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Combined effects of earthworms and biochar on PAHs-contaminated soil remediation: A review

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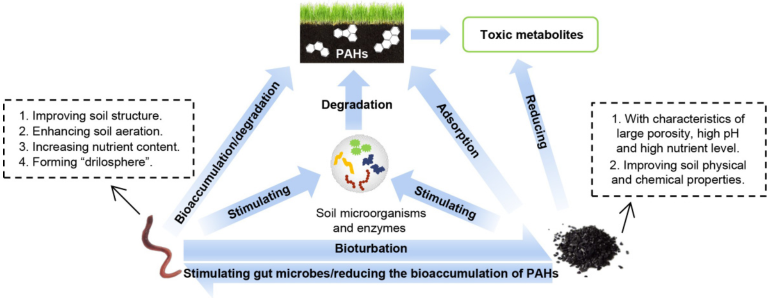
ABSTRACT



- Earthworm remove PAHs from soil by bioaccumulation and stimulating microbial degradation.
- Biochar can adsorb PAHs and promote microbial degradation in soil.
- Earthworm improve the adsorption process of biochar by bioturbation.
- Biochar reduce the vermiaccumulation and improve the decomposition of PAHs by earthworm.

Polycyclic aromatic hydrocarbons (PAHs) in soil pose a threat to the health of humans and other organisms due to their persistence. The remediation method of combined application of biochar and earthworms has received growing attention owing to its effectiveness in PAHs removal. However, the earthworm–biochar interaction and its influence on PAHs in soil has not been systematically reviewed. This review focuses on the effectiveness of combined application of earthworms and biochar in the remediation of PAHs-contaminated soils and the underlying mechanisms, including adsorption, bioaccumulation, and biodegradation. Earthworm–biochar interaction activates the functional microorganisms in soil and the PAHs-degrading microorganisms in earthworm guts, promoting PAHs biodegradation. This review provides a theoretical support for the combined application of biochar and earthworms in the remediation of PAHs-contaminated soils, points out the limitations of this remediation method, and finally shows the prospects for future research.

Keywords earthworm, biochar, soil, PAHs, combined effect

1 Introduction

Soil can be both a source and sink for organic pollutants, including polycyclic aromatic hydrocarbons (PAHs) (Wild and Jones, 1995; Wilcke, 2000). PAHs are mainly produced by anthropogenic activities such as industrial production and daily life (Menzie et al., 1992; Edwards, 2004). They are hydrophobic, lipophilic, and of low volatility, and their hydrophobicity increases while volatility decreases with the increase in aromatic rings (Sims and Overcash, 1983). Some high molecular weight PAHs do not volatilize or photolyze under natural conditions. Therefore, they are persistent in soils (Sims and Overcash, 1983; Kuppusamy et al., 2017). Many PAHs are toxic, threatening human health after being amplified along the food chain (Diggs et al., 2011; Abdel-Shafy and Monsour, 2016). Sixteen PAHs have been listed as priority pollutants by the US Environmental Protection Agency (Hartmann, 1996).

Traditional strategies use physical or chemical methods to remediate organic contaminated soils (Shi et al., 2020), including soil washing, steam extraction, electric remediation, oxidation, reduction, and dechlorination (Scullion, 2006). These methods are both costly and eco-unfriendly due to their complex processes and possibility of causing secondary pollution (Gan et al., 2009; Xu et al., 2018; Dhaliwal et al., 2020). Therefore, alternative techniques for organic contaminated soil remediation are urgently needed. Since the 1980s, eco-friendly remediation methods involving soil microbes, animals, and plants have been increasingly used (Vogel and Grbic-Galic, 1986; Wilson and Jones, 1993; Zou et al., 2000; Juwarkar et al., 2010; Ye et al., 2017; Rodriguez-Campos et al., 2019). Of these methods, vermiremediation has been shown to be an effective method for treating wastewater sludge and municipal solid wastes and removing organic contaminants in soils (Eijsackers et al.,

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2001; Tharakan et al., 2006; Hickman and Reid, 2008; Rodriguez-Campos et al., 2014; Rorat et al., 2017; Zeb et al., 2020). In vermiremediation, earthworms change the physical and chemical properties of soils via burrowing and feeding, thereby increasing the availability of pollutants (Curry and Schmidt, 2007). Earthworms not only directly remove contaminants through absorbing and digesting but also indirectly remove contaminants by stimulating their degradation by microbes (Haimi, 2000; Sinha et al., 2010; Shi et al., 2014; Cao et al., 2015). The remediation method using biochar is also effective in organic pollutant removal from soils (Beesley et al., 2010; Chen et al., 2011a; Marchal et al., 2013). Biochar is a stable carbon-rich material produced through pyrolysis/carbonization of plant or animal biomass (Lehmann et al., 2011; Ahmad et al., 2014; Amoah-Antwi et al., 2020). Biochar application improves the soil biological environment and influences the physical and chemical transformation of soil pollutants (Lehmann et al., 2011; Chen and Yuan, 2011; Ahmad et al., 2014; Nsamba et al., 2015; Sadegh-Zadeh et al., 2017; Sandhu et al., 2017; Suliman et al., 2017; Wang et al., 2017a; Bielská et al., 2018; Toková et al., 2020; Siedt et al., 2021).

Although earthworms have been widely used to remove PAHs from soils, their ingestion and accumulation of contaminants can lead to the transfer of pollutants from soils to the food chain as many small mammals and birds prey on earthworms (Bergknut et al., 2007; Fagervold et al., 2010; Malev et al., 2016). In addition, the ingested PAHs can be excreted back to the soil by earthworms during their activities or released back to the soil when earthworms die and decompose (Coutiño-González et al., 2010). To find a more effective remediation method, many researchers have used earthworms and biochar together for pollutant removal and soil quality improvement (Gomez-Eyles et al., 2011; Wang et al., 2014; Zhang et al., 2019). Biochar has a high adsorption capacity for pollutants, thereby decreasing pollutant bioavailability in soil. It generally has a high pH and contains some toxic substances (Godlewska et al., 2021), which may have an adverse effect on earthworms. However, when applied in organic contaminated soils, it enhances pollutant degradation by microorganisms and reduces pollutant bioaccumulation by earthworms (Cao et al., 2011; Gomez-Eyles et al., 2011; Wang et al., 2012; Sanchez-Hernandez et al., 2019). Earthworms improve biochar migration in soil. Therefore, combined application of biochar and earthworms has been recognized as an effective and eco-friendly remediation method for organic contaminated soils (Eckmeier et al., 2007).

This review is based on a search of the literature published between 1970 and 2022 using six keywords: soil, earthworms, biochar, pollution, organic contaminants, and PAHs, and 319 articles were cited. The following three aspects are focused on in this review to provide an overview of recent developments in the combined application of earthworms and biochar in PAHs-contaminated soil remediation:

(1) The role earthworms play in the remediation of PAHs-contaminated soils;

(2) Influencing factors of biochar characteristics during biochar production, and underlying mechanisms of PAHs-contaminated soil remediation using biochar;

(3) Earthworm–biochar interaction in PAHs-contaminated soil remediation and advantages and limitations of combined application of earthworms and biochar.

2 The role earthworms play in the remediation of PAHs-contaminated soils

Vermiremediation of organic contaminated soils is a complex process involving several mechanisms that are related to soil physical, chemical, and biological properties (Fig. 1) (Michael et al., 1997; Tiunov and Scheu, 1999; Contreras-Ramos et al., 2008; Qi and Chen, 2010). Vermiremediation has been proven to be effective in removing organic pollutants from soils, including PAHs, PCBs, and pesticides (Singer et al., 2001; Lin et al., 2012; Rodriguez-Campos et al., 2019).

2.1 The tolerance of earthworms to PAHs

To successfully apply vermiremediation in PAHs-contaminated soils, it is important to know the lethal dose values of PAHs for earthworms (Rodriguez-Campos et al., 2014). In the early 1980s, some researchers found that earthworms could survive and grow in soils with high concentrations of PAHs (Simmers et al., 1986; Hund and Traunspurger, 1994). Several studies have shown that earthworms could tolerate up to 1000 mg kg^{-1} PAHs in soil or sediment with a survival rate over 80% (Eijsackers et al., 2001; Contreras-Ramos et al., 2006; Natal-da-Luz et al., 2012; Rodriguez-Campos et al., 2014). Gomez-Eyles et al. (2011) discovered that after 56 days of exposure to 773 mg kg^{-1} PAHs in a soil, 97.5% earthworms survived. Even in soils with total petroleum hydrocarbon concentrations close to 12 000 mg kg^{-1}, earthworm densities as high as 512 individual m^{-2} were found (Zavala-Cruz et al., 2014).

Although earthworms can tolerate high concentrations of PAHs, it is evident that their growth and reproduction are negatively affected by PAHs in soils and sediments (Eijsackers et al., 2001; Matscheko et al., 2002; Contreras-Ramos et al., 2006; Gomez-Eyles et al., 2011; Natal-da-Luz et al., 2012). The reduced reproductivity of earthworms in PAHs-contaminated soils could be a result of decreased protein and enzyme contents (e.g., catalase, cellulase, glutathione-S-transferase, and heat-shock proteins) (Tejada and Masciandaro, 2011; Xu et al., 2015). More detailed studies have shown that high levels of PAHs could damage the DNA in earthworms' seminal vesicles, resulting in a high degree of reproductive defect and a reduction in cocoon production (Eom et al., 2007; Tejada and Masciandaro, 2011; Gowri and Thangaraj, 2020; Li et al., 2020a; Zhang et al., 2020).

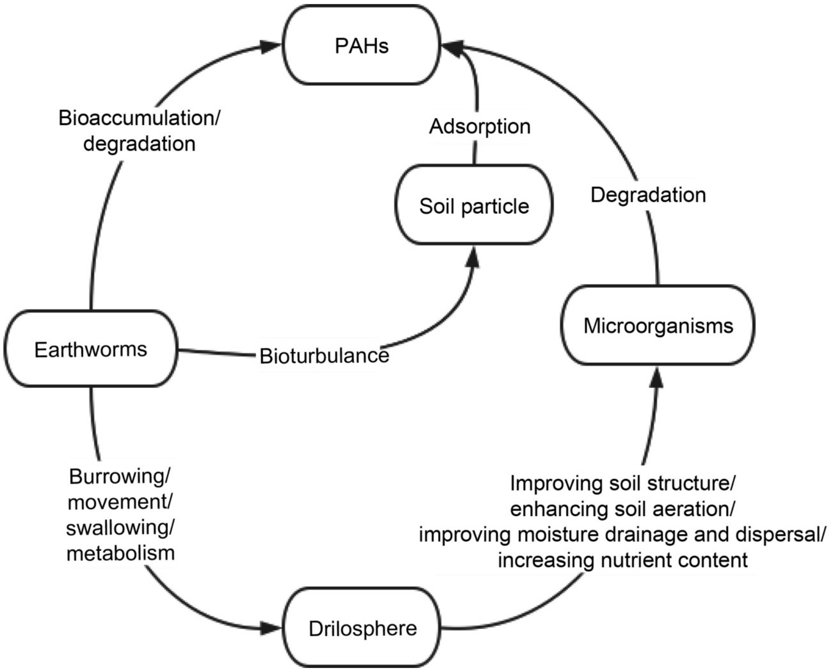

Fig. 1 Graphical representation of vermiremediation of PAHs-contaminated soil.

Application of organic materials to soil has been shown to mitigate the negative effects of PAHs on earthworms (Rodriguez-Campos et al., 2014). In a phenanthrene- and fluoranthene-contaminated soil, the weight loss of earthworms was 27% and 23.3% in treatments with low (10%) and high levels (40%) of organic amendment, respectively, and 25 more earthworm cocoons were produced in the high level treatment (Eijsackers et al., 2001). In the research of Contreras-Ramos et al. (2009), the weight of the earthworms (*Eisenia fetida*) increased by 35% when sewage sludge was added at 5% to the PAHs-contaminated soil, but decreased by 77% after 70 days due to a lack of food.

2.2 Vermiremediation mechanisms

2.2.1 Improvement of soil conditions by earthworm activities

It is well known that earthworm activities improve soil physical and chemical properties. Compacted clayey soils become loose and porous with the burrowing activity of earthworms, while loose sandy soils develop water-stable aggregates with the feeding and casting activities of earthworms (Barré et al., 2009), Therefore, earthworm activities improve the texture of loose or compacted soils, creating a better soil environment for soil microbes and plants (Barré et al., 2009). In addition, the earthworm bioturbation by earthworms enhances pollutant adsorption by soil particles (Hickman and Reid, 2008). In the drilosphere (i.e., burrow walls, gut contents, and casts) the activities of organic pollutant-degrading microorganisms are higher due to the good aeration, high moisture content, and rich nutrients (Michael et al., 1997; Tiunov and Scheu, 1999; Brown et al., 2000; Brown and Doube, 2004). Mary et al. (2011) found that the total carbon content was 23% higher and the microbial biomass was 58% higher in the drilosphere than in the nearby bulk soil. It has also been proven that available nitrogen (NH_4^+-N and NO_3^--N) is closely related to the metabolism of organic pollutants (Tran et al., 2013). The drilosphere indirectly promotes the degradation of organic pollutants by providing a favorable growth environment for the organic pollutant-degrading microbes (Tran et al., 2013).

2.2.2 Vermiaccumulation of pollutants

Vermiaccumulation is the process of contaminant absorption and accumulation by earthworms (Shi et al., 2020). There are two ways of vermiaccumulation of PAHs, passive epidermal uptake and dietary uptake (Shi et al., 2014), The first is related to PAHs with low hydrophobicity, including some volatile PAHs in soil air, while the second is related to highly hydrophobic PAHs (Lu et al., 2004; Qi and Chen, 2010). In other words, highly hydrophobic PAHs accumulate in earthworm guts, while PAHs with low hydrophobicity not only accumulate in earthworm body walls but also in earthworm body fluid and guts as a result of passive diffusion and partition (Shi et al., 2014). Earthworm gut fluid can markedly enhance the release of PAHs from soil particles (Qi and Chen, 2010). The high specific surface area of earthworm gut walls (Qi and Chen, 2010) and the strong diffusion of PAHs in gut fluid (Mayer et al., 2007) reasonably explain the high absorption of PAHs by earthworms. In soils contaminated with petroleum hydrocarbons (kerosene, diesel, and bunker-C), earthworms (*Eisenia fetida*) were found to accumulate the 16 priority PAHs (Moon et al., 2013). In ecological risk evaluation, the biota–sediment accumulation factor

(BSAF) is usually used to estimate contaminant loads in biota. In their study with a soil contaminated with PAHs (0.25–25 mg kg_{dwt}^{-1}), Jager et al. (2003) found a mean BSAF value of 0.23 (kg_{OC} kg_{lip}^{-1}) for the PAHs in the earthworms *Eiseinia andrei*. Cachada et al. (2018) reported BSAF values of 0.41–2.5 and 0.026–0.16 (kg_{OC} kg_{lip}^{-1}) for PAHs in artificially and naturally contaminated soils, respectively. Compared with other PAHs, 4-ring PAHs display a higher accumulation in earthworms, which may be due to the fact that they do not volatilize or degrade, and they are not as persistent as 5–6-ring PAHs (Northcott and Jones, 2001).

2.2.3 Microbial and enzymatic PAHs degradation enhanced by earthworms

Earthworm bioturbation can effectively enhance PAH biodegradation by soil microorganisms which have limited access to PAHs due to their poor mobility (Dendooven et al., 2011). As mentioned above, earthworm bioturbation improves soil aeration and nutrient accessibility, which is favorable for aerobic PAH-degrading microbes (Binet et al., 1998; Marinari et al., 2000; Hickman and Reid, 2008; Pagenkemper et al., 2015). It is worth noting that earthworm gut is a favorable environment for anaerobic PAHs-degrading microorganisms due to the rich organic substrates (Drake and Horn, 2007), and efficient degradation of PAHs and other organic pollutants by earthworm intestinal bacteria has been reported (Contreras-Ramos et al., 2008; Verma et al., 2011).

Produced by plants, animals, and microorganisms, soil enzymes play an important role in the degradation of organic pollutants (Alkorta et al., 2003). Generally, soil enzyme activity is highly correlated with soil organic carbon content and microbial biomass (Martens et al., 1992; Fraser et al., 1994; Parthasarathi and Ranganathan, 2000). Studies showed that earthworms could increase the activities of organic pollutant-degrading enzymes, such as phosphatase, cellulase, amylase, sucrase, urease, catalase, and dehydrogenase (Zhang et al., 2000; Alkorta et al., 2003; Adetunji et al., 2017). In addition, the enzymes in earthworms generally have a high tolerance against organic contaminants, which is of significance for the biodegradation of organic pollutants (Schreck et al., 2008; Liu et al., 2011; Wu et al., 2011).

2.3 Vermiremediation of PAHs-contaminated soils

Many studies have shown that adding earthworms to PAHs-contaminated soils or PAHs-containing sewage sludge could accelerate the removal of PAHs while the earthworms maintain a high survival rate (Contreras-Ramos et al., 2008; Poluszyńska et al., 2017; Rorat et al., 2017). Ma et al. (1995) demonstrated that the degradation of anthracene and phenanthrene in 650 g soil was enhanced by the presence of five earthworms (*Lumbricus rubellus*), and the removal rate of phenanthrene was increased from 11% to 25%. In the study of Contreras-Ramos et al. (2008), more than 90% of the anthracene (1000 mg kg^{-1}) and phenanthrene (150 mg kg^{-1}) and 16% of the benzo(a)pyrene (150 mg kg^{-1}) were removed from the 50 g soil 11 weeks after 10 earthworms (*Eisenia fetida*) were added, and more than 80% of the earthworms survived. According to Coutiño-González and his colleagues (2010), earthworms (*Eisenia fetida*) not only enhanced the degradation of anthracene but also enhanced that of 9,10-anthraquinone, the most abundant degradation product of anthracene.

Earthworms application can effectively improve microbial degradation activity (Sun et al., 2011; Hernández-Castellanos et al., 2013). Sun et al. (2011) reported 1.2 to 1.6 times increases in the microbial degradation rate of pyrene with the addition of earthworms (*Eisenia fetida*) to the artificially contaminated soils. Hernández-Castellano et al. (2013) observed that the addition of earthworms (*Pontoscolex corethrurus*) accelerated the removal of benzo(a)pyrene by four times. They also demonstrated that feeding the earthworms with *M. pruriens* or *B. humidicola* leaves further increased the benzopyrene removal rate by 28.6% and 34.2%, respectively. Vermiremediation has been extensively applied in various soils (Parrish et al., 2006; Rodriguez-Campos et al., 2014; Rorat et al., 2017). It is worth noting that the growth and activity of earthworms are influenced by many factors, such as environmental pH, temperature, humidity, food, and toxic substances (Eom et al., 2007; Eijsackers et al., 2001; Owojori and Reinecke, 2010; Dendooven et al., 2011; Tejada and Masciandaro, 2011; Shi et al., 2020). Therefore, the effectiveness of vermiremediation is influenced by many factors, which warrants more studies. In addition, the fate of the PAHs accumulated by earthworms and the fate of toxic degradation by-products warrants further investigation as well (Coutiño-González et al., 2010; Schmidt et al., 2017).

3 The application of biochar in the remediation of PAHs-contaminated soils

Having a porous structure and a large specific surface area, biochar is increasingly used as an adsorbent in soil remediation (Alexander, 2000; Cornelissen et al., 2005; Zhu et al., 2017; Wang et al., 2020). In addition, biochar is carbon-rich and thereby a good habitat for soil microbes, which indirectly promotes the transformation and degradation of contaminants in soil (Fig. 2).

3.1 Influencing factors of biochar production and biochar characteristics

Feedstock for biochar production can be industrial and agricultural wastes, such as animal wastes, wood chips, crop residues, ash from power stations, and sewage sludge from wastewater treatment plants (Chen et al., 2011a; Cantrell

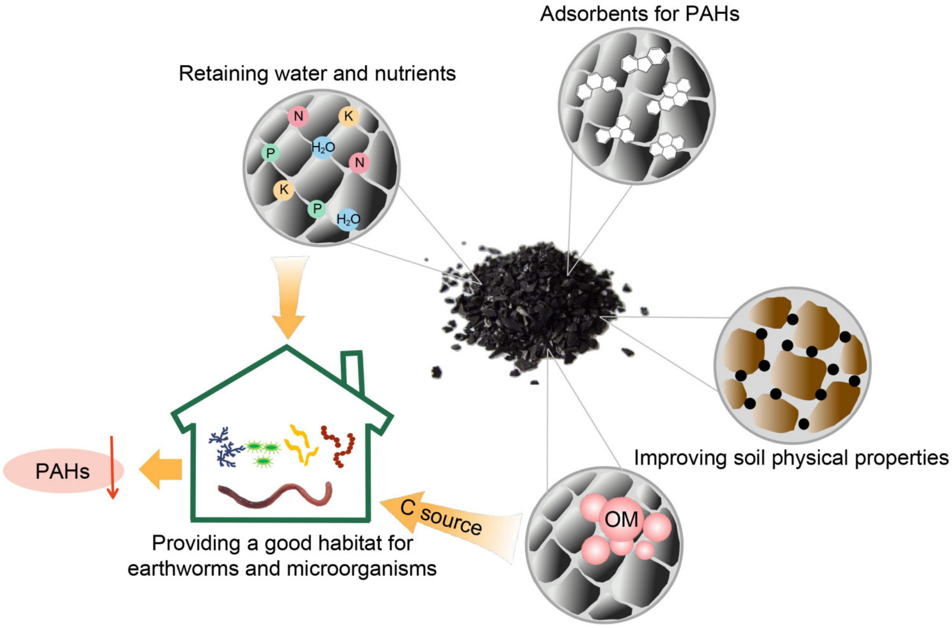

Fig. 2 The role of biochar in the remediation of PAHs-contaminated soil.

et al., 2012; Beesley et al., 2014; Rey-Salgueiro et al., 2016; Peng et al., 2018). Feedstock greatly influences biochar characteristics, including porosity, specific surface area, pH, electrical conductivity, cation exchange capacity (CEC), and elemental content (Gonzaga et al., 2017; Li et al., 2017a; Sandhu et al., 2017; Sun et al., 2018). In the study of Bianco et al. (2021), the total carbon content of biochar derived from different feedstocks varied widely from 22% to 83%. In the study of Gomez-Eyles et al. (2013), acai pit biochar had the highest carbon content and the largest specific surface area, while pine dust biochar had the lowest, with those of peanut hull biochar and barley straw biochar in between.

Based on production conditions, there are four biochar production technologies: slow pyrolysis, fast pyrolysis, gasification, and torrefaction (Wang et al., 2020). Biochar characteristics, such as porosity, surface area, carbon content, and stability, are greatly influenced by production conditions, such as pyrolysis temperature, heating rate, and pyrolysis atmosphere (Gonzaga et al., 2017; Kalinke et al., 2017; Sun et al., 2018; Wang et al., 2020a, 2021). Generally, biochar with a higher carbon content and a larger specific surface area can be obtained at a higher pyrolysis temperature (Chen et al., 2008; Li et al., 2013). This can be due to the release of volatiles and the generation of vascular bundle structures at high pyrolysis temperatures, which lead to a larger specific surface area and a pore structure of biochar (Fu et al., 2011; Li et al., 2013; Wang et al., 2020a). However, too high a pyrolysis temperature would destroy both the acidic and basic groups, leading to an ultimate decrease of the adsorbability of biochar (Chun et al., 2004; James et al., 2005). Slow heating rate and long residence time in slow pyrolysis achieve a high production yield of biochar, while the fast heating rate (10–200 K s^{-1}) and short residence time (0.5−10 s) in fast pyrolysis favors the production of bio-oil (Perego and Bosetti, 2011; Oni et al., 2019; Lee et al., 2020). Long vapor residence time allows the biomass components to repolymerize, increasing the porosity and production yield of biochar (Tripathi et al., 2016; Tsai et al., 1997).

3.2 Remediation mechanisms of biochar

3.2.1 Physicochemical adsorption

The physical and chemical properties of biochar are the main factors affecting its adsorption of organic pollutants (Zhu and Pignatello, 2005). The interaction between biochar and organic pollutants is also influenced by the structure and chemical properties of the organic pollutants (Inyang and Dickenson, 2015). The interactions between biochar and PAHs (Fig. 3) mainly include hydrophobic interaction (e.g., Van der Waals forces), donor-acceptor interaction (e.g., π-π), and other specific interactions (e.g., hydrogen-π, cation-π) (Anyika et al., 2014; Fu et al., 2018; Zhang et al., 2018b; Bianco et al., 2021). The adsorption dominated by hydrophobic interaction can occur in two main phases. One is the partition of PAHs in the hydrophobic domain of biochar, and the other is the weak adsorption of PAHs on the surface of biochar via van der Waals force (Bianco et al., 2021). It has been revealed that the PAHs-adsorption mechanisms differ for biochar prepared at different pyrolysis temperatures. The adsorption of PAHs on low-temperature pyrolyzed biochar is primarily determined by the distribution of non-carbonized biopolymers and van der Waals force (Chen et al., 2012b; Zhu et al., 2018). High-temperature pyrolyzed biochar shows a greater sorption efficiency due to a lower H/C ratio and more unsaturated functional groups,

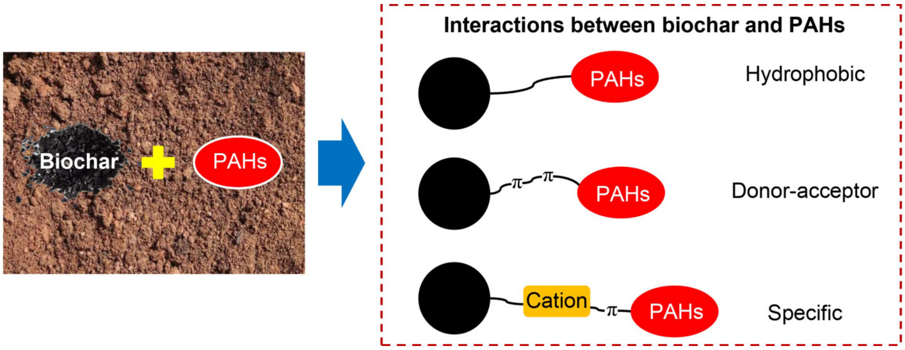

Fig. 3 Interactions between biochar and PAHs.

and it can interact with PAHs through π-π type interaction (Chen et al., 2008; de Jesus et al., 2017). Certain cations (e.g., Na^+ and K^+) and functional groups (e.g., $-COOH$, $-OH$, and $-NH_2$) in biochar undergo specific interactions with PAHs (Yang et al., 2016). The hydrophobic functional groups on biochar surface create a hydrophobic microenvironment, promoting the formation of cationic π-complexes, increasing the aqueous solubility of PAHs (Chen et al., 2007; Jin et al., 2014), and ultimately reducing the adsorption of PAHs by biochar. However, the formation of cation-PAHs bond increases the adsorption of PAHs on biochar. Therefore, PAHs adsorption or dissolution is a result of the relative strength of the PAHs-biochar interactions (Zhang et al., 2011; Jin et al., 2014).

3.2.2 Improving the soil environment by biochar

Biochar application alters soil physical and chemical properties, such as pH, porosity, and water holding capacity, creating hotspots of microbial growth. When applied to acidic soils, alkaline biochar improved the habitats of soil microorganisms (Birk et al., 2008; Van Zwieten et al., 2010). Moreover, owing to its porous structure, high porosity, and large specific surface area, biochar increases soil porosity, CEC, and water holding capacity when applied to soil (Glaser et al., 2002; Karhu et al., 2011; Ameloot et al., 2013; Zhu et al., 2017). Biochar also enhances microbial degradation of organic pollutants by supplying simple organic substrates like sugars and amino acids (Cox et al., 2001; Sadegh-Zadeh et al., 2017). In addition, the black color of biochar helps to raise soil temperature by efficiently absorbing solar radiation, speeding up organic matter decomposition and nutrient transformation (Maroušek et al., 2018; Amoah-Antwi et al., 2020).

3.3 Positive roles of biochar in PAHs-contaminated soil remediation

3.3.1 Adsorption removal of PAHs from soils using biochar

The strong adsorption capacity of biochar leads to the immobilization of PAHs and thus reduces the extractability and bioavailability of PAHs in the environment, thereby reducing the potential health risk of PAHs (Alexander, 2000; Cornelissen et al., 2005; de Resende et al., 2018). Biochar can decrease the bioavailability of PAHs and thereby has been widely applied to PAHs-contaminated soils and sediments (Cornelissen et al., 2005; Beesley et al., 2010; Yang et al., 2018). Zhu et al. (2018) demonstrated that biochar reduced the concentrations of extractable PAHs. In the field experiment conducted by Beesley et al. (2010), the concentrations of the heavier, more toxic 4- and 5-ring PAHs decreased by more than 50% and those of the lighter 2- and 3-ring PAHs decreased by more than 40% 60 days after biochar application. Khan et al. (2013) added sewage sludge biochar (10%) to a PAHs-contaminated soil and found that the total concentration of PAHs in soil decreased by 10%, and the average concentration of PAHs in lettuce plants decreased from 1.72 mg kg^{-1} to 0.68 mg kg^{-1}. It is worth mentioning that soil-PAHs interaction is generally weaker than biochar-PAHs interaction. Therefore, soil-bound PAHs are at a higher risk of being redistributed into soil solution (Zhu et al., 2018). Biochar application increases the adsorption of pollutants to the soil matrix and thereby reduces their presence in soil solution. The adsorption-desorption experiment conducted by Zhang et al. (2010) showed that biochar addition enhanced the apparent adsorption affinity of soil to phenanthrene, which became more obvious at higher application rates, and biochar pyrolyzed at a higher temperature was more able to promote the adsorption of phenanthrene in soil.

3.3.2 PAHs biodegradation enhanced by biochar

Biochar cannot only effectively reduce the extractable and bioavailable PAHs concentration in soil by adsorption but also promote the biodegradation of PAHs by stimulating microorganisms, thereby reducing the environmental risks of PAHs (Beesley et al., 2010; Zhang et al., 2018a). This seems to contradict the fact that reduced extractability and bioavailability would lead to reduced biodegradation efficiency, and consequently, more pollutant would remain in the soil (Arp et al., 2014; Xiong et al., 2017). For example, the addition of black carbon significantly reduced the extractability and microbial mineralization of hydroxypropylcyclodextrin and phenanthrene in soil (Rhodes et al., 2008; Rhodes et al., 2010). Some studies argue that biochar, with a high porosity, a large specific surface area, and rich nutrients, provides a suitable shelter for microorganisms and increases the abundances of pollutant-degrading bacteria (Anyika et al., 2014; Kong et al., 2018; Ye et al., 2019). It is generally believed that contaminant-degrading bacteria degrade the organic contaminants dissolved in soil solution or desorbed from adsorption sites. However, biodegradation of contaminants adsorbed on biochar has also been observed by some researchers (Park et al., 2003; Cornelissen et al., 2005; Chi and Liu, 2016; Ding et al., 2021). For example, Ding et al. (2021) observed that there were pollutant-degrading bacterial assemblages on the biochar retrieved from the contaminated soil in their experiment, indicating the possibility that contaminants adsorbed by biochar undergo biodegradation as well. Moreover, several studies have shown that the degradation of PAHs is affected by molecular weight. Biochar addition reduces the biodegradation of light PAHs while increasing that of heavy PAHs. This is because light PAHs are small and thereby can be easily adsorbed in the pores of biochar (Wang et al., 2006; García-Delgado et al., 2015; Zhang et al., 2018a).

In conclusion, the use of biochar is a reliable and sustainable method for soil organic pollution remediation. PAHs in contaminated soils can attach to the surface of biochar via specific adsorption, resulting in significantly lower concentration in soil solution. Biochar can also alter soil characteristics, improving the soil environment for more efficiently PAHs removal by functional microbes. According to previous studies, the degradation rate of PAHs in soil increases with biochar application time (Table 1). However, much work is still needed to make it clear how to efficiently remove PAHs from soil, because removal efficiency varies with the application rate of biochar produced under different pyrolysis conditions and from different raw materials (Table 1). It is worth mentioning that biochar may contain some toxic byproducts, which may have negative impacts on soil organisms. In some cases, the high pH and salinity of biochar may cause some undesirable results, and its high application rate is a disadvantage as well. Fortunately, these can be avoided by choosing a desirable feedstock and the optimal pyrolysis conditions (Lehmann et al., 2011; Quilliam et al., 2013; Luo et al., 2014; Godlewska et al., 2021).

4 Combined effects of biochar and earthworms on PAHs-contaminated soil remediation

Both earthworms and biochar can be used for soil remediation. However, both have their own shortcomings when they are used alone. Recently, some researchers have applied biochar and earthworms together in organic polluted soils to optimize remediation methods (Table 2). As reviewed in the previous sections, the mechanisms of PAHs removal by

Table 1 The effects of biochar type, application rate, and application time on the removal efficiency of Σ16 PAHs

Feedstock	Pyrolytic temperature (°C)	Addition ratio	Time (d)	Σ16 PAHs removal efficiency	Reference
Agricultural wastes					
Walnut shells, corn cobs	250, 400, 600	2%	75	73.69%−77.01%	Zhang et al., 2021
Rice husk	350	4%	90	7.69%−36.23% (The removal efficiencies of different PAHs)	Liu et al., 2015
	500			−32.67%−86.67% (The removal efficiencies of different PAHs)	
Dairy manure	350			−8.42%−71.74% (The removal efficiencies of different PAHs)	
	500			−4.21%−66.67% (The removal efficiencies of different PAHs)	
Wheat straw	700	5%	30	15.85%	Oleszczuk et al., 2017
Wood materials					
Poplar woodchips	500	1%	105	20.53%	Ren et al., 2021
Various types of conifers	>630	5%	270	41%	Ukalska-Jaruga et al., 2019
Hardwood	600	10%	56	31.84%	Gomez-Eyles et al., 2011
Hardwood	–	30%	60	About 50%	Beesley et al., 2010
Solid wastes					
Sewage sludge	500	1%	180	18%−56%	Tomczyk et al., 2020
Sewage sludge	500, 600, 700	2%	180	27%−4%	Godlewska et al., 2022
Sewage sludge	500	10%	56	10%	Khan et al., 2013

Table 2 The effects of carbonaceous materials on earthworms in organic contaminated soil and the bioaccumulation of organic pollutants in the presence of earthworms and carbonaceous materials

Pollutants	Carbonaceous materials	Application rate	Species	Population of earthworms	Duration	Biochar-amended soil	Weight	Survival rate	Bioaccumulation	Reference
PAHs	Hardwood-derived biochar	–	*Eisenia fetida*	10	28 d	200 g	Decreased by 2.9%	100%	Decreased by 22%	Gomez-Eyles et al., 2011
					56 d		Decreased by 4.9%	100%	Decreased by 44.9%	
PAHs	Powder activated carbon	2% of soil weight	*Eisenia fetida*	30 (field experiment), 10 (laboratory)	28 d	5000 g (field experiment), 500 g (laboratory)	Decreased by 19% (field experiment)	–	Decreased by 72%	Jakob et al., 2012
							Decreased by 32% (laboratory)			
	Granular activated carbon						Decreased by 43% (field experiment)		Decreased by 47%	
							Decreased by 8% (laboratory)			
PAHs	Wine tree cuttings biochar	0, 8, 16, 64, 128, 256, 1024 t ha^{-1}	*Eisenia andrei*	10	60 d	800 g	–	100%, 100%, 100%, < 70%, < 60%, 0, 0		Malev et al., 2016
	Hardwood lump Charcoal biochar							100%, 100%, < 80%, 40%, < 30%, 0, 0		
	Wine tree cuttings biochar	100 t ha^{-1}		30	48 d	2000 g		80.8%	Increased by 54%	
	Hardwood lump Charcoal biochar							60.9%	Increased by 10.7%	
PCBs	Wood waste biochar	0.7% of soil weight	*Eisenia fetida*	50	50 d	2250 g	–	30.8%	–	Denyes et al., 2012
		2.8% of soil weight						70%	Decreased by 53%	
		11.1% of soil weight						35.2%	Decreased by 88%	
PCB28	Rice husk biochar	1%	*Eisenia fetida*	25	24 d	1000 g	–	–	Decreased by 91%	Silvani et al., 2019
PCB101									Decreased by 77%	
PCB28		4%							Decreased by 87%	
PCB101									Decreased by 69%	
PCB28	Mixed wood shavings biochar	1%							Decreased by 55%	
PCB101									Decreased by 43%	

(*Continued*)

Pollutants	Carbonaceous materials	Application rate	Species	Population of earthworms	Duration	Biochar-amended soil	Weight	Survival rate	Bioaccumulation	Reference
PCB28	5%	Decreased by 63%								
PCB101		Decreased by 31%								
DDT	Activated carbon	0.2%	*Eisenia fetida*	5	28 d	200 g	–	–	Decreased by 83.9%−99.4%	Wang et al., 2018
		2%								
	Biochar	0.2%								
		2%								
Atrazine	Dairy manure biochar	0	*Eisenia fetida*	12	210 d	500 g	–	–	Decreased by 47%−73%	Cao et al., 2011
		2.5%					Increased by 19%	100%		
		5%					Increased by 26%	100%		
Pesticide mesotrione	Wheat straw-derived biochar	1%	*Eisenia fetida*	10	28 d	500 g	–	100%	Decreased by 80%	Zhang et al., 2019
		3%						100%	Not detected	
		10%						100%	Not detected	

earthworms and biochar include biochar adsorption, earthworm accumulation, enhanced biodegradation by soil microorganisms and enzymes, and metabolic degradation by the bacteria in earthworm gut. Biochar and earthworms are inevitably affected by each other in soil (Fig. 4). In this section, the potential of combined usage of biochar and earthworms in PAHs removal and the possible negative effects are discussed.

4.1 The effects of biochar on vermiremediation of PAHs-contaminated soils

4.1.1 Biochar addition improves the soil environment for vermiremediation

Owing to the porous structure of biochar (Downie et al., 2009), its tensile strength permits changes in soil mechanical impedance (Goss, 1977; Goss and Russell, 1980). Therefore, biochar application improves the soil environment for easier elongation and proliferation of plant roots (Bengough and Mullins, 1990; Blanco-Canqui, 2017). In addition, biochar application improves soil water and nutrient conditions, leading to better growth and development of plants, soil microorganisms, and animals (Warnock et al., 2007; Major et al., 2010; Noguera et al., 2010; Ren et al., 2018; Palansooriya et al., 2019). Biochar generally has a high pH due to the presence of such salts as calcite ($CaCO_3$) (Cao et al., 2011). Therefore, biochar application is beneficial for earthworms in acidic soils with its acid-neutralizing effect, because earthworms prefer a neutral environment (Edwards and Bohlen, 1996; Tripathi and Bhardwaj, 2004; Van Zwieten et al., 2010). It is important to note that biochar could have the opposite effect when applied to neutral or alkaline soils (Van Zwieten et al., 2010), especially when it is overused (Weyers and Spokas, 2011). Biochar, with a large specific surface area and a porous structure, functions similarly to soil aggregates in terms of retaining water and nutrients and providing a good habitat for soil organisms (Tisdall and Oades, 1982; Lehmann et al., 2011). Compared to many organic substances, biochar can remain stable in soil for a long time (Skjemstad et al., 1996; Lehmann et al., 2005, 2008), even though it may become smaller on a decadal time scale (Nguyen et al., 2008). However, some researchers have pointed out that the strong adsorbability of biochar may reduce the availability of food and water for earthworms in soil (Jonker et al., 2004; Jakob et al., 2012; Zhang et al., 2019). Earthworms usually ingest both carbon and soil particles instead of soil particles only, which may be due to the detoxification and alkalinisation effects of biochar, as well as its stimulating effect on microbial communities (Topoliantz and Ponge, 2003). Therefore, overuse of carbon may lead to less food available to earthworms (Wang et al., 2012), eventually leading to weight loss of earthworms

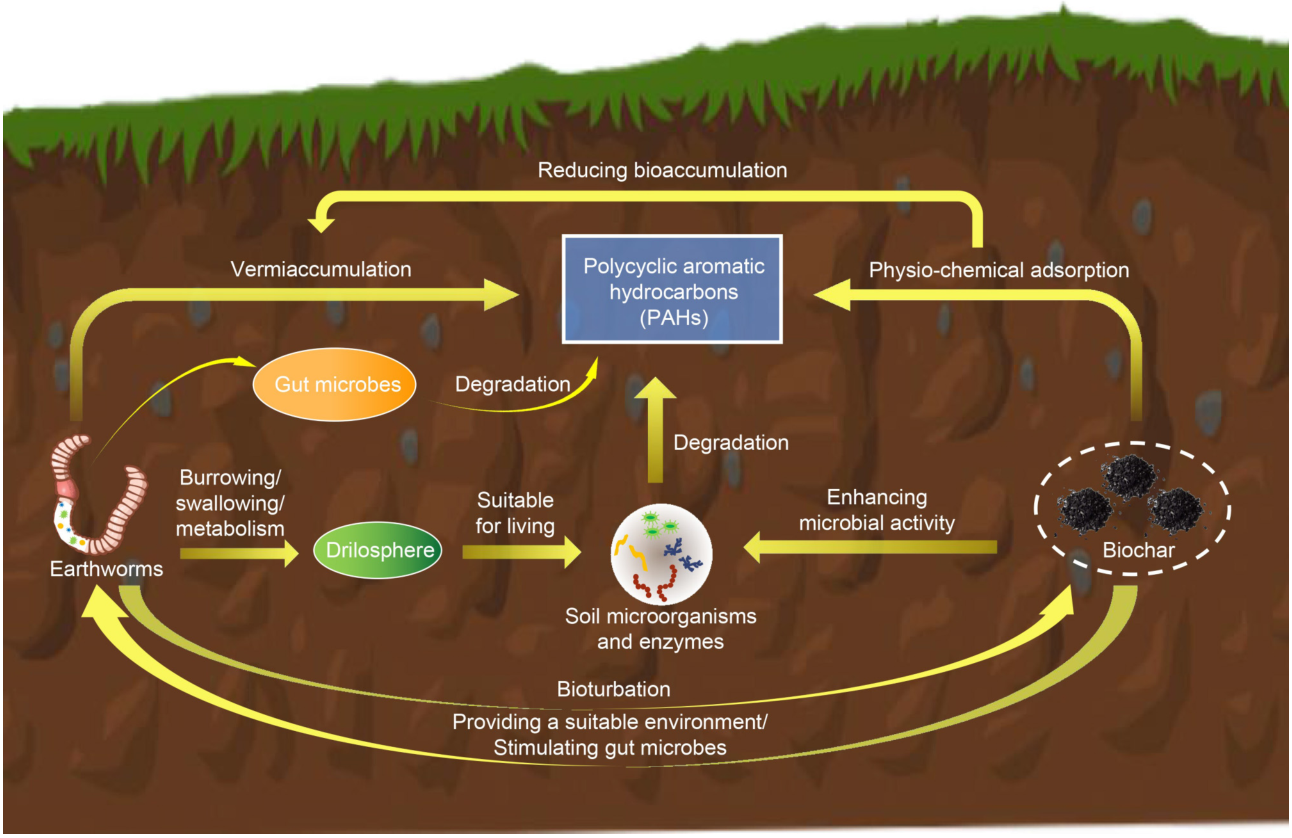

Fig. 4 Graphical representation of how earthworm and biochar work.

(Gomez-Eyles et al., 2011; Zhang, et al., 2019). In addition, earthworms may be subjected to drought stress caused by the application of biochar, which has a strong water-adsorption capacity (Li et al., 2011). To avoid this, irrigation may be needed immediately after biochar application (Domínguezl and Edwards, 1997). For example, Li et al. (2011) observed the avoidance behavior and weight loss of earthworms in soils amended with 100 and 200 mg kg^{-1} biochar, and no avoidance behavior was observed after the soil was irrigated to field capacity.

4.1.2 Biochar affects PAHs accumulation and degradation in earthworms

The hypoxic, humid, and pH-neutral environment of earthworm gut makes it an ideal habitat for pollutant-degrading microorganisms (Drake and Hrn, 2007; Van Groenigen et al., 2019). Microbes in earthworm gut have been proven to be able to effectively degrade PAHs. These microbes include bacteria (e.g., *Pseudomonas* and *Acidobacterium*) and fungi (e.g., *Penicillium*, *Mucor*, and *Aspergillus*) (Pižl and Nováková, 2003; Singleton et al., 2003; Contreras-Ramos et al., 2008). As mentioned above, earthworms prefer to feed on both soil particles and biochar rather than soil particles only (Topoliantz and Ponge, 2003). The surface of biochar is rich in water-soluble organic substances such as alcohols, aldehydes, ketones, and sugars, which are good substrates for the intestinal bacteria in earthworms (Thies and Rillig, 2009). Ding et al. (2019) reported that 0.5% rice biochar significantly increased the gut bacterial community in earthworms but had no effect on the soil bacterial community. Wang et al. (2020) also showed that biochar application significantly increased the bacterial diversity in earthworm gut, which was favorable for pollutant biodegradation.

The strong adsorption of pollutants on biochar not only reduces pollutant concentration in soil solution (Wang et al., 2012), but also effectively reduces pollutant accumulation by soil organisms (Alexander, 2000; Cornelissen et al., 2005; Langlois et al., 2011; de Resende et al., 2018), thereby lowering the risk of organic pollutants entering the food chain. This explains why earthworms prefer biochar-treated soil where the concentration of bioavailable contaminant is lower (Gomez-Eyles et al., 2011; Wang et al., 2014). Besides biochar, some other carbonaceous materials, such as black carbon and activated carbon, can also effectively reduce the accumulation of PAHs by earthworms (Brändli et al., 2008; Jakob et al., 2012). However, the reduction of bioavailable pollutants by biochar is influenced by soil properties. Earthworms absorb lower amounts of PAHs from clay loam than from sandy soil because the interaction between PAHs and clay loam is stronger than that between PAHs and sandy soil (Malev et al., 2016). Wang et al. (2012) pointed out that soils of different properties have different adsorption capacities for pollutants. Therefore, the effectiveness of biochar in decreasing pollutant bioavailability varies in different soils. Furthermore, the effects of biochar on PAHs bioaccumulation vary with the molecular weight of PAHs as well. In the study of Gomez-Eyles et al. (2011), biochar application reduced the total and bioavailable PAHs in soil and the accumulation of total PAHs in earthworms (up to 45%). However, the earthworm accumulation of lighter PAHs (2- and 4-ring) increased, while that of heavier and more toxic PAHs decreased (more than 20% by day 28), which may be attributed to the high affinity of heavier PAHs to biochar (Northcott and Jones, 2001).

4.1.3 Potential of biochar in removing toxic metabolites released by earthworms

The phenomenon that earthworms release toxic metabolites after metabolic conversion of low molecular weight PAHs in their bodies has been reported in previous studies, implying secondary pollution caused by PAHs metabolism in earthworms. Schmdit et al. (2017) found that earthworms released phase II conjugates, the metabolic products of phenanthrene and pyrene, into the soil environment. These persistence toxic metabolites are highly soluble in water and will pose a threat to environmental and human health once leached into groundwater (Schmdit et al., 2017). Another earlier study reported that anthracene was transformed into the more toxic 9,10-anthraquinone through earthworm metabolism (Coutiño-González et al., 2010). Different from anthracene, whose carcinogenicity is not yet known, anthraquinone has been found to induce liver tumors and kidney diseases in mice and classified as a 2B carcinogen by the International Agency for Research on Cancer (IARC) of the World Health Organization. Therefore, the release of toxic metabolites by earthworms after absorption of low molecular weight PAHs deserves more attention, even though Coutiño-González et al. (2010) found that the concentration of toxic metabolites decreased at the later stage of the experiment. PAH-degrading microbes (e.g., Sphingomonas.g and Alphaproteobacteria.c) (Li et al., 2020b) enriched and sheltered by biochar can use the adsorbed PAHs as a sole carbon source for growth, thereby degrading the PAHs (Widada et al., 2002; Li et al., 2020b). Adsorption and degradation of toxic earthworm metabolites on biochar is a safe and effective way to remove them from soil. However, there is limited information on other ways to eliminate toxic earthworm metabolites and the effects of biochar application on such metabolites, especially the metabolic transformation of the more toxic high molecular weight PAHs. More attention and research should be given to this scientific area in the future in order to comprehensively evaluate the combined effects of biochar and earthworms on soils contaminated with PAHs and the potential environmental risks.

4.1.4 Negative effects of biochar on earthworms and corresponding measures

The positive effects of biochar on the soil environment and

PAHs biodegradation have been widely reported. Negative effects of biochar application are usually related to feedstock property, biochar application rate, and soil properties (Chan et al., 2008; Liesch et al., 2010; Weyers and Spokas, 2011; Malev et al., 2016; Gong et al., 2018). The earthworms *Metaphire guillelmi* and *Amynthas corrugatus* have recently been proven to be capable of mineralizing bacterial and fungal cells for carbon and energy (Shan et al., 2010), which has positive effects on the redistribution and stabilization of soil organic matter (Haynes et al., 2003; Simpson et al., 2007; Miltner et al., 2012). But simultaneously, as accompanied effects, the PAHs adsorbed on biochar could have negative effects on earthworms through the microorganisms participating in the biodegradation of PAHs (Shan et al., 2013). The toxic effects of biochar on earthworms can be attributed to the following three aspects: (1) the toxins present in biochar, (2) the high pH of biochar, and (3) the reduction in water and nutrients available to earthworms (Van Zwieten et al., 2010; Jakob et al., 2012; Godlewska et al., 2021).

It is worth noting that the negative influences are mainly attributed to the bioavailable contaminants, which are not stably bound by biochar and thereby can be absorbed and metabolized by microorganisms, animals (Kelsey et al., 1997; Tang et al., 1998), and plants (Alexander, 1995; 2000). This is why the bioavailability of pollutants adsorbed on biochar and their toxic effects have attracted more and more scientific interest in recent years (Spokas et al., 2011; Hale et al., 2012; Hilber et al., 2017). If we pay some more attention to harmful substances which would potentially pollute the soil and its bio-system with biochar input, such as volatile organic compounds, perfluorochemicals, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and other persistent organic pollutants, even certain heavy metals could be brought from the raw material of biochar and could also be produced in the pyrolytic process (Buss and Mašek, 2014; Kim et al., 2015; Weidemann et al., 2018; Antoniadis et al., 2019). PAHs have been commonly found in various biochar (Buss et al., 2016; Weidemann et al., 2018). Their concentrations in biochar, ranging from 0.08 mg kg^{-1} (Freddo et al., 2012) to 172 mg kg^{-1} (Khalid and Klarup, 2015), are affected considerably by feedstock type and pyrolysis conditions. In general, medium temperature (400–600°C), slow pyrolysis, and long residence time, as well as the use of plant material containing few PAHs precursors as feedstock can help to minimize PAHs in biochar (Hale et al., 2012; Wang et al., 2017b; Kończak et al., 2019; Godlewska et al., 2021). In more than 50 biochars produced under different pyrolysis conditions, Hale et al. (2012) found lower levels of dioxin and PAHs in the slow pyrolysis biochars, with the concentrations of bioavailable dioxin below the detection limit and those of bioavailable PAHs ranging from 0.17 ng L^{-1} to 10.0 ng L^{-1}. Zielińska and Oleszczuk (2016) reported low concentrations of free PAHs in sewage sludge biochar produced at various pyrolysis temperatures. Pollutant content in biochar varies greatly and the amount of pollutants adsorbed on biochar depends on interaction time (Qian and Chen, 2013; Ghaffar et al., 2015). With the aging of biochar, hydrophilic functional groups on its surface increase (Moreno-Castilla et al., 1995; Ghaffar et al., 2015), leading to the release of pollutants into the environment and the increase of toxic effects on soil organisms (Anyanwu et al., 2018; Kavitha et al., 2018).

Biochar may have negative effects on the growth and reproduction of earthworms and may even cause DNA damage, which may be attributed to the increased pH and decreased available water and nutrients with the addition of biochar (Cui et al., 2009; Zhang et al., 2019). Specific effects depend on the biochar properties, biochar application rate, and time. Biochar applied at an appropriate rate and for a suitable period has positive effects on the survival, growth, and reproduction of earthworms (Cui et al., 2009; Denyes et al., 2012; Malińska et al., 2016; Gong et al., 2018). In the study of Li and Alvarez (2011), earthworm cocoon production was not affected when biochar was applied at 0.5% but was significantly reduced when biochar was applied at 5%. Similarly, Zhang et al. (2019) found that the average weight of *Eisenia fetida* increased significantly at low biochar rate (1% –3%) but decreased significantly at high biochar rate (10%). Therefore, the negative effects of biochar addition on earthworms can be avoided or minimized by applying the right biochar at an appropriate rate.

4.2 Earthworm-assisted PAHs-contaminated soil remediation using biochar and its limitations

4.2.1 Potential of earthworms in promoting the adsorption and degradation of PAHs on biochar

The deep soil layers, which are important for soil texture, aeration, and microbial activity, could be influenced by biochar incorporation and its mobility in soil (Leifeld et al., 2007). Earthworm activities create biopores in the soil profile, and these pores may be interconnected laterally with each other in the drilosphere (Pagenkemper et al., 2015). The large ingestion capacity of geophagous earthworms (Lavelle, 1988; Brown et al., 2000) play a significant role in the migration and redistribution of the ingested matters, which is a bioturbation process (Hindell et al., 1997; Garcia and Fragoso, 2002). Under the bioturbation of earthworm Pontoscolex corethrurus, charcoal was found to be well mixed with soil (Topoliantz et al., 2002; Topoliantz and Ponge, 2003). According to the research of Bergknut et al. (2007), the bioturbation of earthworm *Pontoscolex corethrurus* resulted in the mobilization and incorporation of biochar in the forest soils (Alfisols and Mollisols) of Central Europe. Earthworm bioturbation enhances the mobility of biochar in soil and leads to closer contact between biochar and contaminated soils, which ultimately increases the adsorption of pollutants on biochar.

Furthermore, bioturbation also significantly influences the activities of microorganisms and extracellular enzymes (Sanchez-Hernandez et al., 2019). The adsorption of enzyme molecules on the hydrophobic surface (low C/N ratio) and in the pores of biochar may lead to enzyme activity decrease (Chintala et al., 2014). The functional groups such as hydroxyl and carboxyl on biochar surface may interact with the amino group of enzyme molecule and thus reduce enzyme affinity to substrates (Khadem and Raiesi, 2019). Recent studies have shown that earthworms could improve the activities of biochar-adsorbing enzymes, which may be related to the gastrointestinal and external mucus secreted by earthworms (Sanchez-Hernandez, 2018). The activities of carboxylesterase, β-glucosidase, alkaline phosphatase, and arylsulfatase of biochar particles increased after earthworm introduction (Sanchez-Hernandez, 2018). Interestingly, carboxylesterase-coated biochar was found to have a high affinity to some highly toxic pesticide metabolites (Wheelock et al., 2008). However, more research is needed on earthworm-assisted remediation of PAHs-contaminated soils using biochar to answer such questions as whether the activities of PAHs-degrading enzymes on biochar surface are stimulated by earthworm introduction and what are the related mechanisms.

4.2.2 Negative effects of earthworms on biochar

The biodegradation of PAHs is strongly influenced by soil properties such as soil pH and organic matter content, specially the former. Generally, slightly acidic and alkaline soil conditions are favorable for microbial degradation of PAHs (Emoyan et al., 2018). Earthworms have been found to lower soil pH by releasing organic acids, while biochar is more likely to increase soil pH, which should be paid attention to when soil pH is an important influencing factor of pollutant transformation (Huang et al., 2020). Sorption to soil particles and dissolved organic matter (DOM) greatly affects the migration and degradation of PAHs (Weber et al., 1992; Pignatello and Xing, 1995). Garau et al. (2022) found that earthworms accelerated the degradation of biochar organic matter and increased DOM content in soil. DOM may compete with soil matrix for PAHs and increase the bioavailable PAHs in soil, weakening the remediation effect of biochar (Ling et al., 2005). In a word, much remains to be explored about the effects of earthworms on PAHs-contaminated soil remediation using biochar, and relevant research is warranted in the future.

5 Conclusion

It is urgent to solve the problem of PAHs pollution of soils. Both earthworm introduction and biochar application have been proved to be effective in PAHs-contaminated soil remediation. Earthworms activities (e.g., feeding, burrowing, and casting) improve soil texture, structure, and nutrient status, creating a better soil environment for soil microbes and consequently accelerating PAHs biodegradation. The high porosity and large specific surface area of biochar endow it a strong ability to adsorb and immobilize PAHs. Furthermore, it was shown that biochar addition in PAHs-contaminated soils reduced PAHs in soil solution and PAHs accumulation in earthworms. In addition, the PAHs-degrading bacteria in earthworm gut are stimulated, reducing pollutant transfer along the food chain. Meanwhile, earthworm bioturbation enhances biochar migration in soil and the activities of enzymes on biochar surfaces. Although the growth and reproduction of earthworms may be negatively affected by biochar, these negative effects can be eliminated, or at least diminished to a negligible level, by choosing the right pyrolysis conditions for biochar production and applying biochar at an appropriate rate. Considering the lack of studies on PAHs removal effects of biochar-vermiremediation and the underlying mechanisms, future studies are needed to better evaluate the physicochemical and biological interactions among biochar, earthworms, and PAHs in soil.

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References

Abdel-Shafy, H.I., Mansour, M.S.M., 2016. A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. Egyptian Journal of Petroleum 25, 107–123.

Adetunji, A.T., Lewu, F.B., Mulidzi, R., Ncube, B., 2017. The biological activities of β-glucosidase, phosphatase and urease as soil quality indicators: a review. Journal of Soil Science and Plant Nutrition 17, 794–807.

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.

Al-Maliki, S., Scullion, J., 2013. Interactions between earthworms and residues of differing quality affecting aggregate stability and microbial dynamics. Applied Soil Ecology 64, 56–62.

Alexander, M., 1995. How toxic are toxic chemicals in soil? Environmental Science & Technology 29, 2713–2717.

Alexander, M., 2000. Aging, bioavailability, and overestimation of risk from environmental pollutants. Environmental Science & Technology 34, 4259–4265.

Alkorta, I., Aizpurua, A., Riga, P., Albizu, I., Amezaga, I., Garbisu, C., 2003. Soil enzyme activities as biological indicators of soil health. Reviews on Environmental Health 18, 65–73.

Ameloot, N., Graber, E.R., Verheijen, F.G.A., De Neve, S., 2013. Interactions between biochar stability and soil organisms: review and research needs. European Journal of Soil Science 64, 379–390.

Amoah-Antwi, C., Kwiatkowska-Malina, J., Thornton, S.F., Fenton, O., Malina, G., Szara, E., 2020. Restoration of soil quality using biochar and brown coal waste: A review. Science of the Total Environment 722, 137852.

Antoniadis, V., Shaheen, S.M., Levizou, E., Shahid, M., Niazi, N.K., Vithanage, M., Ok, Y.S., Bolan, N., Rinklebe, J., 2019. A critical prospective analysis of the potential toxicity of trace element regulation limits in soils worldwide: Are they protective concerning health risk assessments? – A review. Environment International 127, 819–847.

Anyanwu, I.N., Alo, M.N., Onyekwere, A.M., Crosse, J.D., Nworie, O., Chamba, E.B., 2018. Influence of biochar aged in acidic soil on ecosystem engineers and two tropical agricultural plants. Ecotoxicology and Environmental Safety 153, 116–126.

Anyika, C., Abdul Majid, Z., Ibrahim, Z., Zakaria Mohamad, P., Yahya, A., 2014. The impact of biochars on sorption and biodegradation of polycyclic aromatic hydrocarbons in soils—a review. Environmental Science and Pollution Research International 22, 3314–3341.

Arp, H.P.H., Lundstedt, S., Josefsson, S., Cornelissen, G., Enell, A., Allard, A.S., Kleja, D.B., 2014. Native oxy-PAHs, N-PACs, and PAHs in historically contaminated soils from Sweden, Belgium, and France: Their soil-porewater partitioning behavior, bioaccumulation in *Enchytraeus crypticus*, and bioavailability. Environmental Science & Technology 48, 11187–11195.

Athmann, M., Kautz, T., Banfield, C., Bauke, S., Hoang, D.T.T., Lüsebrink, M., Pausch, J., Amelung, W., Kuzyakov, Y., Köpke, U., 2017. Six months of *L. terrestris* L. activity in root-formed biopores increases nutrient availability, microbial biomass and enzyme activity. Applied Soil Ecology 120, 135–142.

Balmer, J.E., Hung, H., Yu, Y., Letcher, R.J., Muir, D.C.G., 2019. Sources and environmental fate of pyrogenic polycyclic aromatic hydrocarbons (PAHs) in the Arctic. Emerging Contaminants 5, 128–142.

Barré, P., McKenzie, B.M., Hallett, P.D., 2009. Earthworms bring compacted and loose soil to a similar mechanical state. Soil Biology & Biochemistry 41, 656–658.

Barrow, C.J., 2012. Biochar: Potential for countering land degradation and for improving agriculture. Applied Geography (Sevenoaks, England) 34, 21–28.

Bauke, S.L., von Sperber, C., Siebers, N., Tamburini, F., Amelung, W., 2017. Biopore effects on phosphorus biogeochemistry in subsoils. Soil Biology & Biochemistry 111, 157–165.

Beesley, L., Inneh, O.S., Norton, G.J., Moreno-Jimenez, E., Pardo, T., Clemente, R., Dawson, J.J.C., 2014. Assessing the influence of compost and biochar amendments on the mobility and toxicity of metals and arsenic in a naturally contaminated mine soil. Environmental Pollution 186, 195–202.

Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J.L., 2010. Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. Environmental Pollution 158, 2282–2287.

Belfroid, A., Van Den Berg, M., Seinen, W., Hermens, J., Van Gestel, K., 1995. Uptake bioavailability and elimination of hydrophobic compounds in earthworms (*Eisenia andrei*) in field-contaminated soil. Environmental Toxicology and Chemistry 14, 605–612.

Bengough, A.G., Mullins, C.E., 1990. Mechanical impedance to root growth: a review of experimental techniques and root growth responses. Journal of Soil Science 41, 341–358.

Bergknut, M., Sehlin, E., Lundstedt, S., Andersson, P.L., Haglund, P., Tysklind, M., 2007. Comparison of techniques for estimating PAH bioavailability: Uptake in Eisenia fetida, passive samplers and leaching using various solvents and additives. Environmental Pollution 145, 154–160.

Bianco, F., Race, M., Papirio, S., Oleszczuk, P., Esposito, G., 2021. The addition of biochar as a sustainable strategy for the remediation of PAH–contaminated sediments. Chemosphere 263, 128274.

Bielská, L., Škulcová, L., Neuwirthová, N., Cornelissen, G., Hale, S. E., 2018. Sorption, bioavailability and ecotoxic effects of hydrophobic organic compounds in biochar amended soils. Science of the Total Environment 624, 78–86.

Binet, F., Fayolle, L., Pussard, M., 1998. Significance of earthworms in stimulating soil microbial activity. Biology and Fertility of Soils 27, 79–84.

Birk, J.J., Steiner, C., Teixiera, W.C., Zech, W., Glaser, B., 2008. Microbial Response to Charcoal Amendments and Fertilization of a Highly Weathered Tropical Soil. Springer Netherlands: Dordrecht.

Blanchart, E., 1992. Restoration by earthworms (megascolecidae) of the macroaggregate structure of a destructured savanna soil under field conditions. Soil Biology & Biochemistry 24, 1587–1594.

Blanchart, E., Lavelle, P., Braudeau, E., Le Bissonnais, Y., Valentin, C., 1997. Regulation of soil structure by geophagous earthworm activities in humid savannas of Côte d'Ivoire. Soil Biology & Biochemistry 29, 431–439.

Blanco-Canqui, H., 2017. Biochar and soil physical properties. Soil Science Society of America Journal 81, 687–711.

Bolan, N.S., Baskaran, S., 1996. Characteristics of earthworm casts affecting herbicide sorption and movement. Biology and Fertility of Soils 22, 367–372.

Bolan, N.S., Thangarajan, R., Seshadri, B., Jena, U., Das, K.C., Wang, H., Naidu, R., 2013. Landfills as a biorefinery to produce biomass and capture biogas. Bioresource Technology 135, 578–587.

Bouché, M. B., 1977. Strategies lombriciennes. Ecological Bulletins 25, 122–132.

Brändli, R.C., Hartnik, T., Henriksen, T., Cornelissen, G., 2008. Sorption of native polyaromatic hydrocarbons (PAH) to black carbon and amended activated carbon in soil. Chemosphere 73, 1805–1810.

Brown, G.G., Barois, I., Lavelle, P., 2000. Regulation of soil organic matter dynamics and microbial activity in the drilosphere and the role of interactions with other edaphic functional domains. European Journal of Soil Biology 36, 177–198.

Brown, G.G., Doube, B.M., 2004. Functional Interactions between Earthworms, Microorganisms, Organic Matter, and Plants. In: Edwards C A. Earthworm Ecology. CRC Press, Boca Raton , pp. 213–239.

Brussaard, L., 1997. Biodiversity and Ecosystem Functioning in Soil. Ambio 26, 563–570.

Brussaard, L., de Ruiter, P.C., Brown, G.G., 2007. Soil biodiversity for agricultural sustainability. Agriculture, Ecosystems & Environment 121, 233–244.

Buss, W., Graham, M.C., MacKinnon, G., Mašek, O., 2016. Strategies for producing biochars with minimum PAH contamination. Journal of Analytical and Applied Pyrolysis 119, 24–30.

Buss, W., Mašek, O., 2014. Mobile organic compounds in biochar—a potential source of contamination—phytotoxic effects on cress seed (*Lepidium sativum*) germination. Journal of Environmental Management 137, 111–119.

Cachada, A., Coelho, C., Gavina, A., Dias, A. C., Patinha, C., Reis, A. P., Ferreira Da Silva, E., Duarte, A. C., Pereira, R., 2018. Availability of polycyclic aromatic hydrocarbons to earthworms in urban soils and its implications for risk assessment. Chemosphere, 191, 196–203.

Cantrell, K.B., Hunt, P.G., Uchimiya, M., Novak, J.M., Ro, K.S., 2012. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. Bioresource Technology 107, 419–428.

Cao, J., Ji, D.G., Wang, C., 2015. Interaction between earthworms and arbuscular mycorrhizal fungi on the degradation of oxytetracycline in soils. Soil Biology & Biochemistry 90, 283–292.

Cao, X.D., Ma, L.N., Liang, Y., Gao, B., Harris, W., 2011. Simultaneous immobilization of lead and atrazine in contaminated soils using dairy-manure biochar. Environmental Science & Technology 45, 4884–4889.

Chan, K.Y., Van Zwieten, L., Meszaros, I., Downie, A., Joseph, S., 2008. Using poultry litter biochars as soil amendments. Soil Research (Collingwood, Vic.) 46, 437–444.

Chen, B.L., Chen, Z.M., Lv, S.F., 2011a. A novel magnetic biochar efficiently sorbs organic pollutants and phosphate. Bioresource Technology 102, 716–723.

Chen, B.L., Yuan, M.X., 2011. Enhanced sorption of polycyclic aromatic hydrocarbons by soil amended with biochar. Journal of Soils and Sediments 11, 62–71.

Chen, B.L., Zhou, D.D., Zhu, L.Z., 2008. Transitional adsorption and partition of nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures. Environmental Science & Technology 42, 5137–5143.

Chen, J.Y., Zhu, D.Q., Sun, C., 2007. Effect of heavy metals on the sorption of hydrophobic organic compounds to wood charcoal. Environmental Science & Technology 41, 2536–2541.

Chen, X., Xia, X.H., Wang, X.L., Qiao, J.P., Chen, H.T., 2011b. A comparative study on sorption of perfluorooctane sulfonate (PFOS) by chars, ash and carbon nanotubes. Chemosphere 83, 1313–1319.

Chen, Z.M., Chen, B.L., Chiou, C.T., 2012b. Fast and slow rates of naphthalene sorption to biochars produced at different temperatures. Environmental Science & Technology 46, 11104–11111.

Chen, Z.M., Chen, B.L., Zhou, D.D., Chen, W., 2012a. Bisolute sorption and thermodynamic behavior of organic pollutants to biomass-derived biochars at two pyrolytic temperatures. Environmental Science & Technology 46, 12476–12483.

Chi, J., Liu, H.Y., 2016. Effects of biochars derived from different pyrolysis temperatures on growth of *Vallisneria spiralis* and dissipation of polycyclic aromatic hydrocarbons in sediments. Ecological Engineering 93, 199–206.

Chintala, R., Schumacher, T.E., Kumar, S., Malo, D.D., Rice, J.A., Bleakley, B., Chilom, G., Clay, D.E., Julson, J.L., Papiernik, S.K., Gu, Z.R., 2014. Molecular characterization of biochars and their influence on microbiological properties of soil. Journal of Hazardous Materials 279, 244–256.

Chun, Y., Sheng, G.Y., Chiou, C.T., Xing, B.S., 2004. Compositions and sorptive properties of crop residue-derived chars. Environmental Science & Technology 38, 4649–4655.

Contreras-Ramos, S.M., Álvarez-Bernal, D., Dendooven, L., 2006. *Eisenia fetida* increased removal of polycyclic aromatic hydrocarbons from soil. Environmental Pollution 141, 396–401.

Contreras-Ramos, S.M., Álvarez-Bernal, D., Dendooven, L., 2008. Removal of polycyclic aromatic hydrocarbons from soil amended with biosolid or vermicompost in the presence of earthworms (*Eisenia fetida*). Soil Biology & Biochemistry 40, 1954–1959.

Contreras-Ramos, S.M., Álvarez-Bernal, D., Dendooven, L., 2009. Characteristics of earthworms (*Eisenia fetida*) in PAHs contaminated soil amended with sewage sludge or vermicompost. Applied Soil Ecology 41, 269–276.

Cornelissen, G., Gustafsson, Ö., Bucheli, T.D., Jonker, M.T.O., Koelmans, A.A., van Noort, P.C.M., 2005. Extensive sorption of organic compounds to black carbon, coal, and kerogen in sediments and soils: Mechanisms and consequences for distribution, bioaccumulation, and biodegradation. Environmental Science & Technology 39, 6881–6895.

Cornish, P.S.N.E., 1993. Soil macrostructure and root growth of establishing seedlings. Plant and Soil 151, 119–126.

Coutiño-González, E., Hernández-Carlos, B., Gutiérrez-Ortiz, R., Dendooven, L., 2010. The earthworm *Eisenia fetida* accelerates the removal of anthracene and 9, 10-anthraquinone, the most abundant degradation product, in soil. International Biodeterioration & Biodegradation 64, 525–529.

Cox, L., Cecchi, A., Celis, R., Hermosín, M.C., Koskinen, W.C., Cornejo, J., 2001. Effect of exogenous carbon on movement of simazine and 2,4-D in soils. Soil Science Society of America Journal 65, 1688–1695.

Cui, X.Y., Wang, H.L., Lou, L.P., Chen, Y.X., Yu, Y.L., Shi, J.Y., Xu, L., Khan, M.I., 2009. Sorption and genotoxicity of sediment-associated pentachlorophenol and pyrene influenced by crop residue ash. Journal of Soils and Sediments 9, 604–612.

Curry, J.P., Schmidt, O., 2007. The feeding ecology of earthworms – A review. Pedobiologia 50, 463–477.

de Jesus, J.H.F., Da, C., Cunha, G., Cardoso, E.M.C., Mangrich, A. S., Romão, L.P.C., 2017. Evaluation of waste biomasses and their biochars for removal of polycyclic aromatic hydrocarbons. Journal of Environmental Management 200, 186–195.

de Resende, M.F., Brasil, T.F., Madari, B.E., Pereira Netto, A.D., Novotny, E.H., 2018. Polycyclic aromatic hydrocarbons in biochar amended soils: Long-term experiments in Brazilian tropical areas. Chemosphere 200, 641–648.

Dendooven, L., Alvarez-Bernal, D., Contreras-Ramos, S.M., 2011. Earthworms, a means to accelerate removal of hydrocarbons (PAHs) from soil? A mini-review. Pedobiologia 54, S187–S192.

Deng, S.G., Zeng, D.F., 2017. Removal of phenanthrene in contaminated soil by combination of alfalfa, white-rot fungus, and earthworms. Environmental Science and Pollution Research International 24, 7565–7571.

Denyes, M.J., Langlois, V.S., Rutter, A., Zeeb, B.A., 2012. The use of biochar to reduce soil PCB bioavailability to *Cucurbita pepo* and *Eisenia fetida*. Science of the Total Environment 437, 76–82.

Dhaliwal, S.S., Singh, J., Taneja, P.K., Mandal, A., 2020. Remediation techniques for removal of heavy metals from the soil contaminated through different sources: a review. Environmental Science and Pollution Research International 27, 1319–1333.

Diggs, D.L., Huderson, A.C., Harris, K.L., Myers, J.N., Banks, L.D., Rekhadevi, P.V., Niaz, M.S., Ramesh, A., 2011. Polycyclic aromatic hydrocarbons and digestive tract cancers: A perspective. Journal of Environmental Science and Health. Part C, Environmental Carcinogenesis & Ecotoxicology Reviews 29, 324–357.

Ding, J., Yin, Y., Sun, A.Q., Lassen, S.B., Li, G., Zhu, D., Ke, X., 2019. Effects of biochar amendments on antibiotic resistome of the soil and collembolan gut. Journal of Hazardous Materials 377, 186–194.

Ding, Z., Huang, J., Chi, J., 2021. Contribution of phenanthrene in different binding sites to its biodegradation in biochar-amended soils. Environmental Pollution 273, 116481.

Domínguez, J., Edwards, C.A., 1997. Effects of stocking rate and moisture content on the growth and maturation of *Eisenia andrei* (Oligochaeta) in pig manure. Soil Biology & Biochemistry 29, 743–746.

Don, A., Steinberg, B., Schöning, I., Pritsch, K., Joschko, M., Gleixner, G., Schulze, E.D., 2008. Organic carbon sequestration in earthworm burrows. Soil Biology & Biochemistry 40, 1803–1812.

Downie, A., Crosky, A., Munroe, P., 2009. Physical Properties of Biochar, in: Lehmann, J. , Joseph, S., Eds. Biochar for Environmental Management, Earthscan, London , pp. 13–32.

Drake, H.L., Horn, M.A., 2007. As the worm turns: The earthworm gut as a transient habitat for soil microbial biomes. Annual Review of Microbiology 61, 169–189.

Eckmeier, E., Gerlach, R., Skjemstad, J.O., Ehrmann, O., Schmidt, M.W., 2007. Minor changes in soil organic carbon and charcoal concentrations detected in a temperate deciduous forest a year after an experimental slash-and-burn. Biogeosciences 4, 377–383.

Eckmeier, E., Gerlach, R., Skjemstad, J.O., Ehrmann, O., Schmidt, M.W.I., 2007. Only small changes in soil organic carbon and charcoal concentrations found one year after experimental slash-and-burn in a temperate deciduous forest. Biogeosciences Discussions 4, 595–614.

Edwards, C.A., 2004. Earthworm Ecology. Second ed. CRC Press, Boca Raton.

Edwards, C.A., 2004. The importance of earthworms as key representatives of the soil fauna. In: Edwards, C.A., Ed. Earthworm Ecology, second ed. CRC Press, Boca Raton , pp. 3–11.

Edwards, C.A., Bohlen, P.L., 1996. Biology and Ecology of Earthworms, Third ed. Chapman & Hall, London.

Edwards, C.A., Lofty, J.R., 1977. Biology of Earthworms. Chapman and Hall, London.

Eijsackers, H., Van Gestel, C.A., De Jonge, S., Muijs, B., Slijkerman, D., 2001. Polycyclic aromatic hydrocarbon-polluted dredged peat sediments and earthworms: a mutual interference. Ecotoxicology (London, England) 10, 35–50.

Emoyan, O.O., Akporido, S.O., Agbaire, P.O., 2018. Effects of soil pH, total organic carbon and texture on fate of polycyclic aromatic hydrocarbons (PAHs) in soils. Global NEST Journal 20, 181–187.

Eom, I.C., Rast, C., Veber, A.M., Vasseur, P., 2007. Ecotoxicity of a polycyclic aromatic hydrocarbon (PAH)-contaminated soil. Ecotoxicology and Environmental Safety 67, 190–205.

Fagervold, S.K., Chai, Y., Davis, J.W., Wilken, M., Cornelissen, G., Ghosh, U., 2010. Bioaccumulation of polychlorinated dibenzo-p-dioxins/dibenzofurans in *E. fetida* from floodplain soils and the effect of activated carbon amendment. Environmental Science & Technology 44, 5546–5552.

Ferreira, T., Hansel, F.A., Maia, C.M.B.F., Guiotoku, M., Cunha, L., Brown, G.G., 2021. Earthworm-biochar interactions: A laboratory trial using *Pontoscolex corethrurus*. Science of the Total Environment 777, 146147.

Fraser, P.M., Haynes, R.J., Williams, P.H., 1994. Effects of pasture improvement and intensive cultivation on microbial biomass, enzyme activities, and composition and size of earthworm populations. Biology and Fertility of Soils 17, 185–190.

Freddo, A., Cai, C., Reid, B.J., 2012. Environmental contextualisation of potential toxic elements and polycyclic aromatic hydrocarbons in biochar. Environmental Pollution 171, 18–24.

Fu, H.Y., Wei, C.H., Qu, X.L., Li, H., Zhu, D.Q., 2018. Strong binding of apolar hydrophobic organic contaminants by dissolved black carbon released from biochar: A mechanism of pseudomicelle partition and environmental implications. Environmental Pollution 232, 402–410.

Fu, P., Yi, W.M., Bai, X.Y., Li, Z.H., Hu, S., Xiang, J., 2011. Effect of temperature on gas composition and char structural features of pyrolyzed agricultural residues. Bioresource Technology 102, 8211–8219.

Gan, S., Lau, E.V., Ng, H.K., 2009. Remediation of soils contaminated with polycyclic aromatic hydrocarbons (PAHs). Journal of Hazardous Materials 172, 532–549.

Garau, M., Sizmur, T., Coole, S., Castaldi, P., Garau, G., 2022. Impact of *Eisenia fetida* earthworms and biochar on potentially toxic element mobility and health of a contaminated soil. Science of the Total Environment 806, 151255.

García, J. A., Fragoso, C., 2002. Growth, reproduction and activity of earthworms in degraded and amended tropical open mined soils: laboratory assays. Applied Soil Ecology, 20, 43–56.

García-Delgado, C., Alfaro-Barta, I., Eymar, E., 2015. Combination of biochar amendment and mycoremediation for polycyclic aromatic hydrocarbons immobilization and biodegradation in creosote-contaminated soil. Journal of Hazardous Materials 285, 259–266.

Ghaffar, A., Ghosh, S., Li, F.F., Dong, X.D., Zhang, D., Wu, M., Li, H., Pan, B., 2015. Effect of biochar aging on surface characteristics and adsorption behavior of dialkyl phthalates. Environmental Pollution 206, 502–509.

Glaser, B., Lehmann, J., Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal: a review. Biology and Fertility of Soils 35, 219–230.

Godlewska, P., Ok, Y.S., Oleszczuk, P., 2021. THE DARK SIDE OF BLACK GOLD: Ecotoxicological aspects of biochar and biochar-amended soils. Journal of Hazardous Materials 403, 123833.

Godlewska, P., Oleszczuk, P., 2022. Effect of biomass addition before sewage sludge pyrolysis on the persistence and bioavailability of polycyclic aromatic hydrocarbons in biochar-amended soil. Chemical Engineering Journal 429, 132143.

Gomez-Eyles, J.L., Sizmur, T., Collins, C.D., Hodson, M.E., 2011. Effects of biochar and the earthworm *Eisenia fetida* on the bioavailability of polycyclic aromatic hydrocarbons and potentially toxic elements. Environmental Pollution 159, 616–622.

Gomez-Eyles, J.L., Yupanqui, C., Beckingham, B., Riedel, G., Gilmour, C., Ghosh, U., 2013. Evaluation of biochars and activated carbons for *in situ* remediation of sediments impacted with organics, mercury, and methylmercury. Environmental Science & Technology 47, 13721–13729.

Gong, X.Q., Cai, L.L., Li, S.Y., Chang, S.X., Sun, X.Y., An, Z.F., 2018. Bamboo biochar amendment improves the growth and reproduction of *Eisenia fetida* and the quality of green waste vermicompost. Ecotoxicology and Environmental Safety 156, 197–204.

Gonzaga, M.I.S., Mackowiak, C.L., Comerford, N.B., Moline, E.F.D. V., Shirley, J.P., Guimaraes, D.V., 2017. Pyrolysis methods impact biosolids-derived biochar composition, maize growth and nutrition. Soil & Tillage Research 165, 59–65.

Goss, M.J., 1977. Effects of mechanical impedance on root growth in barley (*Hordeum vulgare* L.): I. effects on the elongation and branching of seminal root axes. Journal of Experimental Botany 102, 96–111.

Goss, M.J., Russell, R.S., 1980. Effects of mechanical impedance on root growth in barley (*Hordeum vulgare* L.): III. OBSERVATIONS ON THE MECHANISM OF RESPONSE. Journal of Experimental Botany 121, 577–588.

Gowri, S., Thangaraj, R., 2020. Studies on the toxic effects of agrochemical pesticide (Monocrotophos) on physiological and reproductive behavior of indigenous and exotic earthworm species. International Journal of Environmental Health Research 30, 212–225.

Haimi, J., 2000. Decomposer animals and bioremediation of soils. Environmental Pollution 107, 233–238.

Hale, S.E., Lehmann, J., Rutherford, D., Zimmerman, A.R., Bachmann, R.T., Shitumbanuma, V.O., Toole, A., Sundqvist, K.L., Arp, H.P.H., Cornelissen, G., 2012. Quantifying the total and bioavailable polycyclic aromatic hydrocarbons and dioxins in biochars. Environmental Science & Technology 46, 2830–2838.

Hallam, J., Hodson, M.E., 2020. Impact of different earthworm ecotypes on water stable aggregates and soil water holding capacity. Biology and Fertility of Soils 56, 607–617.

Hallam, J., Holden, J., Robinson, D.A., Hodson, M.E., 2021. Effects of winter wheat and endogeic earthworms on soil physical and hydraulic properties. Geoderma 400, 115126.

Hartmann, R., 1996. Polycyclic aromatic hydrocarbons (PAHs) in forest soils: Critical evaluation of a new analytical procedure. International Journal of Environmental Analytical Chemistry 62, 161–173.

Haynes, R.J., Fraser, P.M., Piercy, J.E., Tregurtha, R.J., 2003. Casts of *Aporrectodea caliginosa* (Savigny) and Lumbricus rubellus (Hoffmeister) differ in microbial activity, nutrient availability and aggregate stability. Pedobiologia 47, 882–887.

Hernández-Castellanos, B., Ortíz-Ceballos, A., Martínez-Hernández, S., Noa-Carrazana, J.C., Luna-Guido, M., Dendooven, L., Contreras-Ramos, S.M., 2013. Removal of benzo(a)- pyrene from soil using an endogeic earthworm *Pontoscolex corethrurus* (Müller, 1857). Applied Soil Ecology 70, 62–69.

Hernández-Castellanos, B., Zavala-Cru, J., Martinez-Hernández, S., Dendooven, L., Contreras-Ramos, S.M., Noa-Carrazana, J.C., Fragoso, C., Ortiz-Ceballos, A.I., 2013. Earthworm populations in an aged hydrocarbon contaminated soil. Research Journal of Environmental Sciences 7, 27–37.

Hickman, Z.A., Reid, B.J., 2008. Earthworm assisted bioremediation of organic contaminants. Environment International 34, 1072–1081.

Hilber, I., Bastos, A.C., Loureiro, S., Soja, G., Marsz, A., Cornelissen, G., Bucheli, T.D., 2017. The different faces of biochar: contamination risk versus remediation tool. Journal of Environmental Engineering and Landscape Management 25, 86–104.

Hindell, R.P., McKenzie, B.M., Tisdall, J.M., 1997. Destabilization of soil during the production of earthworm (Lumbricidae) and artificial casts. Biology and Fertility of Soils 24, 153–163.

Huang, C., Wang, W., Yue, S., Adeel, M., Qiao, Y., 2020. Role of biochar and *Eisenia fetida* on metal bioavailability and biochar effects on earthworm fitness. Environmental Pollution, 263(Pt A): 114586.

Hund, K., Traunspurger, W., 1994. Ecotox-evaluation strategy for soil bioremediation exemplified for a PAH-contaminated site. Chemosphere 29, 371–390.

IARC, 2021. Agents Classified by the IARC Monographs, Volumes 1–132.

Inyang, M., Dickenson, E., 2015. The potential role of biochar in the removal of organic and microbial contaminants from potable and reuse water: A review. Chemosphere 134, 232–240.

Jager, T., Baerselman, R., Dijkman, E., de Groot, A.C., Hogendoorn, E.A., de Jong, A., Kruitbosch, J.A., Peijnenburg, W.J., 2003. Availability of polycyclic aromatic hydrocarbons to earthworms (*Eisenia andrei*, Oligochaeta) in field-polluted soils and soil-sediment mixtures. Environmental Toxicology and Chemistry 22, 767–775.

Jakob, L., Hartnik, T., Henriksen, T., Elmquist, M., Brändli, R.C., Hale, S.E., Cornelissen, G., 2012. PAH-sequestration capacity of granular and powder activated carbon amendments in soil, and their effects on earthworms and plants. Chemosphere 88, 699–705.

James, G., Sabatini, D.A., Chiou, C.T., Rutherford, D., Scott, A.C., Karapanagioti, H.K., 2005. Evaluating phenanthrene sorption on various wood chars. Water Research 39, 549–558.

Jin, J., Sun, K., Wu, F.C., Gao, B., Wang, Z.Y., Kang, M.J., Bai, Y. C., Zhao, Y., Liu, X.T., Xing, B.S., 2014. Single-solute and bi-solute sorption of phenanthrene and dibutyl phthalate by plant- and manure-derived biochars. Science of the Total Environment 473–474, 308–316.

Jonker, M.T., Hoenderboom, A.M., Koelmans, A.A., 2004. Effects of sedimentary sootlike materials on bioaccumulation and sorption of polychlorinated biphenyls. Environmental Toxicology and Chemistry 23, 2563–2570.

Jouquet, P., Podwojewski, P., Bottinelli, N., Mathieu, J., Ricoy, M., Orange, D., Toan, D.T., Valentin, C., 2008. Above-ground earthworm casts affect water runoff and soil erosion in Northern Vietnam. Catena 74, 13–21.

Jung, C., Park, J.Y., Lim, K.H., Park, S., Heo, J., Her, N., Oh, J., Yun, S., Yoon, Y., 2013. Adsorption of selected endocrine disrupting compounds and pharmaceuticals on activated biochars. Journal of Hazardous Materials 263, 702–710.

Juwarkar, A.A., Singh, S.K., Mudhoo, A., 2010. A comprehensive overview of elements in bioremediation. Reviews in Environmental Science and Biotechnology 9, 215–288.

Kalinke, C., Oliveira, P.R., Oliveira, G.A., Mangrich, A.S., Marcolino-Junior, L.H., Bergamini, M.F., 2017. Activated biochar: Preparation, characterization and electroanalytical application in an alternative strategy of nickel determination. Analytica Chimica Acta 983, 103–111.

Karhu, K., Mattila, T., Bergström, I., Regina, K., 2011. Biochar addition to agricultural soil increased CH_4 uptake and water holding capacity – Results from a short-term pilot field study. Agriculture, Ecosystems & Environment 140, 309–313.

Kavitha, B., Reddy, P.V.L., Kim, B., Lee, S.S., Pandey, S.K., Kim, K. H., 2018. Benefits and limitations of biochar amendment in agricultural soils: A review. Journal of Environmental Management 227, 146–154.

Kelsey, J.W., Kottler, B.D., Alexander, M., 1997. Selective chemical extractants to predict bioavailability of soil-aged organic chemicals. Environmental Science & Technology 31, 214–217.

Khadem, A., Raiesi, F., 2019. Response of soil alkaline phosphatase to biochar amendments: Changes in kinetic and thermodynamic characteristics. Geoderma 337, 44–54.

Khalid, F.N.M., Klarup, D., 2015. The influence of sunlight and oxidative treatment on measured PAH concentrations in biochar. Environmental Science and Pollution Research International 22, 12975–12981.

Khan, S., Wang, N., Reid, B.J., Freddo, A., Cai, C., 2013. Reduced bioaccumulation of PAHs by *Lactuca satuva* L. grown in contaminated soil amended with sewage sludge and sewage sludge derived biochar. Environmental Pollution 175, 64–68.

Khorram, M.S., Zhang, Q., Lin, D.L., Zheng, Y., Fang, H., Yu, Y.L., 2016. Biochar: A review of its impact on pesticide behavior in soil environments and its potential applications. Journal of Environmental Sciences (China) 44, 269–279.

Kim, J.H., Ok, Y.S., Choi, G.H., Park, B.J., 2015. Residual perfluorochemicals in the biochar from sewage sludge. Chemosphere 134, 435–437.

Kończak, M., Gao, Y., Oleszczuk, P., 2019. Carbon dioxide as a carrier gas and biomass addition decrease the total and bioavailable polycyclic aromatic hydrocarbons in biochar produced from sewage sludge. Chemosphere 228, 26–34.

Kong, L.L., Gao, Y.Y., Zhou, Q.X., Zhao, X.Y., Sun, Z.W., 2018. Biochar accelerates PAHs biodegradation in petroleum-polluted soil by biostimulation strategy. Journal of Hazardous Materials 343, 276–284.

Kuppusamy, S., Thavamani, P., Venkateswarlu, K., Lee, Y.B., Naidu, R., Megharaj, M., 2017. Remediation approaches for polycyclic aromatic hydrocarbons (PAHs) contaminated soils: Technological constraints, emerging trends and future directions. Chemosphere 168, 944–968.

Langlois, V.S., Rutter, A., Zeeb, B.A., 2011. Activated carbon immobilizes residual polychlorinated biphenyls in weathered contaminated soil. Journal of Environmental Quality 40, 1130–1134.

Lavelle, P., 1981. Strategies de reproduction chez les vers de terre. Acta Ecologica Ecologia Generalis 2, 117–133.

Lavelle, P., 1988. Earthworm activities and the soil system. Biology and Fertility of Soils 6, 237–251.

Lavelle, P., Charpentier, F., Villenave, C., Rossi, J.P., Derouard, L., Pashanasi, B., Andre, J., Ponge, J.F., Bernier, N., 2004. Effects of Earthworms on Soil Organic Matter and Nutrient Dynamics at a Landscape Scale Over Decades. In: Edwards, C. A., ed. Earthworm Ecology, second edition. CRC Press, Boca Raton , pp. 145–160.

Lee, X.J., Ong, H.C., Gan, Y.Y., Chen, W.H., Mahlia, T.M.I., 2020. State of art review on conventional and advanced pyrolysis of macroalgae and microalgae for biochar, bio-oil and bio-syngas production. Energy Conversion and Management 210, 112707.

Lehmann, J., 2007. A handful of carbon. Nature 447, 143–144.

Lehmann, J., Gaunt, J., Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems – A review. Mitigation and Adaptation Strategies for Global Change 11, 403–427.

Lehmann, J., Liang, B.Q., Solomon, D., Lerotic, M., Luizão, F., Kinyangi, J., Schäfer, T., Wirick, S., Jacobsen, C., 2005. Near-edge X-ray absorption fine structure (NEXAFS) spectroscopy for mapping nano-scale distribution of organic carbon forms in soil: Application to black carbon particles. Global Biogeochemical Cycles 19, 1–12.

Lehmann, J., Pereira, D.S.J.J., Steiner, C., Nehls, T., Zech, W., Glaser, B., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil 249, 343–357.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota – A review. Soil Biology & Biochemistry 43, 1812–1836.

Lehmann, J., Solomon, D., Kinyangi, J., Dathe, L., Wirick, S., Jacobsen, C., 2008. Spatial complexity of soil organic matter forms at nanometre scales. Nature Geoscience 1, 238–242.

Leifeld, J., Fenner, S., Muller, M., 2007. Mobility of black carbon in drained peatland soils. Biogeosciences 4, 425–432.

Li, B., Zhu, H.K., Sun, H.W., Xu, J.Y., 2017b. Effects of the amendment of biochars and carbon nanotubes on the bioavailability of hexabromocyclododecanes (HBCDs) in soil to ecologically different species of earthworms. Environmental Pollution 222, 191–200.

Li, D., Alvarez, P.J.J., 2011. Avoidance, weight loss, and cocoon production assessment for *Eisenia fetida* exposed to C60 in soil. Environmental Toxicology and Chemistry 30, 2542–2545.

Li, D., Hockaday, W.C., Masiello, C.A., Alvarez, P.J.J., 2011. Earthworm avoidance of biochar can be mitigated by wetting. Soil Biology & Biochemistry 43, 1732–1737.

Li, H., Mahyoub, S.A.A., Liao, W.J., Xia, S.Q., Zhao, H.C., Guo, M. Y., Ma, P.S., 2017a. Effect of pyrolysis temperature on characteristics and aromatic contaminants adsorption behavior of magnetic biochar derived from pyrolysis oil distillation residue. Bioresource Technology 223, 20–26.

Li, M., Liu, Q., Guo, L.J., Zhang, Y.P., Lou, Z.J., Wang, Y., Qian, G. R., 2013. Cu(II) removal from aqueous solution by *Spartina alterniflora* derived biochar. Bioresource Technology 141, 83–88.

Li, X.N., Song, Y., Bian, Y.R., Gu, C.G., Yang, X.L., Wang, F., Jiang, X., 2020b. Insights into the mechanisms underlying efficient rhizodegradation of PAHs in biochar-amended soil: From microbial communities to soil metabolomics. Environment International 144, 105995.

Li, Y.B., Wang, X., Sun, Z.J., 2020a. Ecotoxicological effects of petroleum-contaminated soil on the earthworm *Eisenia fetida*. Journal of Hazardous Materials 393, 122384.

Liesch, A.M., Weyers, S.L., Gaskin, J.W., Das, K.C., 2010. Impact of two different biochars on earthworm growth and survival. Annals of Environmental Science (Boston, Mass.) 4, 1–9.

Lin, Z., Li, X.M., Li, Y.T., Huang, D.Y., Dong, J., Li, F.B., 2012. Enhancement effect of two ecological earthworm species (*Eisenia foetida* and *Amynthas robustus* E. Perrier) on removal and degradation processes of soil DDT. Journal of Environmental Monitoring 14, 1551–1558.

Ling, W., Xu, J., Gao, Y., 2005. Effects of dissolved organic matter from sewage sludge on the atrazine sorption by soils. Science in China. Series C, Life Sciences 48, 57–66.

Liu, H., Wei, Y. F., Luo, J. M., Li, T., Wang, D., Luo, S. L., Crittenden, J. C., 2019. 3D hierarchical porous-structured biochar aerogel for rapid and efficient phenicol antibiotics removal from water. Chemical Engineering Journal (Lausanne, Switzerland: 1996) 368, 639–648.

Liu, L., Chen, P., Sun, M. X., Shen, G. Q., Shang, G. F., 2015. Effect of biochar amendment on PAH dissipation and indigenous degradation bacteria in contaminated soil. Journal of soils and sediments 15, 313–322.

Liu, S., Zhou, Q.X., Wang, Y.Y., 2011. Ecotoxicological responses of the earthworm *Eisenia fetida* exposed to soil contaminated with HHCB. Chemosphere 83, 1080–1086.

Lu, X.X., Reible, D.D., Fleeger, J.W., 2004. Relative importance of ingested sediment versus pore water as uptake routes for PAHs to the deposit-feeding oligochaete *Ilyodrilus templetoni*. Archives of Environmental Contamination and Toxicology 47, 207–214.

Lu, Y.F., Lu, M., 2015. Remediation of PAH-contaminated soil by the combination of tall fescue, arbuscular mycorrhizal fungus and epigeic earthworms. Journal of Hazardous Materials 285, 1–34.

Luo, F., Song, J., Xia, W.X., Dong, M., Chen, M., Soudek, P., 2014. Characterization of contaminants and evaluation of the suitability for land application of maize and sludge biochars. Environmental Science and Pollution Research International 21, 8707–8717.

Ma, W.C., Immerzeel, J., Bodt, J., 1995. Earthworm and food interactions on bioaccumulation and disappearance in soil of polycyclic aromatic hydrocarbons: studies on phenanthrene and fluoranthene. Ecotoxicology and Environmental Safety 32, 226–232.

Major, J., Lehmann, J., Rondon, M., Goodale, C., 2010. Fate of soil-applied black carbon: downward migration, leaching and soil respiration. Global Change Biology 16, 1366–1379.

Malev, O., Contin, M., Licen, S., Barbieri, P., De Nobili, M., 2016. Bioaccumulation of polycyclic aromatic hydrocarbons and survival of earthworms (*Eisenia andrei*) exposed to biochar amended soils. Environmental Science and Pollution Research International 23, 3491–3502.

Malik, K.A., 1990. Use of activated charcoal for the preservation of anaerobic phototrophic and other sensitive bacteria by freeze-drying. Journal of Microbiological Methods 12, 117–124.

Malińska, K., Zabochnicka-Świątek, M., Cáceres, R., Marfà, O., 2016. The effect of precomposted sewage sludge mixture amended with biochar on the growth and reproduction of *Eisenia fetida* during laboratory vermicomposting. Ecological Engineering 90, 35–41.

Marchal, G., Smith, K.E.C., Rein, A., Winding, A., Wollensen de Jonge, L., Trapp, S., Karlson, U.G., 2013. Impact of activated carbon, biochar and compost on the desorption and mineralization of phenanthrene in soil. Environmental Pollution 181, 200–210.

Marinari, S., Masciandaro, G., Ceccanti, B., Grego, S., 2000. Influence of organic and mineral fertilisers on soil biological and physical properties. Bioresource Technology 72, 9–17.

Maroušek, J., Kolář, L., Vochozka, M., Stehel, V., Maroušková, A., 2018. Biochar reduces nitrate level in red beet. Environmental Science and Pollution Research International 25, 18200–18203.

Martens, D.A., Johanson, J.B., Frankenberger, W.T. Jr, 1992. Production and persistence of soil enzymes with repeated addition of organic residues. Soil Science 153, 53–61.

Mary, E.S., Aidan, M.K., Olaf, S., 2011. Distinct microbial and faunal communities and translocated carbon in *Lumbricus terrestris* drilospheres. Soil Biology & Biochemistry 46, 155–162.

Matscheko, N., Lundstedt, S., Svensson, L., Harju, M., Tysklind, M., 2002. Accumulation and elimination of 16 polycyclic aromatic compounds in the earthworm (*Eisenia fetida*). Environmental Toxicology and Chemistry 21, 1724–1729.

Mayer, P., Fernqvist, M.M., Christensen, P.S., Karlson, U., Trapp, S., 2007. Enhanced diffusion of polycyclic aromatic hydrocarbons in artificial and natural aqueous solutions. Environmental Science & Technology 41, 6148–6155.

Menzie, C.A., Potocki, B.B., Santodonato, J., 1992. Exposure to carcinogenic PAHs in the environment. Environmental Science & Technology 26, 1278–1284.

Michael, J., Jürgen, S., Karl-Josef, M., 1997. The inoculation of *Lumbricus terrestris* L. in an acidic spruce forest after liming and its influence on soil properties. Soil Biology & Biochemistry 29, 677–679.

Miltner, A., Bombach, P., Schmidt-Brücken, B., Kästner, M., 2012. SOM genesis: microbial biomass as a significant source. Biogeochemistry 111, 41–55.

Moon, Y., Yim, U., Kim, H., Kim, Y., Shin, W.S., Hwang, I., 2013. Toxicity and bioaccumulation of petroleum mixtures with alkyl PAHs in earthworms. Human and Ecological Risk Assessment 19, 819–835.

Moreno-Castilla, C., Ferro-Garcia, M.A., Joly, J.P., Bautista-Toledo, I., Carrasco-Marin, F., Rivera-Utrilla, J., 1995. Activated carbon surface modifications by nitric acid, hydrogen peroxide, and ammonium peroxydisulfate treatments. Langmuir 11, 4386–4392.

Natal-da-Luz, T., Lee, I., Verweij, R.A., Morais, P.V., Van Velzen, M. J.M., Sousa, J.P., Van Gestel, C.A.M., 2012. Influence of earthworm activity on microbial communities related with the degradation of persistent pollutants. Environmental Toxicology and Chemistry 31, 794–803.

Nguyen, B.T., Lehmann, J., Kinyangi, J., Smernik, R., Riha, S.J., Engelhard, M.H., 2008. Long-term black carbon dynamics in cultivated soil. Biogeochemistry 89, 163–176.

Noguera, D., Rondón, M., Laossi, K., Hoyos, V., Lavelle, P., Cruz, D. C., Maria, H., Barot, S., 2010. Contrasted effect of biochar and earthworms on rice growth and resource allocation in different soils. Soil Biology & Biochemistry 42, 1017–1027.

Northcott, G.L., Jones, K.C., 2001. Partitioning, extractability, and formation of nonextractable PAH residues in soil. 1. Compound differences in aging and sequestration. Environmental Science & Technology 35, 1103–1110.

Nsamba, H.K., Hale, S.E., Cornelissen, G., Bachmann, R.T., 2015. Sustainable technologies for small-scale biochar production—A review. Journal of Sustainable Bioenergy Systems 5, 10–31.

Oleszczuk, P., Kołtowski, M., 2017. Effect of co-application of nano-zero valent iron and biochar on the total and freely dissolved polycyclic aromatic hydrocarbons removal and toxicity of contaminated soils. Chemosphere 168, 1467–1476.

Oni, B.A., Oziegbe, O., Olawole, O.O., 2019. Significance of biochar application to the environment and economy. Annals of Agricultural Science 64, 222–236.

Owojori, O.J., Reinecke, A.J., 2010. Effects of natural (flooding and drought) and anthropogenic (copper and salinity) stressors on the earthworm *Aporrectodea caliginosa* under field conditions. Applied Soil Ecology 44, 156–163.

Pagenkemper, S.K., Athmann, M., Uteau, D., Kautz, T., Peth, St., Horn, R., 2015. The effect of earthworm activity on soil bioporosity – Investigated with X-ray computed tomography and endoscopy. Soil & Tillage Research 146, 79–88.

Palansooriya, K.N., Wong, J.T.F., Hashimoto, Y., Huang, L., Rinklebe, J., Chang, S.X., Bolan, N., Wang, H.L., Ok, Y.S., 2019. Response of microbial communities to biochar-amended soils: a critical review. Biochar 1, 1–20.

Park, J.H., Feng, Y., Ji, P., Voice, T.C., Boyd, S.A., 2003. Assessment of bioavailability of soil-sorbed atrazine. Applied and Environmental Microbiology 69, 3288–3298.

Parrish, Z.D., White, J.C., Isleyen, M., Gent, M.P.N., Iannucci-Berger, W., Eitzer, B.D., Kelsey, J.W., Mattina, M.I., 2006. Accumulation of weathered polycyclic aromatic hydrocarbons (PAHs) by plant and earthworm species. Chemosphere 64, 609–618.

Parthasarathi, K., Ranganathan, L.S., 2000. Aging effect on enzyme activities in pressmud vermicasts of *Lampito mauritii* (Kinberg) and *Eudrilus eugeniae* (Kinberg). Biology and Fertility of Soils 30, 347–350.

Passioura, J.B., 2002. Environmental biology and crop improvement. Functional Plant Biology 29, 537–546.

Paz-Ferreiro, J., Fu, S., Méndez, A., Gascó, G., 2014. Interactive effects of biochar and the earthworm *Pontoscolex corethrurus* on plant productivity and soil enzyme activities. Journal of Soils and Sediments 14, 483–494.

Paz-Ferreiro, J., Liang, C.F., Fu, S.L., Mendez, A., Gasco, G., Hui, D.F., 2015. The effect of biochar and its interaction with the earthworm *Pontoscolex corethrurus* on soil microbial community structure in tropical soils. PLoS One 10, e124891.

Paz-Ferreiro, J., Shenglei, F., Mendez, A., Gasco, G., 2014. Interactive effects of biochar and the earthworm *Pontoscolex corethrurus* on plant productivity and soil enzyme activities. Journal of Soils and Sediments 14, 483–494.

Peng, X., Deng, Y., Peng, Y., Yue, K., 2018. Effects of biochar addition on toxic element concentrations in plants: A meta-analysis. Science of the Total Environment 616–617, 970–977.

Perego, C., Bosetti, A., 2011. Biomass to fuels: The role of zeolite and mesoporous materials. Microporous and Mesoporous Materials 144, 28–39.

Pignatello, J.J., Xing, B., 1995. Mechanisms of slow sorption of organic chemicals to natural particles. Environmental Science & Technology 30, 1–11.

Pižl, V., Nováková, A., 2003. Interactions between microfungi and *Eisenia andrei* (Oligochaeta) during cattle manure vermicomposting. Pedobiologia 47, 895–899.

Poluszyńska, J., Jarosz-Krzemińska, E., Helios-Rybicka, E., 2017. Studying the effects of two various methods of composting on the degradation levels of polycyclic aromatic hydrocarbons (PAHs) in sewage sludge. Water, Air, and Soil Pollution 228, 1–10.

Qi, Y.C., Chen, W., 2010. Comparison of earthworm bioaccumulation between readily desorbable and desorption-resistant naphthalene: Implications for biouptake routes. Environmental Science & Technology 44, 323–328.

Qian, L.B., Chen, B.L., 2013. Interactions of aluminum with biochars and oxidized biochars: Implications for the biochar aging process. Journal of Agricultural and Food Chemistry 62, 373–380.

Quilliam, R.S., Rangecroft, S., Emmett, B.A., Deluca, T.H., Jones, D. L., 2013. Is biochar a source or sink for polycyclic aromatic hydrocarbon (PAH) compounds in agricultural soils? Global Change Biology Bioenergy 5, 96–103.

Ren, X. W., Tang, J. C., Wang, L., Sun, H. W., 2021. Combined effects of microplastics and biochar on the removal of polycyclic aromatic hydrocarbons and phthalate esters and its potential microbial ecological mechanism. Frontiers in Microbiology 12, 647766.

Ren, X.Y., Zeng, G.M., Tang, L., Wang, J.J., Wan, J., Feng, H.P., Song, B., Huang, C., Tang, X., 2018. Effect of exogenous carbonaceous materials on the bioavailability of organic pollutants and their ecological risks. Soil Biology & Biochemistry 116, 70–81.

Rey-Salgueiro, L., Omil, B., Merino, A., Martínez-Carballo, E., Simal-Gándara, J., 2016. Organic pollutants profiling of wood ashes from biomass power plants linked to the ash characteristics. Science of the Total Environment 544, 535–543.

Rhodes, A.H., Carlin, A., Semple, K.T., 2008. Impact of black carbon in the extraction and mineralization of phenanthrene in soil. Environmental Science & Technology 42, 740–745.

Rhodes, A.H., McAllister, L.E., Chen, R.R., Semple, K.T., 2010. Impact of activated charcoal on the mineralisation of ^{14}C-phenanthrene in soils. Chemosphere 79, 463–469.

Rodrigues, D.F., Jaisi, D.P., Elimelech, M., 2013. Toxicity of functionalized single-walled carbon nanotubes on soil microbial communities: Implications for nutrient cycling in soil. Environmental Science & Technology 47, 625–633.

Rodriguez-Campos, J., Dendooven, L., Alvarez-Bernal, D., Contreras-Ramos, S.M., 2014. Potential of earthworms to accelerate removal of organic contaminants from soil: A review. Applied Soil Ecology 79, 10–25.

Rodriguez-Campos, J., Perales-Garcia, A., Hernandez-Carballo, J., Martinez-Rabelo, F., Hernández-Castellanos, B., Barois, I., Contreras-Ramos, S.M., 2019. Bioremediation of soil contaminated by hydrocarbons with the combination of three technologies: bioaugmentation, phytoremediation, and vermiremediation. Journal of Soils and Sediments 19, 1981–1994.

Rorat, A., Wloka, D., Grobelak, A., Grosser, A., Sosnecka, A., Milczarek, M., Jelonek, P., Vandenbulcke, F., Kacprzak, M., 2017. Vermiremediation of polycyclic aromatic hydrocarbons and heavy metals in sewage sludge composting process. Journal of Environmental Management 187, 347–353.

Sadegh-Zadeh, F., Wahid, S.A., Jalili, B., 2017. Sorption, degradation and leaching of pesticides in soils amended with organic matter: A review. Advances in Environmental Technology 3, 119–132.

Sanchez-Hernandez, J.C., 2018. Biochar activation with exoenzymes induced by earthworms: A novel functional strategy for soil quality promotion. Journal of Hazardous Materials 350, 136–143.

Sanchez-Hernandez, J.C., Ro, K.S., Díaz, F.J., 2019. Biochar and earthworms working in tandem: Research opportunities for soil bioremediation. Science of the Total Environment 688, 574–583.

Sandhu, S.S., Ussiri, D.A.N., Kumar, S., Chintala, R., Papiernik, S. K., Malo, D.D., Schumacher, T.E., 2017. Analyzing the impacts of three types of biochar on soil carbon fractions and physiochemical properties in a corn-soybean rotation. Chemosphere 184, 473–481.

Schmidt, N., Boll, E.S., Malmquist, L.M.V., Christensen, J.H., 2017. PAH metabolism in the earthworm *Eisenia fetida* - identification of phase II metabolites of phenanthrene and pyrene. International Journal of Environmental Analytical Chemistry 97, 1151–1162.

Schreck, E., Geret, F., Gontier, L., Treilhou, M., 2008. Neurotoxic effect and metabolic responses induced by a mixture of six pesticides on the earthworm *Aporrectodea caliginosa nocturna*. Chemosphere 71, 1832–1839.

Scullion, J., 2006. Remediating polluted soils. Naturwissenschaften 93, 51–65.

Shan, J., Brune, A., Ji, R., 2010. Selective digestion of the proteinaceous component of humic substances by the geophagous earthworms *Metaphire guillelmi* and *Amynthas corrugatus*. Soil Biology 1 Biochemistry 42, 1455–1462.

Shan, J., Liu, J., Wang, Y.F., Yan, X.Y., Guo, H.Y., Li, X.Z., Ji, R., 2013. Digestion and residue stabilization of bacterial and fungal cells, protein, peptidoglycan, and chitin by the geophagous earthworm *Metaphire guillelmi*. Soil Biology & Biochemistry 64, 9–17.

Shan, J., Wang, Y.F., Gu, J.Q., Zhou, W.Q., Ji, R., Yan, X.Y., 2014. Effects of biochar and the geophagous earthworm *Metaphire guillelmi* on fate of ^{14}C-catechol in an agricultural soil. Chemosphere 107, 109–114.

Sheng, Y.Q., Zhu, L.Z., 2018. Biochar alters microbial community and carbon sequestration potential across different soil pH. Science of the Total Environment 622–623, 1391–1399.

Shi, Z.M., Liu, J.H., Tang, Z.W., Zhao, Y.H., Wang, C.Y., 2020. Vermiremediation of organically contaminated soils: Concepts, current status, and future perspectives. Applied Soil Ecology 147, 103377.

Shi, Z.M., Xu, L., Hu, F., 2014. A hierarchic method for studying the distribution of phenanthrene in *Eisenia fetida*. Pedosphere 24, 743–752.

Siedt, M., Schäffer, A., Smith, K.E.C., Nabel, M., Roß-Nickoll, M., van Dongen, J.T., 2021. Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. Science of the Total Environment 751, 141607.

Silvani, L., Hjartardottir, S., Bielská, L., Škulcová, L., Cornelissen, G., Nizzetto, L., Hale, S.E., 2019. Can polyethylene passive samplers predict polychlorinated biphenyls (PCBs) uptake by earthworms and turnips in a biochar amended soil? Science of the Total Environment 662, 873–880.

Simmers, J.W., Rhett, R.G., Kay, S.H., Marquenie, J.M., 1986. Bioassay and biomonitoring assessments of contaminant mobility from dredged material. Science of the Total Environment 56, 173–182.

Simpson, A.J., Simpson, M.J., Smith, E., Kelleher, B.P., 2007. Microbially derived inputs to soil organic matter: Are current estimates too low? Environmental Science & Technology 41, 8070–8076.

Sims, R.C., Overcash, M.R., 1983. Fate of polynuclear aromatic compounds (PNAs) in soil-plant systems. Residue Reviews 88, 1–68.

Singer, A.C., Jury, W., Luepromchai, E., Yahng, C.S., Crowley, D.E., 2001. Contribution of earthworms to PCB bioremediation. Soil Biology & Biochemistry 33, 765–776.

Singleton, D.R., Hendrix, P.F., Coleman, D.C., Whitman, W.B., 2003. Identification of uncultured bacteria tightly associated with the intestine of the earthworm *Lumbricus rubellus* (Lumbricidae; Oligochaeta). Soil Biology & Biochemistry 35, 1547–1555.

Sinha, R.K., Chauhan, K., Valani, D., Chandran, V., Soni, B.K., Patel, V., 2010. Earthworms: Charles Darwin's 'Unheralded Soldiers of Mankind': Protective & Productive for Man & Environment. Journal of Environmental Protection 1, 251–260.

Sivaram, A.K., Logeshwaran, P., Lockington, R., Naidu, R., Megharaj, M., 2019. Phytoremediation efficacy assessment of polycyclic aromatic hydrocarbons contaminated soils using garden pea (*Pisum sativum*) and earthworms (*Eisenia fetida*). Chemosphere 229, 227–235.

Skjemstad, J.O., Clarke, P., Taylor, J.A., Oades, J.M., McClure, S. G., 1996. The chemistry and nature of protected carbon in soil. Soil Research (Collingwood, Vic.) 34, 251–271.

Spokas, K.A., Novak, J.M., Stewart, C.E., Cantrell, K.B., Uchimiya, M., DuSaire, M.G., Ro, K.S., 2011. Qualitative analysis of volatile organic compounds on biochar. Chemosphere 85, 869–882.

Sri Shalini, S., Palanivelu, K., Ramachandran, A., Raghavan, V., 2020. Biochar from biomass waste as a renewable carbon material for climate change mitigation in reducing greenhouse gas emissions — a review. Biomass Conversion and Biorefinery (5), 1–21.

Suliman, W., Harsh, J.B., Abu-Lail, N.I., Fortuna, A.M., Dallmeyer, I., Garcia-Pérez, M., 2017. The role of biochar porosity and surface functionality in augmenting hydrologic properties of a sandy soil. Science of the Total Environment 574, 139–147.

Sun, H.W., Li, J.M., Wang, C.P., Wang, L., Wang, Y.Y., 2011. Enhanced microbial removal of pyrene in soils in the presence of earthworms. Soil & Sediment Contamination 20, 617–630.

Sun, X., Han, X.G., Ping, F., Zhang, L., Zhang, K.S., Chen, M., Wu, W.X., 2018. Effect of rice-straw biochar on nitrous oxide emissions from paddy soils under elevated CO_2 and temperature. Science of the Total Environment 628–629, 1009–1016.

Tammeorg, P., Parviainen, T., Nuutinen, V., Simojoki, A., Vaara, E., Helenius, J., 2014. Effects of biochar on earthworms in arable soil: avoidance test and field trial in boreal loamy sand. Agriculture, Ecosystems & Environment 191, 150–157.

Tan, X.F., Liu, Y.G., Zeng, G.M., Wang, X., Hu, X.J., Gu, Y.L., Yang, Z.Z., 2015. Application of biochar for the removal of pollutants from aqueous solutions. Chemosphere 125, 70–85.

Tang, J.C., Lv, H.H., Gong, Y.Y., Huang, Y., 2015. Preparation and characterization of a novel graphene/biochar composite for aqueous phenanthrene and mercury removal. Bioresource Technology 196, 355–363.

Tang, J.X., Carroquino, M.J., Robertson, B.K., Alexander, M., 1998. Combined effect of sequestration and bioremediation in reducing the bioavailability of polycyclic aromatic hydrocarbons in soil. Environmental Science & Technology 32, 3586–3590.

Tejada, M., Masciandaro, G., 2011. Application of organic wastes on a benzo(a)pyrene polluted soil. Response of soil biochemical properties and role of Eisenia fetida. Ecotoxicology and Environmental Safety 74, 668–674.

Tharakan, J., Tomlinson, D., Addagada, A., Shafagati, A., 2006. Biotransformation of PCBs in contaminated sludge: Potential for novel biological technologies. Engineering in Life Sciences 6, 43–50.

Thies, J.E., Rillig, M.C., 2009. Characteristics of biochar: biological properties, in: Lehmann, J., Joseph, S., Eds. Biochar for Environmental Management. Earthscan, London , pp. 85–105.

Tisdall, J., Oades, M., 1982. Organic matter and water-stable aggregates in soils. Journal of Soil Science 33, 141–163.

Tiunov, A.V., Scheu, S., 1999. Microbial respiration, biomass, biovolume and nutrient status in burrow walls of *Lumbricus terrestris* L. (Lumbricidae). Soil Biology & Biochemistry 31, 2039–2048.

Toková, L., Igaz, D., Horák, 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 (Basel) 10, 1005.

Tomczyk, B., Siatecka, A., Jędruchniewicz, 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. The Science of the total environment 747, 141123.

Tondoh, J.E., Dimobe, K., Guéi, A.M., Adahe, L., Baidai, Y., N'Dri, J. K., Forkuor, G., 2019. Soil health changes over a 25-year chronosequence from forest to plantations in rubber tree (*Hevea brasiliensis*) landscapes in Southern Côte d'Ivoire: Do earthworms play a role? Frontiers in Environmental Science 7, 73.

Topoliantz, S., Ponge, J., 2003. Burrowing activity of the geophagous earthworm *Pontoscolex corethrurus* (Oligochaeta: Glossoscolecidae) in the presence of charcoal. Applied Soil Ecology 23, 267–271.

Topoliantz, S.X.E., Ponge, J.F., Arrouays, D., Ballof, S., Lavelle, P., 2002. Effect of organic manure and the endogeic earthworm *Pontoscolex corethrurus* (Oligochaeta: Glossoscolecidae) on soil fertility and bean production. Biology and Fertility of Soils 36, 313–319.

Tran, N.H., Urase, T., Ngo, H.H., Hu, J.Y., Ong, S.L., 2013. Insight into metabolic and cometabolic activities of autotrophic and heterotrophic microorganisms in the biodegradation of emerging trace organic contaminants. Bioresource Technology 146, 721–731.

Treseder, K.K., Allen, M.F., 2002. Direct nitrogen and phosphorus limitation of arbuscular mycorrhizal fungi: A model and field test. New Phytologist 155, 507–515.

Tripathi, G., Bhardwaj, P., 2004. Comparative studies on biomass production, life cycles and composting efficiency of *Eisenia fetida* (Savigny) and *Lampito mauritii* (Kinberg). Bioresource Technology 92, 275–283.

Tripathi, M., Sahu, J.N., Ganesan, P., 2016. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. Renewable & Sustainable Energy Reviews 55, 467–481.

Tsai, W.T., Chang, C.Y., Lee, S.L., 1997. Preparation and characterization of activated carbons from corn cob. Carbon 35, 1198–1200.

Ukalska-Jaruga, A., Debaene, G., Smreczak, B., 2020. Dissipation and sorption processes of polycyclic aromatic hydrocarbons (PAHs) to organic matter in soils amended by exogenous rich-carbon material. Journal of Soils and Sediments 20, 836–849.

Uteau, D., Pagenkemper, S.K., Peth, S., Horn, R., 2013. Root and time dependent soil structure formation and its influence on gas transport in the subsoil. Soil & Tillage Research 132, 69–76.

Van Groenigen, J.W., Van Groenigen, K.J., Koopmans, G.F., Stokkermans, L., Vos, H.M.J., Lubbers, I.M., 2019. How fertile are earthworm casts? A meta-analysis. Geoderma 338, 525–535.

Van Zwieten, L., Kimber, S., Morris, S., Chan, K.Y., Downie, A., Rust, J., Joseph, S., Cowie, A., 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. Plant and Soil 327, 235–246.

Verma, A., Ali, D., Farooq, M., Pant, A.B., Ray, R.S., Hans, R.K.,

2011. Expression and inducibility of endosulfan metabolizing gene in *Rhodococcus* strain isolated from earthworm gut microflora for its application in bioremediation. Bioresource Technology 102, 2979–2984.

Vogel, T.M., Grbic-Galic, D., 1986. Incorporation of oxygen from water into toluene and benzene during anaerobic fermentative transformation. Applied and Environmental Microbiology 52, 200–202.

Wang, B., Gao, B., Fang, J., 2017a. Recent advances in engineered biochar productions and applications. Critical Reviews in Environmental Science and Technology 47, 2158–2207.

Wang, C.Y., Wang, Y.D., Herath, H.M.S.K., 2017b. Polycyclic aromatic hydrocarbons (PAHs) in biochar – Their formation, occurrence and analysis: A review. Organic Geochemistry 114, 1–11.

Wang, D., Jiang, P.K., Zhang, H.B., Yuan, W.Q., 2020a. Biochar production and applications in agro and forestry systems: A review. Science of the Total Environment 723, 137775.

Wang, F., Ji, R., Jiang, Z.W., Chen, W., 2014. Species-dependent effects of biochar amendment on bioaccumulation of atrazine in earthworms. Environmental Pollution 186, 241–247.

Wang, H.T., Ding, J., Chi, Q.Q., Li, G., Pu, Q., Xiao, Z.F., Xue, X.M., 2020b. The effect of biochar on soil-plant-earthworm-bacteria system in metal (loid) contaminated soil. Environmental Pollution 263, 114610.

Wang, J., Shi, L., Zhai, L.L., Zhang, H.W., Wang, S.X., Zou, J.W., Shen, Z.G., Lian, C.L., Chen, Y.H., 2021. Analysis of the long-term effectiveness of biochar immobilization remediation on heavy metal contaminated soil and the potential environmental factors weakening the remediation effect: A review. Ecotoxicology and Environmental Safety 207, 111261.

Wang, J., Taylor, A., Xu, C.Y., Schlenk, D., Gan, J., 2018. Evaluation of different methods for assessing bioavailability of DDT residues during soil remediation. Environmental Pollution 238, 462–470.

Wang, T.T., Cheng, J., Liu, X.J., Jiang, W., Zhang, C.L., Yu, X.Y., 2012. Effect of biochar amendment on the bioavailability of pesticide chlorantraniliprole in soil to earthworm. Ecotoxicology and Environmental Safety 83, 96–101.

Wang, X.L., Sato, T., Xing, B.S., 2006. Competitive sorption of pyrene on wood chars. Environmental Science & Technology 40, 3267–3272.

Warnock, D.D., Lehmann, J., Kuyper, T.W., Rillig, M.C., 2007. Mycorrhizal responses to biochar in soil – concepts and mechanisms. Plant and Soil 300, 9–20.

Warnock, D. D., Mummey, D. L., McBride, B., Major, J., Lehmann, J., Rillig, M. C., 2010. Influences of non-herbaceous biochar on arbuscular mycorrhizal fungal abundances in roots and soils: Results from growth-chamber and field experiments. Applied Soil Ecology 46, 450–456.

Wassenberg, D.M., Di Giulio, R.T., 2004. Synergistic embryotoxicity of polycyclic aromatic hydrocarbon aryl hydrocarbon receptor agonists with cytochrome P4501A inhibitors in *Fundulus heteroclitus*. Environmental Health Perspectives 112, 1658–1664.

Weber, W.J.Jr, McGinley, P.M., Katz, L.E., 1992. A distributed reactivity model for sorption by soils and sediments. 1. Conceptual basis and equilibrium assessments. Environmental Science & Technology 26, 1955–1962.

Weidemann, E., Buss, W., Edo, M., Mašek, O., Jansson, S., 2018. Influence of pyrolysis temperature and production unit on formation of selected PAHs, oxy-PAHs, N-PACs, PCDDs, and PCDFs in biochar - a screening study. Environmental Science and Pollution Research International 25, 3933–3940.

Weyers, S.L., Spokas, K.A., 2011. Impact of biochar on earthworm populations: A review. Applied and Environmental Soil Science 2011, 1–12.

Wheelock, C.E., Phillips, B.M., Anderson, B.S., Miller, J.L., Miller, M. J., Hammock, B.D., 2008. Applications of carboxylesterase activity in environmental monitoring and toxicity identification evaluations (TIEs). Reviews of Environmental Contamination and Toxicology 195, 117–178.

Widada, J., Nojiri, H., Kasuga, K., Yoshida, T., Habe, H., Omori, T., 2002. Molecular detection and diversity of polycyclic aromatic hydrocarbon-degrading bacteria isolated from geographically diverse sites. Applied Microbiology and Biotechnology 58, 202–209.

Wilcke, W., 2000. SYNOPSIS polycyclic aromatic hydrocarbons (PAHs) in soil — a review. Journal of Plant Nutrition and Soil Science 163, 229–248.

Wild, S.R., Jones, K.C., 1995. Polynuclear aromatic hydrocarbons in the United Kingdom environment: a preliminary source inventory and budget. Environmental Pollution 88, 91–108.

Wilson, S.C., Jones, K.C., 1993. Bioremediation of soil contaminated with polynuclear aromatic hydrocarbons (PAHs): A review. Environmental Pollution 81, 229–249.

Wu, S.J., Wu, E.M., Qiu, L.Q., Zhong, W.H., Chen, J.M., 2011. Effects of phenanthrene on the mortality, growth, and anti-oxidant system of earthworms (*Eisenia fetida*) under laboratory Chen-conditions. Chemosphere 83, 429–434.

Xiong, B.J., Zhang, Y.C., Hou, Y.W., Arp, H.P.H., Reid, B.J., Cai, C., 2017. Enhanced biodegradation of PAHs in historically contaminated soil by *M. gilvum* inoculated biochar. Chemosphere 182, 316–324.

Xu, J., Chen, X., Li, M.T., 2018. Present situation and evaluation of contaminated soil disposal technique. IOP Conference Series. Earth and Environmental Science 178, 1–4.

Xu, R.K., Xiao, S.C., Yuan, J.H., Zhao, A.Z., 2011. Adsorption of methyl violet from aqueous solutions by the biochars derived from crop residues. Bioresource Technology 102, v10293–v10298.

Xu, X.B., Shi, Y.J., Lu, Y.L., Zheng, X.Q., Ritchie, R.J., 2015. Growth inhibition and altered gene transcript levels in earthworms (*Eisenia fetida*) exposed to 2,2′,4,4′-tetrabromodiphenyl ether. Archives of Environmental Contamination and Toxicology 69, 1–7.

Yamato, M. G. E. T., Okimori, Y., Wibowo, I. F., Anshori, S., Ogawa, M., 2006. Effects of the application of charred bark of *Acacia mangium* on the yield of maize, cowpea and peanut, and soil chemical properties in South Sumatra, Indonesia. Soil Science and Plant Nutrition (Tokyo), 52, 489–495.

Yang, K., Yang, J.J., Jiang, Y., Wu, W.H., Lin, D.H., 2016. Correlations and adsorption mechanisms of aromatic compounds on a high heat temperature treated bamboo biochar. Environmental Pollution 210, 57–64.

Yang, X.N., Chen, Z.F., Wu, Q.H., Xu, M.Y., 2018. Enhanced phenanthrene degradation in river sediments using a combination of biochar and nitrate. Science of the Total Environment 619–620, 600–605.

Ye, S.J., Zeng, G.M., Wu, H.P., Liang, J., Zhang, C., Dai, J., Xiong, W.P., Song, B., Wu, S.H., Yu, J.F., 2019. The effects of activated biochar addition on remediation efficiency of co-composting with contaminated wetland soil. Resources, Conservation and Recycling 140, 278–285.

Ye, S.J., Zeng, G.M., Wu, H.P., Zhang, C., Dai, J., Liang, J., Yu, J. F., Ren, X.Y., Yi, H., Cheng, M., Zhang, C., 2017. Biological technologies for the remediation of co-contaminated soil. Critical Reviews in Biotechnology 37, 1062–1076.

Zavala-Cruz, J., Trujillo-Capistran, F., Ortiz-Ceballos, G.C., Ortiz-Ceballos, A.I., 2014. Tropical endogeic earthworm population in a pollution gradient with weathered crude oil. Research Journal of Environmental Sciences 7, 15–26.

Zeb, A., Li, S., Wu, J.N., Lian, J.P., Liu, W.T., Sun, Y.B., 2020. Insights into the mechanisms underlying the remediation potential of earthworms in contaminated soil: A critical review of research progress and prospects. Science of the Total Environment 740, 140145.

Zhang, B.G., Li, G.T., Shen, T.S., Wang, J.K., Sun, Z., 2000. Changes in microbial biomass C, N, and P and enzyme activities in soil incubated with the earthworms *Metaphire guillelmi* or *Eisenia fetida*. Soil Biology & Biochemistry 32, 2055–2062.

Zhang, G.X., Guo, X.F., Zhu, Y.E., Liu, X.T., Han, Z.W., Sun, K., Ji, L., He, Q.S., Han, L.F., 2018a. The effects of different biochars on microbial quantity, microbial community shift, enzyme activity, and biodegradation of polycyclic aromatic hydrocarbons in soil. Geoderma 328, 100–108.

Zhang, H.H., Lin, K.D., Wang, H.L., Gan, J., 2010. Effect of *Pinus radiata* derived biochars on soil sorption and desorption of phenanthrene. Environmental Pollution 158, 2821–2825.

Zhang, K., Chen, B.L., Mao, J.F., Zhu, L.Z., Xing, B.S., 2018b. Water clusters contributed to molecular interactions of ionizable organic pollutants with aromatized biochar via π-PAHB: Sorption experiments and DFT calculations. Environmental Pollution 240, 342–352.

Zhang, Q.M., Saleem, M., Wang, C.X., 2019. Effects of biochar on the earthworm (*Eisenia foetida*) in soil contaminated with and/or without pesticide mesotrione. Science of the Total Environment 671, 52–58.

Zhang, R.K., Zhou, Z.Q., Zhu, W.T., 2020. Evaluating the effects of the tebuconazole on the earthworm, *Eisenia fetida* by H-1 NMR-Based untargeted metabolomics and mRNA assay. Ecotoxicology and Environmental Safety 194, 110370.

Zhang, W.H., Zhuang, L.W., Yuan, Y., Tong, L.Z., Tsang, D.C.W., 2011. Enhancement of phenanthrene adsorption on a clayey soil and clay minerals by coexisting lead or cadmium. Chemosphere 83, 302–310.

Zhou, Z.L., Shi, D.J., Qiu, Y.P., Sheng, D., 2010. Sorptive domains of pine chars as probed by benzene and nitrobenzene. Environmental Pollution 158, 201–206.

Zhu, D.Q., Pignatello, J.J., 2005. Characterization of aromatic compound sorptive interactions with black carbon (charcoal) assisted by graphite as a model. Environmental Science & Technology 39, 2033–2041.

Zhu, X.M., Chen, B.L., Zhu, L.Z., Xing, B.S., 2017. Effects and mechanisms of biochar-microbe interactions in soil improvement and pollution remediation: A review. Environmental Pollution 227, 98–115.

Zhu, X.M., Wang, Y.S., Zhang, Y.C., Chen, B.L., 2018. Reduced bioavailability and plant uptake of polycyclic aromatic hydrocarbons from soil slurry amended with biochars pyrolyzed under various temperatures. Environmental Science and Pollution Research International 25, 16991–17001.

Zielińska, A., Oleszczuk, P., 2016. Effect of pyrolysis temperatures on freely dissolved polycyclic aromatic hydrocarbon (PAH) concentrations in sewage sludge-derived biochars. Chemosphere 153, 68–74.

Zou, S.W., Anders, K.M., Ferguson, J.F., 2000. Biostimulation and bioaugmentation of anaerobic pentachlorophenol degradation in contaminated soils. Bioremediation Journal 4, 19–25.