhu, Y., Tao, S., Liang, S., Hu, S., Wu, Q., Hou, H., Liu, B., Hu, J., 2020. Novel insights into extracellular polymeric substance degradation, hydrophilic/hydrophobic characteristics, and dewaterability of waste activated sludge pretreated by hydroxylamine enhanced fenton oxidation. ACS ES T Eng. 1 (3), 385–392.

Zhang, G., He, L., Guo, X., Han, Z., Ji, L., He, Q., Han, L., Sun, K., 2020a. Mechanism of biochar as a biostimulation strategy to remove polycyclic aromatic hydrocarbons from heavily contaminated soil in a coking plant. Geoderma 375, 114497.

Zhang, J., Hu, H., Wang, M., Li, Y., Wu, S., Cao, Y., Liang, P., Zhang, J., Naidu, R., Liu, Y., Man, Y.B., Wong, M.H., Zhang, C., Shan, S., 2021a. Land application of sewage sludge biochar: Assessments of soil-plant-human health risks from potentially toxic metals. Sci. Total Environ. 756, 144137.

Zhang, J., Jin, J.W., Wang, M.Y., Naidu, R., Liu, Y.J., Man, Y.B., Liang, X.Q., Wong, M.H., Christie, P., Zhang, Y., Song, C.F., Shan, S.D., 2020b. Co-pyrolysis of sewage sludge and rice husk/bamboo sawdust for biochar with high aromaticity and low metal mobility. Environ. Res. 191.

Zhang, Q.Q., Song, Y.F., Wu, Z., Yan, X.Y., Gunina, A., Kuzyakov, Y., Xiong, Z.Q., 2020c. Effects of six-year biochar amendment on soil aggregation, crop growth, and nitrogen and phosphorus use efficiencies in a rice-wheat rotation. J. Clean. Prod. 242.

Zhang, S.S., Du, Q., Cheng, K., Antonietti, M., Yang, F., 2020d. Efficient phosphorus recycling and heavy metal removal from wastewater sludge by a novel hydrothermal humification-technique. Chem. Eng. J. 394.

Zhang, X., Zhang, P., Yuan, X., Li, Y., Han, L., 2020e. Effect of pyrolysis temperature and correlation analysis on the yield and physicochemical properties of crop residue biochar. Bioresour. Technol. 296, 122318.

Zhang, X., Zhao, B., Liu, H., Zhao, Y., Li, L., 2022a. Effects of pyrolysis temperature on biochar's characteristics and speciation and environmental risks of heavy metals in sewage sludge biochars. Environ. Technol. Innov. 26, 102288.

Zhang, X., Zhao, B.W., Liu, H., Zhao, Y., Li, L.J., 2022b. Effects of pyrolysis temperature on biochar's characteristics and speciation and environmental risks of heavy metals in sewage sludge biochars. Environ. Technol. Innov. 26.

Zhang, Y., Maierdan, Y., Guo, T., Chen, B., Fang, S., Zhao, L., 2022. Biochar as carbon sequestration material combines with sewage sludge incineration ash to prepare lightweight concrete. Constr. Build. Mater. 343, 128116.

Zhang, Y.P., Peng, X.S., Tian, J.Y., Li, F., Fan, X.T., Ma, L.R., Zhang, R.J., 2021b. Synthesis of peroxymonosulfate composite catalyst (Fe-0/Fe3O4/biochar) using waterworks sludge and walnut shell for degrading methylene blue. J. Environ. Chem. Eng. 9 (6).

Zhu, Y., Wei, J., Li, J., 2022. Decontamination of Cr(VI) from water using sewage sludge-derived biochar: Role of environmentally persistent free radicals. Chin. J. Chem. Eng.

Zheng, C.P., Ma, X.Q., Yao, Z.L., Chen, X.F., 2019a. The properties and combustion behaviors of hydrochars derived from co-hydrothermal carbonization of sewage sludge and food waste. Bioresource Technol. 285.

Zheng, H., Liu, B., Liu, G., Cai, Z. and Zhang, C. 2019b Potential toxic compounds in biochar. 349-384.

Zheng, X., Xu, W., Dong, J., Yang, T., Shangguan, Z., Qu, J., Li, X., Tan, X., 2022. The effects of biochar and its applications in the microbial remediation of contaminated soil: a review. J. Hazard. Mater. 438, 129557.

Zhu, K., Wang, X., Geng, M., Chen, D., Lin, H., Zhang, H., 2019. Catalytic oxidation of clofibric acid by peroxydisulfate activated with wood-based biochar: effect of biochar pyrolysis temperature, performance and mechanism. Chem. Eng. J. 374, 1253–1263.