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Review

Biochar Acts as an Emerging Soil Amendment and Its Potential Ecological Risks: A Review

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Abstract: Biochar, known as "Black Gold", has become a novel approach with potential benefits for soil amendment, such as improving soil physicochemical properties, reducing greenhouse gas emissions, and enhancing soil fertility. The previous research studies mainly focus on exploring different methods for the improvement of biochar enriched nutrients as fertilizers; however, the migration and transformation mechanisms of these nutrients induced by biochar are yet to be extensively investigated. This paper provides an overview of recent advances in the application and mechanisms of biochar for soil amendment focusing on soil properties and nutrients improvement. Biochar positively alters microbial-mediated reactions in the soil C and N cycles, i.e., mineralization of C and N, and N_2 fixation, thus enhancing maximizing C and N use efficiency and reducing the potential losses. Moreover, biochar provides reactive surfaces where P and K ions are retained in soil microbial biomass and in exchange sites, leading to increasing the availability of P and K to plants uptake. In addition, the toxic substances and potential ecological risks of biochar were also reviewed and discussed, thereby providing a baseline reference and guiding significance for future biochar applications as promising soil amendments.

Keywords: biochar; soil properties; nutrient improvement; ecological risks

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1. Introduction

As a crucial member of ecosystems, soils have played a critical role in biochemical transformation, element cycling, and supporting plants [1]. Moreover, soils are also essential for food safety because they determine the possible composition of food and substantially support the food chain [2,3]. It was reported that 33% of the global soils were facing soil degradation [4], which led to a decline in soil structural stability and the ability of soils to maintain and store carbon, and increasing erosion risks and global threats [5,6]. Maximillian et al. [7] also reported that all of the world's topsoil might become unproductive within 60 years if the current rates of loss continue. The main factors of soil degradation include loss of organic matter in the soil, soil acidification, a decrease in soil fertility and aggregate, elements imbalance, and other issues [8–11], which in turn induced to alter the biogeochemical processes of ecosystems, adversely affect organisms [12–14]. Given the magnitude of the soil degradation and its significance to sustainable agriculture, it's urgent for worldwide scientists to find a novel option that can effectively remediate soils.

Biochar, known as "Black Gold", is a carbon-rich solid material derived from the thermochemical conversion of biomass (e.g., plant, manure, and sludge) under oxygen limitation [15]. It has been shown by numerous studies that biochar is used as a novel approach with potential benefits to agriculture and the environment [16–18]. After pyrolysis, biochar became more hydrophobic and recalcitrant due to the formation of aromatic structures, and a negative emission potential of biochar [19]. Earlier published reviews on biochar included a summary of the negative effects of biochar addition on soil physicochemical properties (e.g., pH, soil bulk density, soil porosity, and organic matter) [18,20–23]. Biochar amendment has been reported to positively influence soil C stability, especially for soil that lacks organic matter [24]. Biochar acts, therefore, as an emerging and attractive option to effectively improve fertilizer utilization performance. Besides, biochar produced by pyrolysis itself contains N, P, and K, and biochar contributed to N mineralization by regulating microbial-mediated reactions [25,26].

Biochar's application led to a comparatively higher bio-available K fraction due to formation of water soluble kalicinite ($KHCO_3$) minerals [27]. Moreover, previous studies have exhibited that biochar can not only significantly increase the content of available P in soils, but also promote the availability of exogenous P in acidic soils [28]. Therefore, application of nutrient-rich biochars was vital for the restoration of degraded and/or nutrients deficit soils.

To the best of our knowledge, no systematic assessment is available to provide an overview of the mechanisms of biochar application on soil nutrient improvement. A deeper insight into the mechanisms of nutrition release and transportation induced by biochar in the biochar-soil-plants system is also necessary. In this paper, four sections have been proposed and aimed to enhance the understanding of the mechanisms of biochar as a soil amendment, including (1) The positive effects of biochar on soil properties, e.g., pH, cation exchange capacity (CEC), soil bulk density, water retention, and soil enzyme activity. (2) The mechanisms of biochar in the soil nutrients (C, N, P, and K) improvement; (3) Factors effects of biochar on soil nutrient improvement; (4) The toxic substances and adverse effects of biochar on the organisms were also reviewed and discussed, aiming to provide theoretical reference for practical land use of biochar.

2. Basic Properties of Biochar

2.1. Elements

Biochar contains various elements, of which basic elements C, H, O, and N constitute the framework of biochar [29]. Alkali metal elements (K, Ca, Na, and Mg) and common metallic elements (Mn and Fe) are involved in the structural composition of biochar and are regarded as the critical sources of alkaline components of biochar [30]. In addition, mineral element P also exists in biochar and is an essential nutrient for botanic and microbial growth [31,32]. The raw materials and preparation condition control the elemental compositions of biochar. The content of C in plant-derived biochar is generally higher than that of sludge-biochar and manure-biochar, ranging from 39.75% to 90.21% (Table S1). It is believed that the dehydration and depolymerization reaction of plant biochar occurs with the rise of pyrolysis temperature, and lignin and cellulose are decomposed into smaller molecules, which increases the C content [33]. The content of C in sludge biochar is generally low, and concentrations range mainly from 4.69% to 23.4% (Table S1), which is mainly due to the high concentration of minerals in sludge. There are also exceptional cases reported that 53.5% C content of granular sludge biochar was prepared at 300 °C [34], which different sources of sludge may cause.

In contrast to C, the contents of H and O in biochars decreased at a higher pyrolysis temperature (Table S1). As the pyrolysis temperature increases, H and O are mainly dissipated in the form of H_2O, CO_2, CO, and hydrocarbon [35]. Typically, manure biochar contains higher concentrations of P and N [36]. As a nutrient-rich fertilizer, biochar has a vital application prospect for the remediation of nutrition-deficient soil and improving crop growth.

2.2. pH

The pH value of biochar produced from different sources is unique. As shown in Table S1, with the increase in pyrolysis temperature, the pH of biochar also increases. The following two aspects can explain this: (1) The residual inorganic minerals and alkaline components in biochar, such as SiO_2, $CaCO_3$, KCl, $CaSO_4$, and nitrate, are significant factors leading to alkaline pH [37]; (2) Biochar produced from plants sources promotes the decomposition of acidic functional groups (e.g., -COO- and -OH) and the volatilization of organic acids during high temperatures pyrolysis. Thus, most agricultural and forestry wastes have a pH between 7.0 and 10.4 [18,38]. Due to the alkaline pH properties, biochar is often used to improve acidic soils.

2.3. Functional Groups

Many functional groups exist on the surface of biochar, which endow biochar with different physical and chemical characteristics, i.e., adsorption properties, hydrophilic and hydrophobic properties, and acid-base buffering properties [18]. The oxygen-containing functional groups on biochar are mainly carboxyl, lactone, phenolic hydroxyl, and carbonyl [39,40]. In the process of biochar preparation, the types and quantities of oxygen-containing functional groups produced by different feedstock at the same pyrolysis temperature are similar [18]. Leng et al. [41] reviewed the nitrogen-containing functional groups of biochar, pyridinic-N, pyrrolic-N, quaternary-N, amine-N, $NH_4{}^+$-N, Nitrile-N, $NO_3{}^-$-N, and $NO_2{}^-$-N were found on the surface of various biochar. In addition, Janu et al. [42] also found that the dominant parameters, e.g., pyrolysis temperature, specific surface area, ash fraction, and H/C ratio, impact the signals of the functional groups on the biochar.

2.4. Electrical Conductance (EC)

The EC values of biochar range from 0.07 dS m^{-1} to 10.4 ± 0.05 dS m^{-1} (Table S1). The EC values of plant residues biochar and sludge biochars are generally higher than those of manure. The biochar's EC also depends on the pyrolysis temperature and the raw materials. Generally, biochar prepared at higher pyrolysis temperatures has a higher EC value. This phenomenon is mainly due to the loss of volatile substances, increasing residues, and ash in the pyrolysis process [43].

2.5. CEC

Typically, biochar has a CEC value in the range of 6.4–46.62 cmol kg^{-1} [44,45], and even reaching values as high as 75–128.7 cmol kg^{-1} [46] (Table S1). The large variability of CEC may be due to the distinct surface properties of biochar, which is highly affected by carbonization temperature and raw materials. Generally, the higher pyrolysis temperatures contribute to a higher CEC value of biochar. The feedstock of biochar is also an essential factor affecting CEC values. The trend of CEC is consistent with the trend of functional groups based on temperature [47]. High temperatures promote the oxidation of aromatic carbon and the formation of carboxyl functional groups. As external pH increases, more negative charges remain on the surface of biochar due to dissociation of biochar surface functional groups (e.g., -COOH and -OH), favoring the cation exchange between biochar and cationic ions, finally leading to the increase of CEC [48,49].

3. Effects of Biochar on Soil Properties

3.1. pH

Soil pH plays a vital role in plant growth. Low soil pH can lead to toxic effects on plants because elements such as Al which is toxic to plants are easily present as available at low soil pH [50]. According to Dai et al. [51], soils worldwide are mostly acidic (typically $pH < 5.5$) and continue to suffer from soil acidification. Biochar is alkaline and is always used to amend soil pH, generally by increasing acidic soil's pH. Biochar contributed to increasing the soil pH, and the pH dynamic after biochar application is shown in Table 1. A meta-analysis carried out by Jeffery et al. [52] indicated that the biochars significantly increased soil pH (by up to 2.0 units) in acid soils. Kamali et al. [22] also reviewed that biochar increases the soil pH in different acidic soil types, such as alfisols, ultisols, and latosols. There are two main explanations for improving soil pH by biochar: (1) Biochars have various concentrations of alkaline ash. When biochar is directly applied to soil, the alkaline components (e.g., hydroxides, carbonates, Mg, Ca, K, and Na oxides) are released into the soil in soluble form. Subsequently, these soluble substances can react with H^+ and Aluminum monomers in acidic soils to raise soil pH [53–55]. (2) The functional groups on the surface of biochar (i.e., phenolic OH, -COOH, and alcoholic OH) can interact with basic cations in soils based on different reactivity and contribute to an increase of acidic soil pH as a pH buffering [56]. As Novak et al. [48] mentioned, the protonation–deprotonation process of the functional groups on the surface of biochar was the primary mechanism that modified the soil pH.

3.2. Soil Bulk Density

Soil bulk density indicates soil physical properties and is commonly measured after biochar supplement. The decline of soil bulk density with biochar addition would contribute to the decrease of soil compaction. The ideal soil bulk density differs for various crop production, resting with soil textural class [57]. Zhang et al. [18] have demonstrated that low soil bulk density will improve the soil structure and facilitate the release and retention of nutrients.

Biochar contributes to decreasing the soil bulk density (Table 1). Rombola et al. [58] showed that the soil bulk density decreased from 1.44 ± 0.10 g cm^{-3} to 1.38 ± 0.06 g cm^{-3} after orchard pruning biochar application. Khan et al. [59] also found that applying maize straw biochar decreased the soil bulk density in sandy loam. A meta-analysis containing published literature between 2010 and 2019 was conducted by Razzaghi et al. [60] to quantify the effect of biochar on soil bulk density. Biochar application decreased approximately 11% of soil bulk density in the coarse-textured and fine-textured soils and 7% in medium-textured soils. The results have shown that biochar amendment decreased average bulk density in various soil types. In addition, they also found that biochar consistently reduced bulk density in the same soil textural group, regardless of the type of experiment.

3.3. Soil Water Retention

Soil water retention has played a significant role in crop productivity [60]. The evidence has shown that biochar addition affects soil water retention, possibly due to hydrophilic domains, high porosity, and high specific surface area of biochar. The soil water retention dynamic after biochar application was shown in Table 1. Oladele et al. [61] found that rice husk biochar at the rate of 12 t ha^{-1} increased the soil water retention from 36.87% to 32.94% in sandy clay loam. Razzaghi et al. [60] reported that biochar increased field capacity by 51% and 13% in coarse-textured and medium-textured soils, respectively. Moreover, the plant-available water in coarse-, medium and fine-textured soils increased with biochar amendment by 45%, 21%, and 14%, respectively. In addition, Hussaina et al. [62] revealed that many factors, e.g., raw materials type, pyrolysis temperature, biochar particle size, soil type, and compaction state, strongly affected soil water retention.

3.4. CEC

CEC is an important index to measure the adsorption capacity of soil and solid materials for exchangeable cations. It is also an essential indicator of soil fertility for supplying nutrients for plants while reducing the nutrients leaching [63]. The soil CEC will increase due to increased soil cation exchange sites. The soils with higher CEC have more vital adsorption ability of Ca, K, NH_4^+, and Mg, which improves the utilization of nutrient ions in the soil and reduces the loss of nutrients [64]. Many studies have explored the effect of biochar on the CEC of soil (Table 1). Khan et al. [59] showed that maize straw biochar application increased the CEC from 12.9 cmol kg^{-1} to 15.6 cmol kg^{-1}, 17.4 cmol kg^{-1}, and 19.2 cmol kg^{-1} with the addition rate at 4 t ha^{-1}, 12 t ha^{-1}, and 36 t ha^{-1}, respectively. Hossain et al. [65] revealed that approximately 20–40% increase in total soil CEC and charge were found with biochar amendment. Even a small amount of biochar added to the soil will significantly increase the nutrients and alkaline cations in the soil. Chintala et al. [66] also reported that biochar could increase soil CEC, both in acidic and alkaline soils, attributed to more anions on the surface of biochar.

3.5. Soil Enzyme Activity

Soil enzyme activity, which is the proximate agent of organic matter decomposition and indicator of microbial activity, reflects the intensity and direction of various biochemical processes in soils [67]. Biochar has played a vital role in soil microbial activity and community structure [18]. Plants can produce and release soil phosphatases to mineralize P from nucleic acids, phospholipids, and other ester phosphates [67]. Biochar application led to a significant increase of 27.85% in acid phosphatase activity compared to the treatment without biochar after 7 weeks. The soil phosphatase activity increased by biochar particle size [68]. Pandey et al. [69] found that biochar increased dehydrogenase by 27% compared with the control group, and urease activity increased by 7.4–39% with biochar addition. Jia et al. [70] and Pandey et al. [71] revealed that soil enzymes (e.g., urea, invertase, and dehydrogenase) were activated with different types and concentrations of biochar application. Song et al. [72] reported that biochar addition led to an increase of 13.9, 8.4, 21.7, 81.3, and 150.5% in urease, protease, alkaline phosphatase, catalase, and sucrase, respectively.

Recently, a meta-analysis performed by Liao et al. [73] revealed that the pyrolysis temperature potentially controlled the impact of biochar on the activities of soil nutrient acquisition enzymes. Generally, low-temperature biochar (derived at <500 °C) contributes to triggering soil enzymes. However, the effect of high-temperature biochar (derived at ≥500 °C) on soil enzyme activity was weak. In addition, it was also found that soil and biochar characteristics played a secondary role in the process of biochar's influence on enzyme activity. The effect of biochar on soil enzyme activity is closely related to biochar properties and soil types [73]. Therefore, selecting appropriate biochar according to soil properties is the premise of improving soil enzyme activity.

Table 1. The soil properties changes with biochar application.

Biochar Type	Pyrolysis Conditions	Highlighted Properties (Biochar)	Soil Type	Highlighted Properties (Soil)	Addition Rate	Duration	pH	CEC	Bulk Density	Water Holding Capacity	Ref.
Orchard pruning biomass	3 h at 500 °C	71.4% C, 0.7% N, 1.5% H, and 5.9% O (dry weight)	Sandy clay loam	70% sand, 15% silt and 15% clay.	0	9 months	5.18 ± 0.30	11.8 ± 0.9 meq 100 g^{-1}	1.44 ± 0.10 g cm^{-3}	-	[58]
					16.5 t ha^{-1} in 2009 and further 16.5 t ha^{-1} in 2010	9 months	6.76 ± 0.18	24.3 ± 1.8 meq 100 g^{-1}	1.38 ± 0.06 g cm^{-3}	-	
					16.5 t ha^{-1}	9 months	6.54 ± 0.25	18.32 ± 1.05 meq 100 g^{-1}	1.42 ± 0.07 g cm^{-3}	-	
					0	1 year	5.25 ± 0.15	11.5 ± 1.5 meq 100 g^{-1}	1.45 ± 0.06 g cm^{-3}	-	
					16.5 t ha^{-1} in 2009 and further 16.5 t ha^{-1} in 2010	1 year	6.59 ± 0.20	24.1 ± 1.8 meq 100 g^{-1}	1.38 ± 0.25 g cm^{-3}	-	
					16.5 t ha^{-1}	1 year	6.32 ± 0.14	18.14 ± 0.83 meq 100 g^{-1}	1.40 ± 0.03 g cm^{-3}	-	
Peanut shells biochar	650 °C for 6 h	-	Silt loam acidic soil	5.58% clay, 49.5% silts, and 44.92% sand	2% (w/w)	42 d	6.11 ±0.15	-	-	-	[74]
					4% (w/w)	42 d	6.67 ± 0.16	-	-	-	
					6% (w/w)	42 d	6.91 ± 0.18	-	-	-	
Maize straw biochar	350–550 °C	-	Sandy loam	Bulk density 1.41 g mL^{-1}, water holding capacity 0.38 cm^3 cm^{-3}	0 tons ha^{-1} biochar	1 year	7.26	12.9 cmol kg^{-1}	1.45 g cm^{-3}	-	[59]
					4 t ha^{-1}	1 year	7.39	15.6 cmol kg^{-1}	1.43 g cm^{-3}	-	
					12 t ha^{-1}	1 year	7.54	17.4 cmol kg^{-1}	1.40 g cm^{-3}	-	
					36 t ha^{-1}	1 year	7.64	19.2 cmol kg^{-1}	1.36 g cm^{-3}	-	
Grains husks and paper	500 °C	Total C 531 g kg^{-1} and total N 14 g kg^{-1}	Haplic Luvisol	9.13 g kg^{-1} soil organic carbon and pH 5.71	0 t ha^{-1}	1 year	-	153.93 ± 6.45 Mmol kg^{-1}	-	-	[75]
					10 t ha^{-1}	1 year		160.15 ± 10.40 Mmol kg^{-1}	-	-	
					20 t ha^{-1}	1 year		177.70 ± 13.33 Mmol kg^{-1}	-	-	

Table 1. *Cont.*

Biochar Type	Pyrolysis Conditions	Highlighted Properties (Biochar)	Soil Type	Highlighted Properties (Soil)	Addition Rate	Duration	pH	CEC	Bulk Density	Water Holding Capacity	Ref.
Rice husk biochar	350 °C for 1.25 h	pH 8.50 and 51.13% TOC	Typic Paleustalf Alfisol	68.8% sand, 25.1% clay and 6.1% silt	0	2 years	5.27	7.18 cmol kg^{-1}	-	32.94%	[61]
					3 t ha^{-1}	2 years	6.54	9.69 cmol kg^{-1}	-	32.94%	
					6 t ha^{-1}	2 years	6.66	9.91 cmol kg^{-1}	-	34.87%	
					12 t ha^{-1}	2 years	6.73	12.30 cmol kg^{-1}	-	36.87%	
Sawdust	350 °C for 4 h	-	Loamy sand	65.3% sand, 25.4% silt, 9.3% clay	0	11 weeks	6.85	13.48 cmol kg^{-1}	-	-	[76]
					10 t ha^{-1}	11 weeks	7.24	17.63 cmol kg^{-1}	-	-	
					20 t ha^{-1}	11 weeks	7.30	21.57 cmol kg^{-1}	-	-	

4. Effects of Biochar Addition on Soil Nutrients

4.1. C

Soil carbon has played an essential role in food security, environmental health, and ecosystem functioning, especially in global climate change mitigation. The United Nations Sustainable Development Goals (SDGs) highlight C sequestration and soil fertility improvement and set reasonable targets for nations to achieve by 2030. The SDGs emphasize the need for soil security to improve soil fertility and provide adequate and balanced nutrients for plants [77].

Generally, the organic carbons (OC) in biochar consist of at least two C pools, i.e., labile and stable OC, which exhibit low and high ability to resist mineralization [33]. Biochar produced at low temperature ($\leq$400 °C) has higher labile OC (e.g., low molecular weight aliphatic compounds) than at high temperature (>400 °C) [78]. As summarized by Han et al. [79], the mineralization rate of biochar application in soil increased with time, and the amount of mineralization was as high as 15–20%. The mineralization of biochar depends on the biochar feedstock type and pyrolysis temperature. Manure and crop-produced biochar had a higher mineralized OC percentage than wood-derived biochar. The percentage of mineralized OC decreased with increasing pyrolysis temperature [79], possibly due to the increased portion of aromatic C and the higher degree of aromatic condensation in biochar, as reported previously [17].

The biochar amendment greatly influenced the soil total carbons (TC) as an exogenous carbon source. A global meta-analysis on the effect of biochar on soil carbon pools presented by Chagas et al. [80] reported that biochar addition rate is the most important factor which affects soil TC than other factors, e.g., raw material, pyrolysis temperature, biochar C content, experiment duration, experiment type, climate zone, soil pH, and soil texture. The higher biochar rate applied in the soil led to a significant increase in soil TC, with a range from 28.9% to 140.0%. Yin et al. [81] also explored the effect of biochar amendment on the soil total organic carbon (TOC) and labile OC. The amendments of biochar derived from wood (pyrolysis at 650 °C) significantly increased soil TOC. Yan and Liu [82] reported a similar result, biochar with a high carbon content (39.98–41.47%) led to the increase of soil TOC. Yan and Liu [82] also proved that different particle sizes do not significantly impact the TOC content in soil. This result might be because biochar with different particle sizes was almost identical in the composition ratio of their carbon-containing substances.

Biochar contributes to increasing soil microbial biomass carbons (MBC). Liu et al. [83] reported that soil MBC increased by 12–24% with biochar application. An overall increase of 25% induced by biochar in soil MBC was obtained via a meta-analysis [80]. The effect of biochar on soil MBC depends on the soil type. Liu et al. [83] showed that biochar addition significantly increases soil MBC content in acid soils compared to neutral or alkaline soil conditions. Perhaps this is because biochar is primarily alkaline, its application to acidic soils acts as a buffer, thus increasing the microbial population [84]. Soil MBC was also significantly impacted by the soil C content, biochar rate, and climatic zone [80].

Soil dissolved organic carbon (DOC) plays a vital role in the C cycle [85]. The pure spruce woodchips biochar [86] and Wood pellet biochar [87] contribute to increasing soil DOC. Hernandez-Soriano et al. [88] also reported that biochar increased humic-like fluorescent components in DOC from soil leachate. Biochar amendment to the soil could change DOC contents and composition, in turn, affect overall water quality. However, Liu et al. [89] reported that DOC increase with biochar application was temporary, and this effect quickly disappeared with the aging of the biochar. This finding suggested there was little risk of biochar application altering soil water quality through DOC leaching [80].

Biochar is vital in improving soil TC, TOC, BMC, and DOC. Factors such as soil C content, biochar rate, soil type, and experiment duration affect soil C dynamics with biochar application [80]. Therefore, selecting appropriate biochar and addition rate according to soil type and experimental conditions is essential for soil C improvement.

4.2. N

In biochar, the content of N ranges from <0.10% to 9% and decreases as the pyrolysis temperature increases (Table S1). Lang et al. [90] revealed that the volatilization of N is the primary way of the loss of total N, and 21–71% of N in the form of HCN, NH_3, and HCNO migrated into gaseous pyrolysis products [91,92]. This also means that pyrolysis temperature plays a critical role in the content of N of biochar. As described by Liu et al. [28], the N in biochar is mainly divided into inorganic N (hydrolyzable-N water-soluble-N, and nonhydrolyzable-N) and organic N (including NH_4^+-N, NO_2^--N, and NO_3^--N which are easy to absorb and intake by plants and bacteria) (Figure 1). Factors affecting the conversion of nitrogen in biochar preparation, such as biomass materials, pyrolysis temperature, heating rate and time, and atmosphere, were reviewed in detail by Yuan et al. [93].

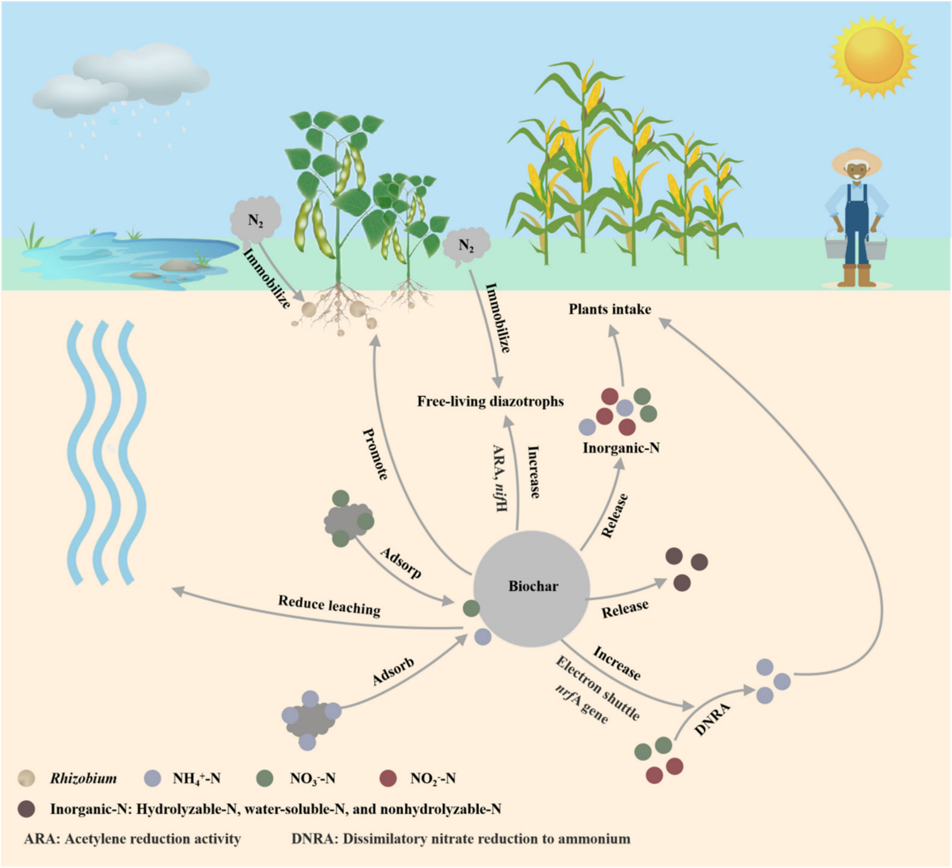

Figure 1. The mechanisms of biochar application on N improvement in soil [94–97].

Several studies have reported that biochar application could increase soil total nitrogen (TN) content [94,98]. Consistently, increasing biochar application rates led to extra soil total N accumulation from 0.09 to 0.30 g kg^{-1} compared to the control. There is a significant linear correlation between the TN content, and the amount of biochar added, indicating that the amount of biochar is an important factor affecting the TN content in the soil. In addition, the concentrations of different N forms (e.g., NH_4^+, NO_3^-, microbial biomass nitrogen, and dissolved organic nitrogen) also increased with biochar addition during the incubation, among which the peak value of NO_3^- was lagging behind NH_4^+ [99]. Joseph et al. [100] also revealed that soil N content is directly increased through biochar supplement and indirectly achieved via the N transportation of manure biochar by insects.

As a promising soil amendment, biochar effectively reduced N loss due to its high adsorption capacity to NO_3^--N and NH_4^+-N [101] (Figure 1). Nano-biochar effectively reduced soil nitrate loss (13.6–59.8%) compared to the control [102]. Similarly, a study in which different rates of 0.5–4% (*w*/*w*) winter-pruned apple branches biochar reduced the leaching ratio of NO_3^--N (9.9–68.7%) and nitrogen oxides flux (6.3–19.2%) in the soil [103]. Nelissen et al. [26] demonstrated that NH_4^+ is immobilized quickly by adsorption of maize biochar, which reduces available N and concomitantly minimizes potential soil N losses in the short-term study. A similar result was obtained by Yao et al. [104], biochar exhibited NH_4^+ adsorption. Many acidic functional groups (e.g., phenols, carboxylic groups, and carbonyls), which have a negative charge, have been found on the biochar surface and adsorb NH_4^+-N via electrostatic attraction [105]. Ventura et al. [106] also reported that biochar significantly decreased NO_3^- leaching by 75% in an apple orchard. Compared to NO_3^--N, NH_4^+-N is more strongly held by biochar due to the higher CEC of most biochars. In addition, more outstanding negative surface charges carried by biochar may lead to weak adsorption of NO_3^--N [107]. Amonette and Joseph. [108] and Montes-Morán et al. [105] found that chromenes, ketones, pyrones, etc., functional groups on the surface of biochar, can facilitate NO_3^--N adsorption. Another possible chemisorption mechanism between biochar and NO_3^--N via unconventional H-bonding was illustrated by Kammann et al. [109] and Lawrinenko et al. [110]. Nguyen et al. [111] also found a significant correlation between biochar CEC and NH_4^+-N adsorption through boosted regression tree analysis.

Soil application of biochar contributes to increasing N mineralization (Figure 1). Nelissen et al. [26] showed a 185–221% increase in gross N mineralization, 10–69% in nitrification, and up to a 508% increase in NH_4^+ rates when the soil was amended with maize biochar. It is found that biochar produced at low pyrolysis temperature has a more apparent promoting effect on soil N mineralization and increased NH_4^+ content compared to biochar produced at high pyrolysis temperature due to a more significant labile C fraction [26]. Generally, the biochar produced with high N feedstock content significantly promotes N mineralization [95]. Singh et al. [25] reported that manure biochar increased N mineralization compared to plant-based biochars due to the lower C/N ratio. In addition, Zimmerman et al. [112] found that the promotion of N mineralization by biochar is short-term. With the extension of application time, N mineralization decreased because organic substrates were adsorbed by biochar and soil to decrease their availability for microorganisms. The effects of biochar on soil N mineralization are mainly influenced by feedstock, pyrolysis temperature, incubation time, and the C/N ratio of biochar [100,111].

Biological N_2 fixation (BNF) is a complementary N source for plants, and symbiotic bacteria contain the nitrogenase enzyme [113]. Generally, BNF consists of two primary pathways: symbiotic and free-living [114]. The positive effect of biochar toward stimulating BNF was more pronounced in the symbiotic relative to the nonsymbiotic BNF (35.8 vs. 28.1% increment over the control) [115]. Symbiotic N_2-fixation (SNF) occurred via a molecular "crosstalk" between plants (only limited to leguminous crops) and the N_2-fixing symbionts in plant roots [116]. Many kinds of literature have reported that BNF was enhanced with biochar supplement [94–97] (Figure 1). Azeem et al. [94] applied sugarcane bagasse biomass and pyrolysis at 350 °C in mash bean plots with the application rate of 10 t ha^{-1}. An 83% increase in N_2 fixation was found compared with the control treatments. The selection of suitable biochar according to the types of soils and plants can promote the BNF in root nodules or by association with free-living bacteria [117]. Horel et al. [118] also exhibit that biochar amendment contributes to improving the microclimate of microbial growth, which might lead to a significant decline of soil N, but a significant increase in N_2 fixation rate in alder. Based on the results obtained by Anderson et al. [119], the population of N_2 fixing microorganisms, i.e., Frankiaceae and Bradyrhizobium, increased with biochar supplement. A pot experiment with clay loam soil was carried out by Rondon et al. [120], and 31% greater N_2 fixation by Rhizobium strains associated with bean plants was found with wood biochar amendment. On the other hand, free-living N_2-fixation (FNF), carried out by cyanobacteria in association with moss or other free-living diazotrophs in litter and soil, is nearly ubiquitous in terrestrial ecosystems [121]. Biochar with a 2% application rate significantly increased acetylene reduction activity (ARA) and *nif*H abundance in

56 days. Through the analysis of soil diazotrophic community composition, *Azotobacter*, *Bradyrhizobium*, and *Skermanella* were the most dominant genera. *Azotobacter*, a free-living diazotroph, reached the maximum in soil [99] (Figure 1). The variation in the diazotrophic community was associated with soil EC, DOC, and pH [99]

In addition, the enhancement of dissimilatory nitrate reduction to ammonium (DNRA) is well known as beneficial for the environment and agriculture because DNRA increases nitrogen retention in soil. According to Yuan et al. [122], adding rice straw biochar led to an increased DNRA with an increased rate of 0.2 to 0.7 mg kg^{-1} $NH_4{}^+$-N dry soil d^{-1}. Moreover, biochar simultaneously increased the expression levels of the *nrf*A gene, which was the DNRA functional gene [123]. Through correlation analysis, the application of biochar enhanced DNRA due to its electron shuttle potential [123] (Figure 1). The capacity of biochar for paddy-soil N conservation and N_2O mitigation is expected to amplify by improving the electron shuttle function of biochar [122,124].

4.3. P

P is a decisive macronutrient element for all biological communities, without which plant growth and crop yields would be substantially limited [125]. Biochar has positively affected soil phosphorus transformation in agricultural soils [126]. Biochar contains the element P with the level of 0.01–6.1% (Table S1), and the total P content of biochar was influenced by the types of raw materials and pyrolysis temperature. As shown in Table S1, the P content in biochar derived from manure and sludge is higher than in plant biomass biochar.

Biochar has been provided with various P supplements to the soil as a P source. Different P forms, such as stable P (crandallite, wavellite, and poly-P), semi-labile P ($CaHPO_4$, phytic acid, phospholipid, DNA, and $Na_4P_2O_7$), and labile P (orthophosphate), were found in biochar [127]. With the biochar addition to soil, the unstable P and part of semi-stable P were released first. Qian et al. [128] revealed that almost 50% of P was released in the forms of pyrophosphate and orthophosphate in the first 8 h. Furthermore, a similar result obtained by Jin et al. [36] showed that biochar supplement gave an orthophosphate release from 77.5–83.4% to 92.9–96.3%. The release patterns of P from biochar and its feedstock are quite different.

Through the comparative study of the P release rate in biochar and raw materials, Liang et al. [129] described P release from manure as fast desorption. However, manure biochar was initially controlled by diffusion and subsequently by stable P's slow and sustained dissolution. In addition, many environmental factors, e.g., soil pH, ionic strength, and soil microorganisms, had also been reported to affect the P release from biochar in soil [28,130,131]. Therefore, it is imperative to select reasonable biochar to improve the lack of P element in the soil and improve soil fertility according to the actual situation.

Numerous studies have shown that the application of biochar has led to an increase in soil available P via different mechanisms (Figure 2). (1) The biochar can release the bioavailable P to the soil due to desorption, anion exchange, or dissolution [127]. (2) Soil P complexation was influenced by biochar addition, mainly by modifying soil pH. Gao et al. [16] showed that the precipitation of P with Ca^{2+}, Fe^{2+}, Fe^{3+}, and Al^{3+} was affected by altering soil pH and activities of these cations. (3) The dissolved organic matter (DOM) released from biochar resulted in competition with P for sorption in soil and led to the increase of P release [24,132]. (4) Biochar promoted the available soil P by improving soil phosphate-solubilizing microorganisms (PSMs) biomass. In soil, PSMs are consistent with P-solubilizing fungi, P-solubilizing bacteria, and actinomycetes which can solubilize the P [133,134]. Jaafar et al. [135] reported that biochar gave PSMs a suitable habitat. Zheng et al. [136] indicated that the survival rate of PSMs and the available P content in biochar-emendation soil were higher than in the control. In addition, biochar can promote the P uptake by plants via the increase of mycorrhizae [137]. (5) Soil phosphatase activity was a significant influencing factor of available soil P with biochar application. Jin et al. [36] found that alkaline phosphomonoesterase increased by 28.5% in clay-loam soil and 95.1%

in silt loam soil with manure biochar supplement. To sum up, the application of biochar to enhance the available P is mainly by decreasing the complexation of P with soil components and promoting the P metabolism of soil.

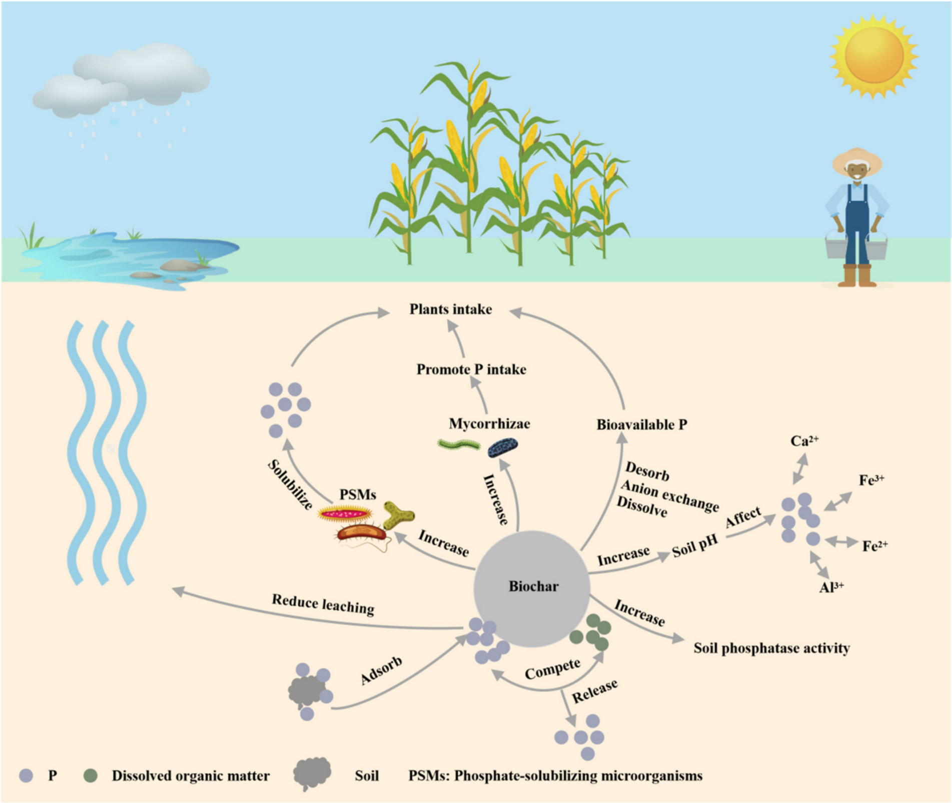

Figure 2. The mechanisms of biochar application on P improvement in soil [24,127,132–137].

Although the presence of biochar contributed to releasing soluble P into the soil and increasing the available P in soil, little evidence has proven that biochar can reduce the leaching of P [104,138,139] (Figure 2). Biochar can decrease the leaching of P from soil to groundwater and surface water via increased P retention [140,141]. P has complex interactions with the soil-biochar system. The mechanism mainly involves pore filling, complexation, cation bridge, electrostatic attraction, competitive adsorption sites, and precipitation reaction [142,143]. In addition, Xu et al. [63] also showed that biochar decreased the leaching of P in soil due to the promotion of P intake by plants or the decrease of water loss from soil. In summary, adding biochar into soil led to an increase in the soil P available and a decrease in the leaching loss of soil P, and these positive effects are either direct or indirect. In particular, the interfacial interaction between biochar and soil components remains to be explored.

4.4. K

Potassium is a vital macronutrient for plant growth, such as regulating plant metabolism and improving grain yields [144,145]. In recent years, the potassium content in the soil has decreased dramatically due to exhaustive contemporary agriculture and a lack of timely potassium supply [31]. Therefore, the search for new potassium fertilizer substitutes has a good application prospect because imported potassium fertilizer is relatively expensive.

Many studies have investigated biochar as a new type of K fertilizer for soil improvement [31,146,147]. As shown in Table S1, the amount of potassium in biochar ranges from 0.60 to 42.40 mg kg^{-1}. It was found that potassium in biochar increases gradually with pyrolysis temperature but volatilizes in the form of gas when the temperature is above 600 °C [148]. The available water-soluble K, such as K_2SO_4, KCl, KNO_2, and KNO_3, accounts for 50–58% of total potassium in biochar. Mineral K, mainly presented as the forms of layer-K and complex-K, comprises the remaining 42–50% [28].

The improvement of K in soil by biochar is firstly manifested in the supplement of K in soil (Figure 3). Oram et al. [149] found that biochar application increased K availability and increased the competitive ability of red clover to grass and plantain. With the increase in biochar level, the contents of soluble and available potassium in soil increased significantly. With 60 Mg ha^{-1} biochar addition, the contents of soluble and available potassium increased by 10% and 27%, respectively, compared with the control group. Moreover, biochar also increased the soil potential buffering capacity of potassium in calcareous sandy soil [150]. However, the contents of soluble and available potassium in the soil increased significantly even at low levels of biochar addition [150]. It can be explained by that free nutrient cations are produced during biochar pyrolysis, and biochar application to the soil will improve the availability of base cations (such as potassium) [151,152].

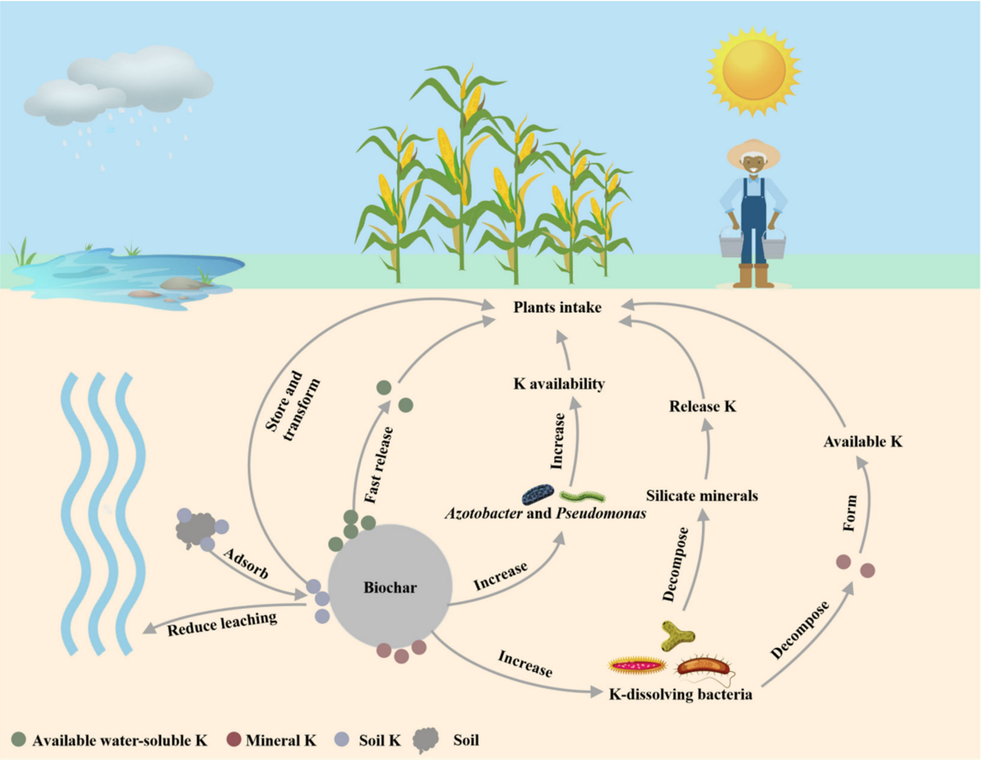

Figure 3. The mechanisms of biochar application on K improvement in soil [146,147,153–155].

Generally, biochar provides soil and crops with potassium in the short term [89]. Limwikran et al. [153] revealed that 8–64% of the K in biochar is rapidly dissolved in water, of which 0–40% is rapidly released into the soil. After the application of biochar to soil, the loss of water-soluble potassium from biochar mainly occurred within one week, whereas insoluble K was relatively slow. Most of the water-soluble K is lost within eight weeks in biochar, such as durian shell, mangosteen shell, eucalyptus wood, and pineapple peel [153]. However, recent studies have shown that biochar still promotes soil K improvement under long-term application [31]. Farmyard manure and woodchip biochar significantly increased soil available K contents compared to CK and led to higher grain K contents and K use efficiency than their feedstock treatments during both years [31]. The soil K showed significant positive correlations with biological and grain yields [31]. Through a four-year biochar study, Zhang et al. [146] found that biochar increased the K availability due to the enhancement of the activity of *Azotobacter* and *Pseudomonas* (Figure 3). Xia et al. [147] also reported that the biochar supplement significantly increased the content of K-dissolving bacteria which can decompose silicate minerals and release K that can be directly used by plants [154] (Figure 3). Based on the gene prediction, biochar led to positive alterations in bacterial function, which involved amino acid transport, production and translation of energy, and ribosomal structure.

In addition, biochar has a high adsorption capacity and can adsorb K lost in the soil, thus providing a stable potassium source for plant growth [146,155] (Figure 3). Among them, soluble potassium and mineral potassium are absorbed by plants or stored in the soil as available potassium through different transformation pathways. Water-soluble potassium is directly absorbed by plants in the form of potassium ions to meet their short-term metabolic demand for K [28].

The effects of biochar on soil nutrient also vary over time. Jílková et al. [156] investigated the effects of biochar on soil nutrients in different incubation time and found that biochar supported microbial activity for several days or weeks at the beginning of the incubation until its stock of readily available nutrients had been depleted. They revealed that the biochar can only be used as a slow-release nutrients fertilizer during the six-month incubation period. Xia et al. also reported that peanut shell biochar improved soil K level after 30 months of application [147]. However, biochar application has no significant differences in soil nutrients, microbial growth, mycorrhizal colonization or weed emergence compared to the unamended soil after 3 years incubation [157]. Whilst biochar amendment is unquestionably a strategy for the improved soil nutrient levels or crop performance, it seemed to be short lived. Therefore, it is necessary to need more long-term field studies to provide data that can meaningfully inform agronomic management decisions.

5. The Adverse Effects of Biochar on Soil Organisms

5.1. Toxic Substances of Biochar

Biochar may be an essential source that introduces organic and inorganic contaminants (mainly HMs) to the soil system, leading to toxic effects on biota (Figure 4). Some of these contaminants exist naturally in biochar pyrolysis materials, and some are formed during the pyrolysis process, including improper or incomplete pyrolysis [158,159]. Many efforts have been made to identify these contaminants in biochar, and the toxic substances of biochar have summarized in Table 2. The PAHs are the main chemical composition of these contaminants in biochar, with the total PAHs content ranging from 1.609–355.2 mg kg^{-1} [160]. Moreover, the biochar prepared at low-temperature processes has a lower content of 3–4 ring PAHs than that of biochar prepared at high temperatures. Lyu et al. [161] and Hale et al. [160] explored the concentration of PCDD/Fs in nearly 20 biochars prepared from different temperatures and raw materials and found that a total PCDD/Fs range from 50 pg g^{-1} to 610 pg g^{-1} and toxic dioxin concentration range from 0.005 pg g^{-1} to 1.20 pg g^{-1}. The volatile organic compounds (VOCs), mainly consisting of organic acids, aldehydes, furans, ketones, alcohols, and phenols, were generated during pyrolysis. Buss et al. [162] found that the prominent member of VOCs in softwood pellets biochar is phenols, with a concentration from 20 to 240 ug g^{-1}. Recently, the MCN was reported as the critical toxic compound in biochar, and CN- contents were detected from 1.0 to 251 mg kg^{-1}. The higher concentrations in corn protein biochar, food waste, and phycocyanin biochar are 23,251, 40,286, and 85,870 mg kg^{-1}, respectively [163]. The PTEs, which mainly include Cu, Pb, Zn, Hg, Mn, Ni, As, Cr, Cd, etc., are other primary contaminants in biochar. PTEs can be found in various biochar derived from different feedstock, e.g., sludge, manure, and plant biomass [164,165].

More importantly, the toxic substrate in biochar depends on the pyrolysis raw material and temperature. In generally, sludge biochar contains more heavy metals and plant-derived biochar contains more PAHs. Sørmo et al. [166] reported that biochar derived with a high salt content raw material contained a significant amount of dioxins. High temperature has a stronger fixation effect on HMs on biochar and reduces their leaching. The PAH content in biochar generally decreases as the pyrolysis time and temperature increase [167]. Therefore, before applying biochar, it is necessary to strictly monitor the concentration of pollutants and select the appropriate dosage to reduce ecological risks.

Figure 4. A general view of the contaminants present in biochar regarding to their effect towards living organisms.

Table 2. Main pollutants of biochar obtained under different biomass and preparation conditions.

Pollutants Types	Biochar Types	Pyrolysis Conditions	Concentration	Ref.
PAHs	Sewage sludge	500 °C for 3 h	Total PAHs: 2263 µg kg^{-1}	[168]
		600 °C for 3 h	Total PAHs: 1730 µg kg^{-1}	
		700 °C for 3 h	Total PAHs: Total PAHs: 1449 µg kg^{-1}	
	Sewage sludge	500 °C	Total PAHs: 612 to 766 µg kg^{-1}	[169]
	Straw	350 °C for 2 h	Total PAHs: 3.72 ± 0.422 mg kg^{-1}	[170]
		500 °C for 2 h	Total PAHs: 5.48 ± 1.02 mg kg^{-1}	
		650 °C for 2 h	Total PAHs: 4.94 ± 0.315 mg kg^{-1}	
	Paper mill sludge	200 °C	Nap: 2.5 mg kg^{-1} Flu: 8.5 mg kg^{-1} Phe: 32 mg kg^{-1} Pyr: 15.46 mg kg^{-1} BaA: 2.01 mg kg^{-1} CHR: 246.23 mg kg^{-1} BbF: 1.51 mg kg^{-1} BkF: 1.07 mg kg^{-1}	[171]
		300 °C	Nap: 8.5 mg kg^{-1} Flu: 39.5 mg kg^{-1} Phe: 55.5 mg kg^{-1} Pyr: 12.64 mg kg^{-1} BaA: 24.2 mg kg^{-1} CHR: 157.42 mg kg^{-1} BbF: 3.61 mg kg^{-1} BkF: 2.43 mg kg^{-1}	
		400 °C	Nap: 860 mg kg^{-1} Flu: 343.5 mg kg^{-1} Phe: 913 mg kg^{-1} Pyr: 492.3 mg kg^{-1} BaA: 224.7 mg kg^{-1} CHR: 534.9 mg kg^{-1} BbF: 195.39 mg kg^{-1} BkF: 172.3 mg kg^{-1}	

Table 2. *Cont.*

Pollutants Types	Biochar Types	Pyrolysis Conditions	Concentration	Ref.
		500 °C	Nap: 372.5 mg kg^{-1} Flu: 1198 mg kg^{-1} Phe: 3700 mg kg^{-1} Pyr: 1394.7 mg kg^{-1} BaA: 769.5 mg kg^{-1} CHR: 859.02 mg kg^{-1} BbF: 2310 mg kg^{-1} BkF: 2182 mg kg^{-1}	[172]
		600 °C	Nap: 4.5 mg kg^{-1} Flu: 79 mg kg^{-1} Phe: 197 mg kg^{-1} Pyr: 165.8 mg kg^{-1} BaA: 17.5 mg kg^{-1} CHR: 127.5 mg kg^{-1} BbF: 134.29 mg kg^{-1} BkF: 121.8 mg kg^{-1}	
		700 °C	Flu: 16.5 mg kg^{-1} Phe: 60 mg kg^{-1} Pyr: 21 mg kg^{-1} BaA: 25 mg kg^{-1} CHR: 12.28 mg kg^{-1} BbF: 9.01 mg kg^{-1} BkF: 8.2 mg kg^{-1}	
	Sewage sludge	300 °C for 3 h	2 ring PAHs: 5.7 mg kg^{-1} 3 ring PAHs: 4.8 mg kg^{-1} 4 ring PAHs: 1.8 mg kg^{-1} 5 ring PAHs: 0.6 mg kg^{-1} 6 ring PAHs: 0.8 mg kg^{-1}	
		400 °C for 3 h	2 ring PAHs: 6.0 mg kg^{-1} 3 ring PAHs: 4.0 mg kg^{-1} 4 ring PAHs: 3.1 mg kg^{-1} 5 ring PAHs: 1.3 mg kg^{-1} 6 ring PAHs: 1.0 mg kg^{-1}	
		500 °C for 3 h	2 ring PAHs: 6.9 mg kg^{-1} 3 ring PAHs: 1.4 mg kg^{-1} 4 ring PAHs: 0.3 mg kg^{-1} 5 ring PAHs: 0.6 mg kg^{-1}	
		600 °C for 3 h	2 ring PAHs: 1.3 mg kg^{-1} 3 ring PAHs: 2.4 mg kg^{-1} 4 ring PAHs: 2.4 mg kg^{-1}	
		700 °C for 3 h	2 ring PAHs: 1.0 mg kg^{-1} 3 ring PAHs: 0.5 mg kg^{-1} 4 ring PAHs: 0.4 mg kg^{-1}	
	Corn stover	350 °C	Total PAHs: 1609 μg kg^{-1}	[160]
		450 °C	Total PAHs: 1959 μg kg^{-1}	
		550 °C	Total PAHs: 1770 μg kg^{-1}	
	Wood pellets	500 °C for 30 min	Total PAHs: 33,700 μg kg^{-1}	[173]
PCDD/Fs	Sawdust	250 °C for 3 h	Total PCDD/Fs: 2.7 × 10^{2} pg g^{-1}	[161]
		300 °C for 3 h	Total PCDD/Fs: 6.1 × 10^{2} pg g^{-1}	
		400 °C for 3 h	Total PCDD/Fs: 3.6 × 10^{2} pg g^{-1}	
		500 °C for 3 h	Total PCDD/Fs: 67 pg g^{-1}	
		700 °C for 3 h	Total PCDD/Fs: 50 pg g^{-1}	

Table 2. *Cont.*

Pollutants Types	Biochar Types	Pyrolysis Conditions	Concentration	Ref.
	Food waste	300 °C	Total 2,3,7,8-substitutes dioxin concentration:13.3 pg g^{-1} Toxic dioxin concentration: 1.20 pg g^{-1}	[160]
		400 °C	Total 2,3,7,8-substitutes dioxin concentration: 12.2 pg g^{-1} Toxic dioxin concentration: 0.15 pg g^{-1}	
		500 °C	Total 2,3,7,8-substitutes dioxin concentration: 0.39 pg g^{-1} Toxic dioxin concentration: 0.008 pg g^{-1}	
		600 °C	Total 2,3,7,8-substitutes dioxin concentration: 7.5 pg g^{-1} Toxic dioxin concentration: 0.16 pg g^{-1}	
	Digested dairy manure	600 °C	Total 2,3,7,8-substitutes dioxin concentration: 8.0 pg g^{-1} Toxic dioxin concentration: 0.13 pg g^{-1}	
	Pine wood	900 °C	Total 2,3,7,8-substitutes dioxin concentration: 10.7 pg g^{-1} Toxic dioxin concentration: 0.15 pg g^{-1}	
	Lodgepole pine	-	Total 2,3,7,8-substitutes dioxin concentration: 10.5 pg g^{-1} Toxic dioxin concentration: 0.18 pg g^{-1}	
	Laurel oak	650 °C	Total 2,3,7,8-substitutes dioxin concentration: 1.5 pg g^{-1} Toxic dioxin concentration: 0.02 pg g^{-1}	
	Eastern gamma grass	650 °C	Total 2,3,7,8-substitutes dioxin concentration: 2.4 pg g^{-1} Toxic dioxin concentration: 0.02 pg g^{-1}	
	Pine wood	800 °C	Total 2,3,7,8-substitutes dioxin concentration: 0.5 pg g^{-1} Toxic dioxin concentration: 0.005 pg g^{-1}	
	Switch grass	800 °C	Total 2,3,7,8-substitutes dioxin concentration: 0.8 pg g^{-1} Toxic dioxin concentration: 0.008 pg g^{-1}	
	Switch grass	900 °C	Total 2,3,7,8-substitutes dioxin concentration: 2.2 pg g^{-1} Toxic dioxin concentration: 0.22 pg g^{-1}	
	Paper mill waste	600 °C	Total 2,3,7,8-substitutes dioxin concentration: 0.6 pg g^{-1} Toxic dioxin concentration: 0.006 pg g^{-1}	
VOCs	Softwood pellets	At 500 for 20 min (a liquid contaminated biochar)	Phenol: 110 µg g^{-1} 3-methyl-1,2-cyclopentadione: 91 µg g^{-1} 2-methylphenol: 130 µg g^{-1} 3/4-methylphenol: 200 µg g^{-1} 3,4-dimethylphenol: 240 µg g^{-1} 4-ethylphenol: 110 µg g^{-1} 3-ethyl-5-methylphenol: 64 µg g^{-1} 4-ethyl-3-methylphenol: 110 µg g^{-1} 1,2-benzenediol: 66 µg g^{-1} 4-methyl-1,2-benzenediol: 45 µg g^{-1}	[162]
		At 500 for 20 min (a gas contaminated biochar)	Phenol: 49 µg g^{-1} 4-methyl-1,2-cyclopentadione: 60 µg g^{-1} 2-methylphenol: 60 µg g^{-1} 3,4-methylphenol: 92 µg g^{-1} 3,4-dimethylphenol: 120 µg g^{-1} 2-methoxy-5-methylphenol: 23 µg g^{-1} 4-ethylphenol: 61 µg g^{-1} 3-ethyl-5-methylphenol: 20 µg g^{-1} 4-ethyl-3-methylphenol: 59 µg g^{-1} 1,2-benzenediol: 49 µg g^{-1} 4-methyl-1,2-benzenediol: 31 µg g^{-1}	

Table 2. *Cont.*

Pollutants Types	Biochar Types	Pyrolysis Conditions	Concentration	Ref.
MCN	Food waste	800 °C for 1 h	40,286 mg kg^{-1}	[163]
	Soybean residue	800 °C for 1 h	17.4 mg kg^{-1}	
	Rapeseed residue	800 °C for 1 h	9.6 mg kg^{-1}	
	Phycocyanin	800 °C for 1 h	85,870 mg kg^{-1}	
	Algae protein	800 °C for 1 h	10.3 mg kg^{-1}	
	Vinasse	800 °C for 1 h	6.9 mg kg^{-1}	
	Corn protein	800 °C for 1 h	9.3 mg kg^{-1}	
	Wheat straw	800 °C for 1 h	1.0 mg kg^{-1}	
	Corn straw	800 °C for 1 h	105.4 mg kg^{-1}	
	Cow dung	800 °C for 1 h	5.9 mg kg^{-1}	
	Kitchen waste	800 °C for 1 h	15.9 mg kg^{-1}	
	Fungi residue	800 °C for 1 h	251.1 mg kg^{-1}	
	Biogas residue	800 °C for 1 h	50.9 mg kg^{-1}	
	Corn protein with K_2CO_3	800 °C for 1 h	23,251 mg kg^{-1}	
Heavy metals	Sewage sludge	300 °C	Zn: 10,400.17 ± 97.21 mg kg^{-1}	[164]
			Cu: 316.55 ± 20.08 mg kg^{-1}	
			Cr: 297.37 ± 9.88 mg kg^{-1}	
			Ni: 217.32 ± 6.27 mg kg^{-1}	
			Cd: 0.793 ± 0.103 mg kg^{-1}	
			Mn: 1859.43 ± 20.75 mg kg^{-1}	
		400 °C	Zn: 11,134.92 ± 69.83 mg kg^{-1}	
			Cu: 347.53 ± 18.39 mg kg^{-1}	
			Cr: 314.35 ± 11.37 mg kg^{-1}	
			Ni: 238.57 ± 8.21 mg kg^{-1}	
			Cd: 0.852 ± 0.091 mg kg^{-1}	
			Mn: 2082.52 ± 33.62 mg kg^{-1}	
		500 °C	Zn: 12,550.41 ± 93.04 mg kg^{-1}	
			Cu: 374.05 ± 23.01 mg kg^{-1}	
			Cr: 360.75 ± 8.78 mg kg^{-1}	
			Ni: 260.14 ± 5.08 mg kg^{-1}	
			Cd: 0.928 ± 0.055 mg kg^{-1}	
			Mn: 2256.54 ± 52.01 mg kg^{-1}	
		600 °C	Zn: 13,080.32 ± 70.55 mg kg^{-1}	
			Cu: 392.15 ± 10.55 mg kg^{-1}	
			Cr: 376.82 ± 7.99 mg kg^{-1}	
			Ni: 272.39 ± 2.09 mg kg^{-1}	
			Cd: 0.866 ± 0.042 mg kg^{-1}	
			Mn: 2319.54 ± 41.27 mg kg^{-1}	
		700 °C	Zn: 14,109.92 ± 91.39 mg kg^{-1}	
			Cu: 426.92 ± 20.02 mg kg^{-1}	
			Cr: 411.96 ± 10.11 mg kg^{-1}	
			Ni: 299.49 ± 7.44 mg kg^{-1}	
			Cd: 0.139 ± 0.027 mg kg^{-1}	
			Mn: 2525.01 ± 72.13 mg kg^{-1}	
	Pig manure	400 °C for 2 h	Water-soluble Cu: 1.21 mg kg^{-1}	[174]
			Water-soluble Zn: 0.17 mg kg^{-1}	
			DTPA-Cu: 23.44 mg kg^{-1}	
			DTPA-Zn: 122.89 mg kg^{-1}	
		700 °C for 2 h	Water-soluble Cu: 2.38 mg kg^{-1}	
			Water-soluble Zn: 0.81 mg kg^{-1}	
			DTPA-Cu: 31.05 mg kg^{-1}	
			DTPA-Zn: 129.24 mg kg^{-1}	

Table 2. *Cont.*

Pollutants Types	Biochar Types	Pyrolysis Conditions	Concentration	Ref.
	Pig manure	300 °C	Cr: 513.40 ± 3.50 mg kg^{-1} Mn: 1390.6 ± 5.30 mg kg^{-1} Cu: 673.40 ± 3.80 mg kg^{-1} Zn: 4310.30 ± 16.00 mg kg^{-1}	[165]
		350 °C	Cr: 518.10 ± 7.70 mg kg^{-1} Mn: 1430.60 ± 6.40 mg kg^{-1} Cu: 780.90 ± 6.20 mg kg^{-1} Zn: 4670.90 ± 29.10 mg kg^{-1}	
		400 °C	Cr: 521.70 ± 4.90 mg kg^{-1} Mn: 1510.30 ± 1.30 mg kg^{-1} Cu: 824.60 ± 7.50 mg kg^{-1} Zn: 4950.80 ± 26.30 mg kg^{-1}	
		450 °C	Cr: 553.50 ± 10.30 mg kg^{-1} Mn: 1580.00 ± 8.50 mg kg^{-1} Cu: 838.70 ± 7.30 mg kg^{-1} Zn: 5040.70 ± 33.40 mg kg^{-1}	
		500 °C	Cr: 666.20 ± 9.40 mg kg^{-1} Mn: 1660.40 ± 6.70 mg kg^{-1} Cu: 950.70 ± 5.30 mg kg^{-1} Zn: 5630.00 ± 28.30 mg kg^{-1}	
		550 °C	Cr: 559.50 ± 5.20 mg kg^{-1} Mn: 1520.30 ± 4.30 mg kg^{-1} Cu: 810.20 ± 1.90 mg kg^{-1} Zn: 4900.80 ± 37.20 mg kg^{-1}	
		600 °C	Cr: 476.90 ± 2.50 mg kg^{-1} Mn: 1550.20 ± 8.50 mg kg^{-1} Cu: 901.50 ± 6.60 mg kg^{-1} Zn: 5160.80 ± 51.50 mg kg^{-1}	
		650 °C	Cr: 569.70 ± 11.30 mg kg^{-1} Mn: 1860.80 ± 9.10 mg kg^{-1} Cu: 981.80 ± 16.10 mg kg^{-1} Zn: 6010.80 ± 40.10 mg kg^{-1}	
		700 °C	Cr: 819.90 ± 10.30 mg kg^{-1} Mn: 1920.60 ± 2.30 mg kg^{-1} Cu: 1080.70 ± 9.60 mg kg^{-1} Zn: 7720.30 ± 46.70 mg kg^{-1}	

FLO-fluorene. PHE-phenantrene. ANT-anthracene. FLA-fluoranthene. PYR-pyrene. BaA-benzo(a)anthracene. CHR-chrysene. BbF-benzo(b)fluoranthene. BkF-benzo(k)fluoranthene. BaP-benzo(a)pyrene. DahA-dibenzo(ah)anthracene. BghiP-benzo(ghi)perylene. IcdP-indeno(cd)pyrene.

Once these pollutants are introduced to soil, potential risks to humans and ecology (e.g., phytotoxicity, cytotoxicity, ecotoxicity, etc.) will occur. In addition, the negative effect of biochar on microbiology and plants has received more attention in recent years

5.2. Negative Effects of Biochar on Microbiology

As an essential member of the soil environment, the structure and number of microbial communities are also important indicators of soil quality and crop production. Although many studies have reported that biochar can promote microbial diversity and increase the number of microbial communities after soil amendment [175,176], the toxic effect of biochar on microorganisms is still a problem that cannot be ignored. As shown in Table 3, biochar's adverse effects on microbiology were summarized.

Table 3. The negative effect of biochar on soil organisms.

Negative Impacted Groups	Biochar Feedstock	Pyrolysis Conditions	Soil Type	Addition Rate	Incubation Time	Negative Effects	Ref.
Microbiology	Maize corn cob	450–500 °C	Sandy loam	5 t·ha^{-1}	2, 14 and 24 months	The application of biochar significantly reduced soil microbial biomass (phospholipid fatty acid, PLFA).	[177]
	Rice straw	At 500 °C for 3 h.	Hydromorphic paddy soil	10, 15 and 20% (*w*/*w*)	3–4 days	The biochar significantly reduced fungi in soil by 22.2–30.2% compared with control.	[178]
	Corn stover, ponderosa pine wood chips, switchgrass	The reactor temperature ramps from 150 °C to 850 °C with residence time of 4 h and 4 min	Sandy, mixed, frigid entic hapludolls	10 g kg^{-1}, and 50 g kg^{-1}.	120 days	The short-term incubation study showed that biochar had negative effects on microbial activity (FDA and DHA) and some enzymes including β-glucosidase and protease.	[66]
	Rice straw	At 500 °C for 2 h	Clay loam texture	22.5 t ha^{-1}	48 h	The addition of biochar limited the growth of methanotrophs and nitrifiers.	[179]
	Sewage sludge	At 500 °C, 600 °C, and 700 °C for 5 h	Loamy sand	1% (*w*/*w*)	6 months	Biochar derived at 500 °C has a higher toxic effect on *Aliivibrio fischeri* than that at 600 °C and 700 °C.	[169]
	Switchgrass, mixed hardwood, and mixed softwood pellets	500 °C, 700 °C, 800 °C	-	10% (*w*/*w*)	6 weeks	Mycorrhizal fungi were inhibited by biochar addition.	[180]
	Solid residue from biogas production	400, 600 and 800 °C	Artificial soil	0.5–5% (*w*/*w*)	-	Depending on the temperature at which it was produced, biochar caused mortality of *F. candida* at a level from 20 to 30% (0.5% dose) and from 30 to 50% (5.0% dose), and reproduction inhibition occurred from 70 to 100% (0.5% dose) and 100% (5.0% dose) for all temperatures.	[181]
	Rice husk	>480 °C	Pristine agricultural soil	0.5–50% (*w*/*w*)	90 days	Biochar amendment reduced fungal population with shift in community structure and abundance, over time.	[182]
	Walnut shells and corn cobs	At 250 °C, 400 °C, and 600 °C for 4 h	-	2% (*w*/*w*)	75 days	Application of biochars to the soil decreases Proteobacteria richness (23–29%).	[183]
Invertebrates	Rice husk	>480 °C	-	0.5–50% (*w*/*w*)	90 days	The growth of the exposed earthworms was strongly reduced by biochar, especially for 50% biochar addition.	[182]
	Sewage sludge	At 500 °C, 600 °C, and 700 °C for 5 h	Loamy sand	1% (*w*/*w*)	6 months	Biochar exhibited toxic activity towards *Folsomia candida* after six months incubation, and biochar produced at higher temperatures exhibited lower toxicity than that prepared at lower temperature.	[169]

Table 3. *Cont.*

Negative Impacted Groups	Biochar Feedstock	Pyrolysis Conditions	Soil Type	Addition Rate	Incubation Time	Negative Effects	Ref.
Plants	Wheat straws	At 500 °C for 4 h	Artificial soil	10% (*w*/*w*)	28 days	About 10% of biochar applications induced DNA damage to earthworms.	[184]
	Wood	700 °C	Sandy loam cambisol	10% (*w*/*w*)	-	Reproduction rates of earthworms reduced by 38% in comparison to unamended soil.	[185]
	Rice husk	~600 °C	Sandy loam cambisol	10% (*w*/*w*)	-	Reproduction rates of earthworms reduced by27% compared to unamended soil.	
	Walnut shells and corn cobs	250 °C, 400 °C, and 600 °C for 4 h	-	2% (*w*/*w*)	75 days	Most of six biochars significantly increased the concentrations of Σ16PAHs in Chinese cabbage by 30.10–74.22%.	[183]
	Beech, hazel, oak, birch	500 °C	-	100 and 120 t ha^{-1}	-	A general reduction of wheat biomass was observed.	[186]
	Rice husk	>480 °C	-	0.5–50% (*w*/*w*)	90 days	Biochar led to the direct toxic influence on the roots of *Oryza sativa* and *Solanum lycopersicum*	[182]
	Sewage sludge	At 500 °C, 600 °C, and 700 °C for 5 h	Loamy sand	1% (*w*/*w*)	6 months	The biochar exhibited toxic activity towards *Lepidium sativum* after six months incubation, and biochar produced at higher temperatures exhibited lower toxicity than that prepared at lower temperature.	[169]
	Switchgrass, mixed hardwood, and mixed softwood pellets	500 °C, 700 °C, 800 °C	-	10% (*w*/*w*)	6 weeks	Biochar amendment tended to reduce the aboveground biomass of *Allium porrum* ' Musselburgh'.	[180]
	Corn stover	At 600 °C for 20 min	-	2, and 5% (*w*/*w*)	28 days	The addition of biochar contributed to weight loss in *Aporrectodea caliginosa*.	[187]
	Mixed wood sievings	At 500 °C for 20 min	Haplic Cambisols	8% (*w*/*w*)	1 month	The biochar led to a decline of *Lactuca sativa* biomass.	[188]
	Paper sludge + wheat husks	At 500 °C for 20 min	Haplic Cambisols	8% (*w*/*w*)	1 month	About 33% lower stem length of *Lactuca Sativa* was found after biochar amendment.	
	Sewage sludge	At 500 °C for 20 min	Haplic Cambisols	8% (*w*/*w*)	1 month	The biochar reduced 15–38% of the stem length and root (dry weight).	

Andrés et al. [177] applied biochar from maize corn cob at 450–500 °C to amend sandy loam soil. The biochar significantly reduced soil microbial biomass with an additional 5 t ha^{-1}. Similar results were also obtained by Li et al. [178] and Nan et al. [179]. The biochar led to an adverse impact on microbial and enzymatic activity. In addition, biochar prepared at low temperatures is more toxic to microorganisms than derived at high temperatures. Tomczyk et al. [169] reported that biochar derived from sewage sludge at 500 °C contributed to a higher toxic effect on *Aliivibrio fischeri* than that at 600 °C and 700 °C. In addition, Palansooriya et al. [189] reported that possible adverse effects of biochar application on the soil microbial community might depend on the feedstock type, distinct types of charred material, soil types, and dosage. According to Godlewska et al. [167], the toxic effect of biochar on microbiology mainly occurred through the changes in soil properties and releasing heavy metals or organic chemicals in biochar. Biochar amendment led to the increase of soil pH, which broke the balance between fungi and bacteria due to the insensitivity of fungi to the pH [190]. Du et al. [191] investigated the toxic effect of DOMs in biochar prepared from sewage sludge at different temperatures and revealed that DOMs solutions of sludge biochar prepared at 300 °C (SSB_{300}) and 400 °C (SSB_{400}) contained more toxic pollutants due to a significant luminescence inhibitory on *Vibrio qinghaiensis* Q67. Further positive control experiments showed that the toxicity of DOM solution of $SSB_{300}/_{400}$ to *Vibrio qinghaiensis* Q67 was equivalent to 7.92 mg L^{-1} and 6.18 mg L^{-1} of 3–5 dichlorophenol. DOMs solutions of biochar prepared at 500–800 °C showed the nearly same degree of luminescence quenching effect, suggesting that the DOMs from sludge biochar obtained at the pyrolysis temperature over 500 °C had no obvious potential risk on the *Vibrio qinghaiensis* Q67 [191].

5.3. Negative Effects of Biochar on Invertebrates

Earthworms are widely distributed on earth and are the most crucial member of belowground soil biomass, with approximately 60–90% [192]. Earthworms were reported to influence soil's physical, chemical, and biological properties and were reviewed by Xiao et al. [193], that took part in potential toxic elements (PTEs) biogeochemical cycling in soils. Earthworms are able to consume these contaminants by ingestion of soil particles and passive diffusion through the skin [184]. Several studies have proven that biochar's application led to a negative effect on earthworms. The adverse effects of biochar on invertebrates are summarized in Table 3. Anyanwu et al. [182] showed that biochar derived from rice husk significantly reduced the exposed earthworm growth after 90 days of incubation. Bielská et al. [185] also obtained similar results, wood biochar prepared at 700 °C and rice husk derived at ~600 °C decreased reproduction rates of earthworms by 38% and 27% after 30 days, respectively, in comparison to unamended soil. Godlewska et al. [167] reviewed that biochar negatively influence earthworms, mainly due to toxic substances present in biochar. In recent years, the toxicity of biochar to earthworm mainly includes epidermal damage, oxidative stress, and DNA damage, and intestinal injury. Han et al. [194] reported that 5% rice straw-derived biochar negatively affected earthworm skin, not only involving fracture irregular arrangement in microvilli and thickening of upper stratum corneum, but also a fault zone between stratum corneum and epidermis occurred. Environmental persistent free radicals in biochar may pose a potential environmental risk because they can induce the formation of reactive oxygen species (ROS) with high phytotoxicity and cytotoxicity within environmental media [167]. Biochar addition disturbed antioxidant enzyme activities and increased malondialdehyde content, which revealed that earthworm suffer oxidative stress, also showing a potential vermitoxicity of biochar on earthworms. A 5% application not only led to decrease in activities of digestion-related enzymes including Na^{+}-K^{+}-ATPase and cellulose, but also facilitated some abnormities of intestinal epithelial tissue [195].

In addition, in recent years, *Folsomia candida* was treated as a model organism to investigate the toxic effect of biochar on the soil system. Tomczyk et al. [169] exhibited that sewage sludge biochar prepared at 500 °C, 600 °C, and 700 °C led to toxic activity towards

Folsomia candida with an additional rate of 1% in loamy sand soil after six months. Thus, it can be seen that biochar has strong biotoxicity to invertebrates in the soil.

5.4. Negative Effects of Biochar on Plants

The application of biochar on soil is mainly due to its usefulness in agriculture. The toxic effect of biochar on plants was regarded as an essential indicator to measure biochar's impact on a particular soil's toxicity. Although many kinds of literature have reported the positive effects of biochar on plants, such as improving plant growth and reducing the accumulation of harmful substances in plants [183,190], the toxic effects of biochar on plants still cannot be ignored. The adverse effects of biochar on plants in amend-soil are summarized in Table 3.

As is known that germination, root and shoot length, and produced plant biomass are the most frequently evaluated eco-toxicological parameters for plants. Du et al. [191] investigated the toxicity of DOMs in biochar toward pak choi seed by the germination test. They found that DOMs derived from low temperatures led to higher inhibition of germination. The seed germination index (SGI) significantly increased with pyrolysis temperature. DOMs solutions of sludge biochar derived at 800 °C (SSB_{800}) had a maximum SGI of 85.8%. Anyanwu et al. [182] showed that rice husk biochar led to a direct toxic impact on the roots of *Oryza sativa* and *Solanum lycopersicum* after 30, 60, and 90 d. With the increase in pyrolysis temperature, the inhibitory effect on root growth gradually weakened, and DOMs solutions of SSB_{800} showed a slight inhibition effect at approximately 14.2% [191]. The inhibition of mycorrhizal fungus that occurred by biochar might be why biochar amendment reduced root growth [180]. In addition, there is evidence that biochar exhibited toxic activity toward plants. Tomczyk et al. [169] exhibited that sewage sludge biochar led to harmful activity to *Lepidium sativum*. Zhang et al. [183] also found that biochar prepared from walnut shells and corn cobs increased the concentrations of Σ16PAHs in Chinese cabbage by 30.10–74.22%, with 2% biochar addition after 75 days of incubation. Interestingly, the significant reduction of Proteobacteria after biochar amendment most likely resulted in the decrease in dissipation of PAHs. Some evidence has shown that Proteobacteria could be associated with the biodegradation of low solubility and bioavailable hydrocarbons, particularly PAHs. In addition, the richness of Bacteroidetes which were also related to the biodegradation of PAHs decreased [183].

In addition, the toxic effects of biochar on plants can be associated with the addition rates of biochar. Méndez et al. [196] reported that higher addition rates of sewage sludge biochar led to the higher bioavailable fraction content of HMs in biochar-amended soils. With 4% and 8% addition rates, the bioavailable fraction content of Cu, Ni, Pb, and Zn was from 1.5 to 1.6, 3.0 to 3.5, 1.6 to 1.8, and 1.2 to 1.5-times higher, respectively, compared to soil without biochar addition. Visioli et al. [197] investigated the effects of different addition rates (0.5, 1, 2, 5, 10, 20, 50%) of biochar on the plant growth and revealed that EC and Cu negatively affected both germination and root elongation at a biochar application rate of $\geq 5\%$ (w/w), EC and Cu altered both germination and root elongation at 5% addition rate, together with Zn at 10% and elevated pH at 20%. Moreover, high rates (20 and 50%) of biochar decreased the Germination.

At present, the toxic effects of biochar on the soil-plant system are also limited. The comprehensive mechanisms by which biochar negatively affects the environment at the microcellular and molecular levels should be further explored. In the future, we should focus on exploring the toxic effects of biochar at the cellular and molecular levels to reveal the underlying mechanisms at the molecular level. Much more effort should be made to comprehensively evaluate the potentially negative impacts during biochar amendment and develop high-efficiency strategies for mitigation of biochar contaminants release.

6. Conclusions

As an emerging soil amendment, biochar positively impacts soil's physical and chemical properties. It is crucial in improving acid soil, soil water holding capacity, CEC, and enzyme activity. More importantly, biochar is involved in soil nutrient transportation and improvement. Biochar could significantly increase soil C content, including TC, OC, MBC, and DOC. Biochar also releases N, P, and K elements directly to the soil. Moreover, biochar promotes the mineralization of N, P, and K and increases the abundance of responsive metabolic bacteria to achieve nutrient supplementation. In addition, the adsorption of N, P, and K in soil by biochar further enhanced the retention of these elements in the soil. In order to effectively use biochar as a substitute for chemical fertilizers, it is necessary to understand the composition and morphology of the elements in biochar and the properties of the modified soil. The physicochemical properties of biochar are primarily affected by raw materials, pyrolysis temperature, pyrolysis time, and other factors. The application of biochar in soil involves a slow degradation process. Its physical and chemical properties and eco-environmental benefits have different effects with time, and its impact on the eco-environment needs a long-term and large-scale study. In addition, biochar contains many pollutants, such PAHs, PCDD/Fs, VOCs, MCN, and HMs, which have toxic effects on organisms after being applied to the soil. Thus, much more effort should be made to comprehensively evaluate the potential negative impacts at the microcellular and molecular levels during biochar amendment and develop high-efficiency strategies for the mitigation of biochar contaminants release.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16010410/s1, Table S1: Differences in physical and chemical properties of different types of biochar. References [198–212] are cited in the Supplementary Materials.

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References

1. Food and Agriculture Organization of the United Nations (FAO). *Status of the World's Soil Resources—Main Report*; Bulletin of National Institute for Agro-Environmental Sciences; Food and Agriculture Organization of the United Nations: Rome, Italy, 2015.
2. Borrelli, P.; Robinson, D.A.; Panagos, P.; Lugato, E.; Yang, J.E.; Alewell, C.; Wuepper, D.; Montanarella, L.; Ballabio, C. Land use and climate change impacts on global soil erosion by water (2015–2070). *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 21994–22001. [CrossRef] [PubMed]
3. Miguez-Macho, G.; Fan, Y. Spatiotemporal origin of soil water taken up by vegetation. *Nature* **2021**, *598*, 624–628. [CrossRef] [PubMed]
4. Food and Agriculture Organization of the United Nations (FAO). *Recarbonization of Global Soils—A Dynamic Response to Offset Global Emissions*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2019.
5. Ferreira, C.S.S.; Seifollahi-Aghmiuni, S.; Destouni, G.; Ghajarnia, N.; Kalantari, Z. Soil degradation in the European Mediterranean region: Processes, status and consequences. *Sci. Total Environ.* **2022**, *805*, 150106. [CrossRef] [PubMed]
6. Jin, Q.; Wang, C.; Sardans, J.; Vancov, T.; Fang, Y.; Wu, L.; Huang, X.; Gargallo-Garriga, A.; Peñuelas, J.; Wang, W. Effect of soil degradation on the carbon concentration and retention of nitrogen and phosphorus across Chinese rice paddy fields. *Catena* **2022**, *209*, 105810. [CrossRef]
7. Maximillian, J.; Brusseau, M.L.; Glenn, E.P.; Matthias, A.D. Pollution and Environmental Perturbations in the Global System. In *Pollution and Environmental Perturbations in the Global System*, 3rd ed.; Brusseau, M.L., Pepper, I.L., Gerba, C.P., Eds.; Academic Press: London, UK, 2019; pp. 457–476.

8. Bashagaluke, J.B.; Logah, V.; Opoku, A.; Sarkodie-Addo, J.; Quansah, C.; Marelli, B. Soil nutrient loss through erosion: Impact of different cropping systems and soil amendments in Ghana. *PLoS ONE* **2018**, *13*, e0208250. [CrossRef] [PubMed]
9. Liu, S.; Schleuss, P.M.; Kuzyakov, Y. Carbon and Nitrogen Losses from Soil Depend on Degradation of Tibetan *Kobresia* Pastures. *Land Degrad. Dev.* **2017**, *28*, 1253–1262. [CrossRef]
10. Jin, Q.; Peñuelas, J.; Sardans, J.; Romero, E.; Chen, S.; Liu, X.; Lin, S.; Wang, W. Changes in soil carbon, nitrogen, and phosphorus contents, storages, and stoichiometry during land degradation in jasmine croplands in subtropical China. *Exp. Agric.* **2021**, *57*, 113–125. [CrossRef]
11. Tamene, L.; Sileshi, G.W.; Ndengu, G.; Mponela, P.; Kihara, J.; Sila, A.; Tondoh, J. Soil structural degradation and nutrient limitations across land use categories and climatic zones in Southern Africa. *Land Degrad. Dev.* **2019**, *30*, 1288–1299. [CrossRef]
12. Chen, X.H.; Yu, W.H.; Cai, Y.Y.; Zhang, S.W.; Muneer, M.A.; Zhu, Q.C.; Xu, D.H.; Ma, C.C.; Yan, X.J.; Li, Y.; et al. How to identify and adopt cleaner strategies to improve the continuous acidification in orchard soils? *J. Clean. Prod.* **2022**, *330*, 129826. [CrossRef]
13. Ata-Ul-Karim, S.T.; Cang, L.; Wang, Y.; Zhou, D. Effects of soil properties, nitrogen application, plant phenology, and their interactions on plant uptake of cadmium in wheat. *J. Hazard. Mater.* **2020**, *384*, 121452. [CrossRef]
14. Lu, H.; Wu, Y.; Liang, P.; Song, Q.; Zhang, H.; Wu, J.; Wu, W.; Liu, X.; Dong, C. Alkaline amendments improve the health of soils degraded by metal contamination and acidification: Crop performance and soil bacterial community responses. *Chemosphere* **2020**, *257*, 127309. [CrossRef] [PubMed]
15. Manyà, J.J. Pyrolysis for Biochar Purposes: A Review to Establish Current Knowledge Gaps and Research Needs. *Environ. Sci. Technol.* **2012**, *46*, 7939–7954. [CrossRef] [PubMed]
16. Gao, S.; DeLuca, T.H.; Cleveland, C.C. Biochar additions alter phosphorus and nitrogen availability in agricultural ecosystems: A meta-analysis. *Sci. Total Environ.* **2019**, *654*, 463–472. [CrossRef] [PubMed]
17. Xiao, X.; Chen, B. A Direct Observation of the Fine Aromatic Clusters and Molecular Structures of Biochars. *Environ. Sci. Technol.* **2017**, *51*, 5473–5482. [CrossRef] [PubMed]
18. Zhang, Y.; Wang, J.; Feng, Y. The effects of biochar addition on soil physicochemical properties: A review. *Catena* **2021**, *202*, 105284. [CrossRef]
19. Azzi, E.S.; Karltun, E.; Sundberg, C. Prospective Life Cycle Assessment of Large-Scale Biochar Production and Use for Negative Emissions in Stockholm. *Environ. Sci. Technol.* **2019**, *53*, 8466–8476. [CrossRef]
20. Xiao, X.; Chen, B.; Chen, Z.; Zhu, L.; Schnoor, J.L. Insight into Multiple and Multilevel Structures of Biochars and Their Potential Environmental Applications: A Critical Review. *Environ. Sci. Technol.* **2018**, *52*, 5027–5047. [CrossRef]
21. Tang, H.; Chen, M.; Wu, P.; Faheem, M.; Feng, Q.W.; Lee, X.Q.; Wang, S.S.; Wang, B. Engineered biochar effects on soil physicochemical properties and biota communities: A critical review. *Chemosphere* **2023**, *311*, 137025. [CrossRef]
22. Ji, M.Y.; Wang, X.X.; Usman, M.; Liu, F.H.; Dan, Y.T.; Zhou, L.; Campanaro, S.; Luo, G.; Sang, W.J. Effects of different feedstocks-based biochar on soil remediation: A review. *Environ. Pollut.* **2022**, *294*, 118655. [CrossRef]
23. Kamali, M.; Sweygers, N.; Al-Salem, S.; Appels, L.; Aminabhavi, T.M.; Dewil, R. Biochar for soil applications-sustainability aspects, challenges and future prospects. *Chem. Eng. J.* **2022**, *428*, 131189. [CrossRef]
24. Riaz, M.; Roohi, M.; Arif, M.S.; Hussain, Q.; Yasmeen, T.; Shahzad, T.; Shahzad, S.M.; Muhammad, H.F.; Arif, M.; Khalid, M. Corncob-derived biochar decelerates mineralization of native and added organic matter (AOM) in organic matter depleted alkaline soil. *Geoderma* **2017**, *294*, 19–28. [CrossRef]
25. Singh, B.P.; Cowie, A.L.; Smernik, R.J. Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. *Environ. Sci. Technol.* **2012**, *46*, 11770–11778. [CrossRef] [PubMed]
26. Nelissen, V.; Rütting, T.; Huygens, D.; Staelens, J.; Ruysschaert, G.; Boeckx, P. Maize biochars accelerate short-term soil nitrogen dynamics in a loamy sand soil. *Soil Biol. Biochem.* **2012**, *55*, 20–27. [CrossRef]
27. Karim, A.A.; Kumar, M.; Singh, E.; Kumar, A.; Kumar, S.; Ray, A.; Dhal, N.K. Enrichment of primary macronutrients in biochar for sustainable agriculture: A review. *Crit. Rev. Environ. Sci. Technol.* **2022**, *59*, 1449–1490. [CrossRef]
28. Liu, Y.Y.; Tian, Z.X.; Gong, H.B.; Huang, Q.Y. Migration and transformation mechanisms of nutrient elements (N, P, K) within biochar in straw-biochar-soil-plant systems: A review. *ACS Sustain. Chem. Eng.* **2019**, *7*, 22–32. [CrossRef]
29. Kaal, J.; Schneider, M.P.W.; Schmidt, M.W.I. Rapid molecular screening of black carbon (biochar) thermosequences obtained from chestnut wood and rice straw: A pyrolysis-GC/MS study. *Biomass Bioenergy* **2012**, *45*, 115–129. [CrossRef]
30. Guo, J.; Chen, B. Insights on the Molecular Mechanism for the Recalcitrance of Biochars: Interactive Effects of Carbon and Silicon Components. *Environ. Sci. Technol.* **2014**, *48*, 9103–9112. [CrossRef]
31. Ilyas, M.; Arif, M.; Akhtar, K.; Riaz, M.; Wang, H.Y. Diverse feedstock's biochars as supplementary K fertilizer improves maize productivity, soil organic C and KUE under semiarid climate. *Soil Tillage Res.* **2021**, *211*, 105015. [CrossRef]
32. Wang, Y.; Lin, Y.; Chiu, P.C.; Imhoff, P.T.; Guo, M. Phosphorus release behaviors of poultry litter biochar as a soil amendment. *Sci. Total Environ.* **2015**, *512–513*, 454–463. [CrossRef]
33. Xing, J.; Xu, G.; Li, G. Comparison of pyrolysis process, various fractions and potential soil applications between sewage sludge-based biochars and lignocellulose-based biochars. *Ecotoxicol. Environ. Saf.* **2021**, *208*, 111756. [CrossRef]
34. Kim, H.-B.; Kim, S.-H.; Jeon, E.-K.; Kim, D.-H.; Tsang, D.C.W.; Alessi, D.S.; Kwon, E.E.; Baek, K. Effect of dissolved organic carbon from sludge, Rice straw and spent coffee ground biochar on the mobility of arsenic in soil. *Sci. Total Environ.* **2018**, *636*, 1241–1248. [CrossRef] [PubMed]

35. Zhu, L.; Zhang, Y.; Lei, H.; Zhang, X.; Wang, L.; Bu, Q.; Wei, Y. Production of hydrocarbons from biomass-derived biochar assisted microwave catalytic pyrolysis. *Sustain. Energy Fuels* **2018**, *2*, 1781–1790. [CrossRef]
36. Jin, Y.; Liang, X.Q.; He, M.M.; Liu, Y.; Tian, G.M.; Shi, J.Y. Manure biochar influence upon soil properties, phosphorus distri-bution and phosphatase activities: A microcosm incubation study. *Chemosphere* **2016**, *142*, 128–135. [CrossRef]
37. Chan, K.Y.; Xu, Z.H. Biochar: Nutrient Properties and Their Enhancement. In *Biochar for Environmental Management*, 1st ed.; Lehmann, J., Joseph, S., Eds.; Routledge: London, UK, 2009; p. 18.
38. Shi, R.-Y.; Li, J.-Y.; NI, N.; Xu, R.-K. Understanding the biochar's role in ameliorating soil acidity. *J. Integr. Agric.* **2019**, *18*, 1508–1517. [CrossRef]
39. Banik, C.; Lawrinenko, M.; Bakshi, S.; Laird, D.A. Impact of pyrolysis temperature and feedstock on surface charge and functional group chemistry of biochars. *J. Environ. Qual.* **2018**, *47*, 452–461. [CrossRef] [PubMed]
40. Ma, Z.; Yang, Y.; Ma, Q.; Zhou, H.; Luo, X.; Liu, X.; Wang, S. Evolution of the chemical composition, functional group, pore structure and crystallographic structure of biochar from palm kernel shell pyrolysis under different temperatures. *J. Anal. Appl. Pyrolysis* **2017**, *127*, 350–359. [CrossRef]
41. Leng, L.; Xu, S.; Liu, R.; Yu, T.; Zhuo, X.; Leng, S.; Xiong, Q.; Huang, H. Nitrogen containing functional groups of biochar: An overview. *Bioresour. Technol.* **2020**, *298*, 122286. [CrossRef]
42. Janu, R.; Mrlik, V.; Ribitsch, D.; Hofman, J.; Sedláček, P.; Bielská, L.; Soja, G. Biochar surface functional groups as affected by biomass feedstock, biochar composition and pyrolysis temperature. *Carbon Resour. Convers.* **2021**, *4*, 36–46. [CrossRef]
43. Singh, B.; Dolk, M.M.; Shen, Q.H.; Arbestain, M.C. Biochar pH, Electrical Conductivity and Liming Potential. In *A Guide to Analytical Methods*; Singh, B., Camps-Arbestain, M., Lehmann, J., Eds.; CSIRO: Victoria, UK, 2017; pp. 23–38.
44. Li, H.; Meng, J.; Liu, Z.Q.; Lan, Y.; Yang, X.; Huang, Y.W.; He, T.Y.; Chen, W.F. Effects of biochar on N_2O emission in denitrification pathway from paddy soil: A drying incubation study. *Sci. Total Environ.* **2021**, *787*, 147591. [CrossRef]
45. Tsadik, Y.K.G.; Hailu, A.M.; Asfaw, S.L.; Mekonnen, Y.S. The effect of brewery sludge biochar on immobilization of bio-available cadmium and growth of *Brassica carinata*. *Heliyon* **2020**, *6*, e05573. [CrossRef]
46. Ghodszad, L.; Reyhanitabar, A.; Oustan, S.; Alidokht, L. Phosphorus sorption and desorption characteristics of soils as affected by biochar. *Soil Tillage Res.* **2022**, *216*, 105251. [CrossRef]
47. Gul, S.; Whalen, J.K.; Thomas, B.W.; Sachdeva, V.; Deng, H.Y. Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. *Agric. Ecosyst. Environ.* **2015**, *206*, 46–59. [CrossRef]
48. Novak, J.M.; Busscher, W.J.; Laird, D.L.; Ahmedna, M.; Watts, D.W.; Niandou, M.A.S. Impact of Biochar Amendment on Fertility of a Southeastern Coastal Plain Soil. *Soil Sci.* **2009**, *174*, 105–112. [CrossRef]
49. Van Zwieten, L.; Kimber, S.; Morris, S.; Chan, K.Y.; Downie, A.; Rust, J.; Joseph, S.; Cowie, A. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant Soil* **2010**, *327*, 235–246. [CrossRef]
50. Rouphael, Y.; Rea, E.; Cardarelli, M.; Bitterlich, M.; Schwarz, D.; Colla, G. Can adverse effects of acidity and aluminum toxicity be alleviated by appropriate rootstock selection in cucumber? *Front. Plant Sci.* **2016**, *7*, 1283. [CrossRef]
51. Dai, Z.; Zhang, X.; Tang, C.; Muhammad, N.; Wu, J.; Brookes, P.C.; Xu, J. Potential role of biochars in decreasing soil acidification—A critical review. *Sci. Total Environ.* **2017**, *581–582*, 601–611. [CrossRef]
52. Jeffery, S.; Verheijen, F.G.A.; van der Velde, M.; Bastos, A.C. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agric. Ecosyst. Environ.* **2011**, *144*, 175–187. [CrossRef]
53. Brennan, A.; Jiménez, E.M.; Puschenreiter, M.; Alburquerque, J.A.; Switzer, C. Effects of biochar amendment on root traits and contaminant availability of maize plants in a copper and arsenic impacted soil. *Plant Soil* **2014**, *379*, 351–360. [CrossRef]
54. Brewer, C.E.; Hu, Y.-Y.; Schmidt-Rohr, K.; Loynachan, T.E.; Laird, D.A.; Brown, R.C. Extent of Pyrolysis Impacts on Fast Pyrolysis Biochar Properties. *J. Environ. Qual.* **2012**, *41*, 1115–1122. [CrossRef]
55. Enders, A.; Hanley, K.; Whitman, T.; Joseph, S.; Lehmann, J. Characterization of biochars to evaluate recalcitrance and agronomic performance. *Bioresour. Technol.* **2012**, *114*, 644–653. [CrossRef]
56. Xu, R.-K.; Zhao, A.-Z.; Yuan, J.-H.; Jiang, J. pH buffering capacity of acid soils from tropical and subtropical regions of China as influenced by incorporation of crop straw biochars. *J. Soils Sediments* **2012**, *12*, 494–502. [CrossRef]
57. Palladino, M.; Romano, N.; Pasolli, E.; Nasta, P. Developing pedotransfer functions for predicting soil bulk density in Campania. *Geoderma* **2022**, *412*, 115726. [CrossRef]
58. Rombolà, A.G.; Fabbri, D.; Baronti, S.; Vaccari, F.P.; Genesio, L.; Miglietta, F. Changes in the pattern of polycyclic aromatic hydrocarbons in soil treated with biochar from a multiyear field experiment. *Chemosphere* **2019**, *219*, 662–670. [CrossRef]
59. Khan, I.; Chen, T.; Farooq, M.; Luan, C.; Wu, Q.; Wanning, D.; Xu, S.; Li-Xue, W. The residual impact of straw mulch and biochar amendments on soil physiochemical properties and yield of maize under rainfed system. *Agron. J.* **2021**, *113*, 1102–1120. [CrossRef]
60. Razzaghi, F.; Obour, P.B.; Arthur, E. Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma* **2020**, *361*, 114055. [CrossRef]
61. Oladele, S.; Adeyemo, A.; Awodun, M.; Ajayi, A.; Fasina, A. Effects of biochar and nitrogen fertilizer on soil physicochemical properties, nitrogen use efficiency and upland rice (*Oryza sativa*) yield grown on an Alfisol in Southwestern Nigeria. *Int. J. Recycl. Org. Waste Agric.* **2019**, *8*, 295–308. [CrossRef]
62. Hussaina, R.K.; Ravia, K.; Ankit, G. Influence of biochar on the soil water retention characteristics (SWRC): Potential application in geotechnical engineering structures. *Soil Tillage Res.* **2020**, *204*, 104713. [CrossRef]

63. Xu, G.; Zhang, Y.; Sun, J.; Shao, H. Negative interactive effects between biochar and phosphorus fertilization on phosphorus availability and plant yield in saline sodic soil. *Sci. Total Environ.* **2016**, *568*, 910–915. [CrossRef]
64. Liang, B.; Lehmann, J.; Solomon, D.; Kinyangi, J.; Grossman, J.; O'Neill, B.; Skjemstad, J.O.; Thies, J.; Luizão, F.J.; Petersen, J.; et al. Black Carbon Increases Cation Exchange Capacity in Soils. *Soil Sci. Soc. Am. J.* **2006**, *70*, 1719–1730. [CrossRef]
65. Hossain, M.K.; Strezov, V.; Chan, K.Y.; Nelson, P.F. Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (Lycopersicon esculentum). *Chemosphere* **2010**, *78*, 1167–1171. [CrossRef]
66. 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.; et al. Molecular characterization of biochars and their influence on microbiological properties of soil. *J. Hazard. Mater.* **2014**, *279*, 244–256. [CrossRef] [PubMed]
67. Sinsabaugh, R.L.; Lauber, C.L.; Weintraub, M.N.; Ahmed, B.; Allison, S.D.; Crenshaw, C.; Contosta, A.R.; Cusack, D.; Frey, S.; Gallo, M.E.; et al. Stoichiometry of soil enzyme activity at global scale. *Ecol. Lett.* **2008**, *11*, 1252–1264. [CrossRef] [PubMed]
68. Mao, Q.; Hu, B.; Agathokleous, E.; Wang, L.; Koike, T.; Ma, M.; Rennenberg, H. Biochar application improves karstic lime soil physicochemical properties and enzymes activity and enhances sweet tea seedlings physiological performance. *Sci. Total Environ.* **2022**, *830*, 154815. [CrossRef] [PubMed]
69. Pandey, V.; Patel, A.; Patra, D.D. Biochar ameliorates crop productivity, soil fertility, essential oil yield and aroma profiling in basil (*Ocimum basilicum* L.). *Ecol. Eng.* **2016**, *90*, 361–366. [CrossRef]
70. Jia, W.; Wang, B.; Wang, C.; Sun, H. Tourmaline and biochar for the remediation of acid soil polluted with heavy metals. *J. Environ. Chem. Eng.* **2017**, *5*, 2107–2114. [CrossRef]
71. Pandey, B.; Suthar, S.; Chand, N. Effect of biochar amendment on metal mobility, phytotoxicity, soil enzymes, and met-al-uptakes by wheat (*Triticum aestivum*) in contaminated soils. *Chemosphere* **2022**, *307*, 135889. [CrossRef]
72. Song, X.; Li, H.; Song, J.; Chen, W.; Shi, L. Biochar/vermicompost promotes Hybrid Pennisetum plant growth and soil enzyme activity in saline soils. *Plant Physiol. Biochem.* **2022**, *183*, 96–110. [CrossRef]
73. Liao, X.; Kang, H.; Haidar, G.; Wang, W.; Malghani, S. The impact of biochar on the activities of soil nutrients acquisition enzymes is potentially controlled by the pyrolysis temperature: A meta-analysis. *Geoderma* **2022**, *411*, 115692. [CrossRef]
74. Ibrahim, M.; Li, G.; Tang, Y.-T. Biochar effects acidic soil remediation and *Brassica oleracea* L. toxicity—A case study in subtropical area of China. *Environ. Technol. Innov.* **2021**, *23*, 101588. [CrossRef]
75. Wang, D.Y.; Fonte, S.J.; Parikh, S.J.; Six, J.; Scow, K.M. Biochar additions can enhance soil structure and the physical stabilization of C in aggregates. *Geoderma* **2017**, *303*, 110–117. [CrossRef]
76. Akolgo, G.A.; Kemausuor, F.; Awafo, E.A.; Amankwah, E.; Atta-Darkwa, T.; Essandoh, E.O.; Bart-Plange, A.; Branco de Freitas Maia, C.M. Biochar as a Soil Amendment Tool: Effects on Soil Properties and Yield of Maize and Cabbage in Brong-Ahafo Region, Ghana. *Open J. Soil Sci.* **2020**, *10*, 91–108. [CrossRef]
77. El-Naggar, A.; El-Naggar, A.H.; Shaheen, S.M.; Sarkar, B.; Chang, S.X.; Tsang, D.C.W.; Rinklebe, J.; Ok, Y.S. Biochar composition-dependent impacts on soil nutrient release, carbon mineralization, and potential environmental risk: A review. *J. Environ. Manag.* **2019**, *241*, 458–467. [CrossRef]
78. Keiluweit, M.; Nico, P.S.; Johnson, M.G.; Kleber, M. Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environ. Sci. Technol.* **2010**, *44*, 1247–1253. [CrossRef]
79. Han, L.; Sun, K.; Yang, Y.; Xia, X.; Li, F.; Yang, Z.; Xing, B. Biochar's stability and effect on the content, composition and turnover of soil organic carbon. *Geoderma* **2020**, *364*, 114184. [CrossRef]
80. Chagas, J.K.M.; de Figueiredo, C.C.; Ramos, M.L.G. Biochar increases soil carbon pools: Evidence from a global meta-analysis. *J. Environ. Manag.* **2022**, *305*, 114403. [CrossRef]
81. Yin, Y.-F.; He, X.-H.; Gao, R.; Ma, H.-L.; Yang, Y.-S. Effects of Rice Straw and Its Biochar Addition on Soil Labile Carbon and Soil Organic Carbon. *J. Integr. Agric.* **2014**, *13*, 491–498. [CrossRef]
82. Yan, S.; Liu, G. Effect of increasing soil carbon content on tobacco aroma and soil microorganisms. *Phytochem. Lett.* **2020**, *36*, 42–48. [CrossRef]
83. Liu, S.; Zhang, Y.; Zong, Y.; Hu, Z.; Wu, S.; Zhou, J.; Jin, Y.; Zou, J. Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: A meta-analysis. *GCB Bioenergy* **2016**, *8*, 392–406. [CrossRef]
84. Steiner, C.; Glaser, B.; Geraldes Teixeira, W.; Lehmann, J.; Blum, W.E.H.; Zech, W. Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. *J. Plant Nutr. Soil Sci.* **2008**, *171*, 893–899. [CrossRef]
85. Buurman, P.; Jongmans, A.G. Podzolisation and soil organic matter dynamics. *Geoderma* **2005**, *125*, 71–83. [CrossRef]
86. Cui, J.L.; Glatzel, S.; Bruckman, V.J.; Wang, B.Z.; Lai, D.Y.F. Long-term effects of biochar application on greenhouse gas production and microbial community in temperate forest soils under increasing temperature. *Sci. Total Environ.* **2021**, *767*, 145021. [CrossRef]
87. Yang, X.Y.; Chang, K.-H.; Kim, Y.J.; Zhang, J.; Yoo, G. Effects of different biochar amendments on carbon loss and leachate characterization from an agricultural soil. *Chemosphere* **2019**, *226*, 625–635. [CrossRef]
88. Hernandez-Soriano, M.C.; Kerré, B.; Kopittke, P.M.; Horemans, B.; Smolders, E. Biochar affects carbon composition and stability in soil: A combined spectroscopy-microscopy study. *Sci. Rep.* **2016**, *6*, 25127. [CrossRef]
89. Liu, C.; Wang, H.; Li, P.; Xian, Q.; Tang, X. Biochar's impact on dissolved organic matter (DOM) export from a cropland soil during natural rainfalls. *Sci. Total Environ.* **2019**, *650*, 1988–1995. [CrossRef]
90. Lang, T.; Jensen, A.D.; Jensen, P.A. Retention of Organic Elements during Solid Fuel Pyrolysis with Emphasis on the Peculiar Behavior of Nitrogen. *Energy Fuels* **2005**, *19*, 1631–1643. [CrossRef]

91. Cao, X.; Harris, W. Properties of dairy-manure-derived biochar pertinent to its potential use in remediation. *Bioresour. Technol.* **2010**, *101*, 5222–5228. [CrossRef]
92. Tian, S.; Tan, Z.; Kasiulienė, A.; Ai, P. Transformation mechanism of nutrient elements in the process of biochar preparation for returning biochar to soil. *Chin. J. Chem. Eng.* **2017**, *25*, 477–486. [CrossRef]
93. Yuan, S.; Tan, Z.; Huang, Q. Migration and transformation mechanism of nitrogen in the biomass–biochar–plant transport process. *Renew. Sustain. Energy Rev.* **2018**, *85*, 1–13. [CrossRef]
94. Azeem, M.; Hayat, R.; Hussain, Q.; Ahmed, M.; Pan, G.; Ibrahim, T.M. Biochar improves soil quality and N_2-fixation and reduces net ecosystem CO_2 exchange in a dryland legume-cereal cropping system. *Soil Tillage Res.* **2019**, *186*, 172–182. [CrossRef]
95. Thies, J.E.; Rillig, M.C.; Graber, E.R. Biochar Effects on the Abundance Activity and Diversity of the Soil Biota. In *Biochar for Environmental Management: Science, Technology and Implementation*, 2nd ed.; Lehmann, J., Stephen, J., Eds.; Routledge: London, UK, 2015; pp. 327–389.
96. Quilliam, R.S.; DeLuca, T.H.; Jones, D.L. Biochar application reduces nodulation but increases nitrogenase activity in clover. *Plant Soil* **2013**, *366*, 83–92. [CrossRef]
97. Xu, C.Y.; Bai, S.H.; Hao, Y.; Rachaputi, R.N.; Wang, H.; Xu, Z.; Wallace, H. Effect of biochar amendment on yield and photosynthesis of peanut on two types of soils. *Environ. Sci. Pollut. Res.* **2015**, *22*, 6112–6125. [CrossRef]
98. Wu, X.; Sun, Y.; Deng, L.; Meng, Q.; Jiang, X.; Bello, A.; Sheng, S.; Han, Y.; Zhu, H.; Xu, X. Insight to key diazotrophic community during composting of dairy manure with biochar and its role in nitrogen transformation. *Waste Manage.* **2020**, *105*, 190–197. [CrossRef]
99. Zhao, J.W.; Tao, Q.; Li, B.; Luo, J.P.; Zhang, H.Y.; Lu, C.L.; Li, Q.Q.; Xu, Q.; Huang, R.; Li, H.X.; et al. Low-pyrolysis-temperature biochar promoted free-living N_2-fixation in calcareous purple soil by affecting diazotrophic composition. *Geoderma* **2021**, *388*, 114969. [CrossRef]
100. Joseph, S.; Pow, D.; Dawson, K.; Mitchell, D.R.G.; Rawal, A.; Hook, J.; Taherymoosavi, S.; Van Zwieten, L.; Rust, J.; Donne, S.; et al. Feeding Biochar to Cows: An Innovative Solution for Improving Soil Fertility and Farm Productivity. *Pedosphere* **2015**, *25*, 666–679. [CrossRef]
101. Clough, T.J.; Condron, L.M.; Kammann, C.; Muller, C.W. A Review of Biochar and Soil Nitrogen Dynamics. *Agronomy* **2013**, *3*, 275–293. [CrossRef]
102. Chen, X.; Zhou, B.; Wang, Q.; Tao, W.; Lin, H. Nano-biochar reduced soil erosion and nitrate loss in sloping fields on the Loess Plateau of China. *Catena* **2020**, *187*, 104346. [CrossRef]
103. Cao, H.; Ning, L.; Xun, M.; Feng, F.; Li, P.; Yue, S.; Song, J.; Zhang, W.; Yang, H. Biochar can increase nitrogen use efficiency of Malus hupehensis by modulating nitrate reduction of soil and root. *Appl. Soil Ecol.* **2019**, *135*, 25–32. [CrossRef]
104. Yao, Y.; Gao, B.; Zhang, M.; Inyang, M.; Zimmerman, A.R. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere* **2012**, *89*, 1467–1471. [CrossRef]
105. Montes-Morán, M.A.; Suárez, D.; Menéndez, J.A.; Fuente, E. On the nature of basic sites on carbon surfaces: An overview. *Carbon* **2004**, *42*, 1219–1225. [CrossRef]
106. Ventura, M.; Sorrenti, G.; Panzacchi, P.; George, E.; Tonon, G. Biochar Reduces Short-Term Nitrate Leaching from A Horizon in an Apple Orchard. *J. Environ. Qual.* **2013**, *42*, 76–82. [CrossRef]
107. Kameyama, K.; Miyamoto, T.; Shiono, T.; Shinogi, Y. Influence of Sugarcane Bagasse-derived Biochar Application on Nitrate Leaching in Calcaric Dark Red Soil. *J. Environ. Qual.* **2012**, *41*, 1131–1137. [CrossRef] [PubMed]
108. Amonette, J.E.; Joseph, S. Characteristics of Biochar: Microchemical Properties. In *Biochar for Environmental Management: Science and Technology*, 1st ed.; Lehmann, J., Joseph, S., Eds.; Earthscan: London, UK, 2009; pp. 33–52.
109. Kammann, C.I.; Schmidt, H.-P.; Messerschmidt, N.; Linsel, S.; Steffens, D.; Müller, C.; Koyro, H.-W.; Conte, P.; Joseph, S. Plant growth improvement mediated by nitrate capture in co-composted biochar. *Sci. Rep.* **2015**, *5*, 11080. [CrossRef] [PubMed]
110. Lawrinenko, M. Anion Exchange Capacity of Biochar. Master's Thesis, Iowa State University, Ames, IA, USA, 2014.
111. Nguyen, T.T.N.; Xu, C.-Y.; Tahmasbian, I.; Che, R.; Xu, Z.; Zhou, X.; Wallace, H.M.; Bai, S.H. Effects of biochar on soil available inorganic nitrogen: A review and meta-analysis. *Geoderma* **2017**, *288*, 79–96. [CrossRef]
112. Zimmerman, A.R.; Gao, B.; Ahn, M.Y. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biol. Biochem.* **2011**, *43*, 1169–1179. [CrossRef]
113. Santachiara, G.; Salvagiotti, F.; Rotundo, J.L. Nutritional and environmental effects on biological nitrogen fixation in soybean: A meta-analysis. *Field Crops Res.* **2019**, *240*, 106–115. [CrossRef]
114. Reed, S.C.; Cleveland, C.C.; Townsend, A.R. Functional Ecology of Free-Living Nitrogen Fixation: A Contemporary Perspective. *Annu. Rev. Ecol. Evol. Syst.* **2011**, *42*, 489–512. [CrossRef]
115. Ahmad, Z.; Mosa, A.; Zhang, L.; Gao, B. Biochar modulates mineral nitrogen dynamics in soil and terrestrial ecosystems: A critical review. *Chemosphere* **2021**, *278*, 130378. [CrossRef]
116. Ajeng, A.A.; Abdullah, R.; Ling, T.C.; Ismail, S.; Lau, B.F.; Ong, H.C.; Chew, K.W.; Show, P.L.; Chang, J.-S. Bioformulation of biochar as a potential inoculant carrier for sustainable agriculture. *Environ. Technol. Innov.* **2020**, *20*, 101168. [CrossRef]
117. Biederman, L.A.; Harpole, W.S. Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenergy* **2013**, *5*, 202–214. [CrossRef]
118. Horel, A.; Potyó, I.; Szili-Kovács, T.; Molnár, S. Potential nitrogen fixation changes under different land uses as influenced by seasons and biochar amendments. *Arab. J. Geosci.* **2018**, *11*, 1–10. [CrossRef]

119. Anderson, C.R.; Condron, L.M.; Clough, T.J.; Fiers, M.; Stewart, A.; Hill, R.A.; Sherlock, R.R. Biochar induced soil microbial community change: Implications for biogeochemical cycling of carbon, nitrogen and phosphorus. *Pedobiologia* **2011**, *54*, 309–320. [CrossRef]
120. Rondon, M.; Lehmann, J.; Ramírez, J.; Hurtado, M. Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) in-creases with biochar additions. *Biol. Fertil. Soils* **2007**, *43*, 699–708. [CrossRef]
121. Li, D.; Zhang, Q.; Xiao, K.; Wang, Z.; Wang, K. Divergent responses of biological nitrogen fixation in soil, litter and moss to temperature and moisture in a karst forest, southwest China. *Soil Biol. Biochem.* **2018**, *118*, 1–7. [CrossRef]
122. Yuan, D.; Wang, G.Q.; Hu, C.S.; Zhou, S.G.; Clough, T.J.; Wrage-Mönnig, N.; Luo, J.F.; Qin, S.P. Electron shuttle potential of biochar promotes dissimilatory nitrate reduction to ammonium in paddy soil. *Soil Biol. Biochem.* **2022**, *172*, 108760. [CrossRef]
123. Zhao, Y.; Bu, C.; Yang, H.; Qiao, Z.; Ding, S.; Ni, S.-Q. Survey of dissimilatory nitrate reduction to ammonium microbial community at national wetland of Shanghai, China. *Chemosphere* **2020**, *250*, 126195. [CrossRef] [PubMed]
124. Sathishkumar, K.; Li, Y.; Sanganyado, E. Electrochemical behavior of biochar and its effects on microbial nitrate reduction: Role of extracellular polymeric substances in extracellular electron transfer. *Chem. Eng. J.* **2020**, *395*, 125077. [CrossRef]
125. Wang, T.; Camps-Arbestain, M.; Hedley, M.; Bishop, P. Predicting phosphorus bioavailability from high-ash biochars. *Plant Soil* **2012**, *357*, 173–187. [CrossRef]
126. Zhang, H.; Chen, C.; Gray, E.M.; Boyd, S.E.; Yang, H.; Zhang, D. Roles of biochar in improving phosphorus availability in soils: A phosphate adsorbent and a source of available phosphorus. *Geoderma* **2016**, *276*, 1–6. [CrossRef]
127. Li, F.; Liang, X.; Niyungeko, C.; Sun, T.; Liu, F.; Arai, Y. Effects of biochar amendments on soil phosphorus transformation in agricultural soils. *Adv. Agron.* **2019**, *158*, 131–172. [CrossRef]
128. Qian, T.; Zhang, X.; Hu, J.; Jiang, H. Effects of environmental conditions on the release of phosphorus from biochar. *Chemosphere* **2013**, *93*, 2069–2075. [CrossRef]
129. Liang, Y.; Cao, X.; Zhao, L.; Xu, X.; Harris, W. Phosphorus Release from Dairy Manure, the Manure-Derived Biochar, and Their Amended Soil: Effects of Phosphorus Nature and Soil Property. *J. Environ. Qual.* **2014**, *43*, 1504–1509. [CrossRef]
130. He, H.; Qian, T.-T.; Liu, W.-J.; Jiang, H.; Yu, H.-Q. Biological and chemical phosphorus solubilization from pyrolytical biochar in aqueous solution. *Chemosphere* **2014**, *113*, 175–181. [CrossRef]
131. Qian, T.; Yang, Q.; Jun, D.C.F.; Dong, F.; Zhou, Y. Transformation of phosphorus in sewage sludge biochar mediated by a phosphate-solubilizing microorganism. *Chem. Eng. J.* **2018**, *359*, 1573–1580. [CrossRef]
132. Xu, G.; Sun, J.; Shao, H.; Chang, S.X. Biochar had effects on phosphorus sorption and desorption in three soils with differing acidity. *Ecol. Eng.* **2014**, *62*, 54–60. [CrossRef]
133. Pastore, G.; Kernchen, S.; Spohn, M. Microbial solubilization of silicon and phosphorus from bedrock in relation to abundance of phosphorus-solubilizing bacteria in temperate forest soils. *Soil Biol. Biochem.* **2020**, *151*, 108050. [CrossRef]
134. Pradhan, A.; Pahari, A.; Mohapatra, S.; Mishra, B.B. Phosphate-Solubilizing Microorganisms in Sustainable Agriculture: Genetic Mechanism and Application. In *Advances in Soil Microbiology: Recent Trends and Future Prospects*; Adhya, T., Mishra, B., Annapurna, K., Verma, D., Kumar, U., Eds.; Springer Singapore: Singapore, 2017; pp. 81–97.
135. Jaafar, N.M.; Clode, P.L.; Abbott, L.K. Soil Microbial Responses to Biochars Varying in Particle Size, Surface and Pore Properties. *Pedosphere* **2015**, *25*, 770–780. [CrossRef]
136. Zheng, B.-X.; Ding, K.; Yang, X.-R.; Wadaan, M.A.M.; Hozzein, W.N.; Peñuelas, J.; Zhu, Y.-G. Straw biochar increases the abundance of inorganic phosphate solubilizing bacterial community for better rape (Brassica napus) growth and phosphate uptake. *Sci. Total Environ.* **2019**, *647*, 1113–1120. [CrossRef]
137. Zwetsloot, M.J.; Lehmann, J.; Bauerle, T.; Vanek, S.; Hestrin, R.; Nigussie, A. Phosphorus availability from bone char in a P-fixing soil influenced by root-mycorrhizae-biochar interactions. *Plant Soil* **2016**, *408*, 95–105. [CrossRef]
138. Chen, Q.; Qin, J.; Cheng, Z.; Huang, L.; Sun, P.; Chen, L.; Shen, G. Synthesis of a stable magnesium-impregnated biochar and its reduction of phosphorus leaching from soil. *Chemosphere* **2018**, *199*, 402–408. [CrossRef]
139. Yuan, H.; Lu, T.; Wang, Y.; Chen, Y.; Lei, T. Sewage sludge biochar: Nutrient composition and its effect on the leaching of soil nutrients. *Geoderma* **2016**, *267*, 17–23. [CrossRef]
140. Peng, Y.; Sun, Y.; Fan, B.; Zhang, S.; Bolan, N.S.; Chen, Q.; Tsang, D.C. Fe/Al (hydr)oxides engineered biochar for reducing phosphorus leaching from a fertile calcareous soil. *J. Clean. Prod.* **2021**, *279*, 123877. [CrossRef]
141. Sachdeva, V.; Hussain, N.; Husk, B.R.; Whalen, J.K. Biochar-induced soil stability influences phosphorus retention in a temperate agricultural soil. *Geoderma* **2019**, *351*, 71–75. [CrossRef]
142. Ghodszad, L.; Reyhanitabar, A.; Maghsoodi, M.R.; Lajayer, B.A.; Chang, S.X. Biochar affects the fate of phosphorus in soil and water: A critical review. *Chemosphere* **2021**, *283*, 131176. [CrossRef]
143. Yang, L.; Wu, Y.; Wang, Y.; An, W.; Jin, J.; Sun, K.; Wang, X. Effects of biochar addition on the abundance, speciation, availability, and leaching loss of soil phosphorus. *Sci. Total Environ.* **2021**, *758*, 143657. [CrossRef]
144. Rezaeian, M.; Petroudi, E.R.; Mohseni, M.; Haddadi, M.H. Effects of row spacing, nitrogen and potassium fertilizer on yield of silage corn after wheat harvesting. *Int. J. Plant Anim. Eviron. Sci.* **2014**, *4*, 358–361.
145. Li, Z.; Liu, Z.; Zhang, M.; Li, C.; Li, Y.C.; Wan, Y.; Martin, C.G. Long-term effects of controlled-release potassium chloride on soil available potassium, nutrient absorption and yield of maize plants. *Soil Tillage Res.* **2020**, *196*, 104438. [CrossRef]

146. Zhang, M.Y.; Riaz, M.; Xia, H.; Li, Y.X.; Wang, X.L.; Jiang, C.C. Four-year biochar study: Positive response of acidic soil microenvironment and citrus growth to biochar under potassium deficiency conditions. *Sci. Total Environ.* **2022**, *813*, 152515. [CrossRef]
147. Xia, H.; Riaz, M.; Liu, B.; Li, Y.; El-Desouki, Z.; Jiang, C. Over two years study: Peanut biochar promoted potassium availability by mediating the relationship between bacterial community and soil properties. *Appl. Soil Ecol.* **2022**, *176*, 104485. [CrossRef]
148. Salo, K.; Mojtahedi, W. Fate of alkali and trace metals in biomass gasification. *Biomass Bioenergy* **1998**, *15*, 263–267. [CrossRef]
149. Orama, N.J.; van de Voorde, T.F.J.; Ouwehand, G.J.; Bezemer, T.M.; Mommer, L.; Jeffery, S.; Groenigena, J.W.V. Soil amendment with biochar increases the competitive ability of legumes via increased potassium availability. *Agric. Ecosyst. Environ.* **2014**, *191*, 92–98. [CrossRef]
150. Amin, A.E.-E.A.Z. Impact of Corn Cob Biochar on Potassium Status and Wheat Growth in a Calcareous Sandy Soil. *Commun. Soil Sci. Plant Anal.* **2016**, *47*, 2026–2033. [CrossRef]
151. Gaskin, J.W.; Steiner, C.; Harris, K.; Das, K.C.; Biben, B. Effect of low-temperature pyrolysis conditions on biochar for agricultural use. *Trans. ASABE* **2008**, *51*, 2061–2069. [CrossRef]
152. Gaskin, J.W.; Speir, R.A.; Harris, K.; Das, K.C.; Lee, R.D.; Morris, L.A.; Fisher, D.S. Effect of Peanut Hull and Pine Chip Biochar on Soil Nutrients, Corn Nutrient Status, and Yield. *Agron. J.* **2010**, *102*, 623–633. [CrossRef]
153. Limwikran, T.; Kheoruenromne, I.; Suddhiprakarn, A.; Prakongkep, N.; Gilkes, R.J. Dissolution of K, Ca, and P from biochar grains in tropical soils. *Geoderma* **2018**, *312*, 139–150. [CrossRef]
154. Chi, J.L.; Ge, Y.H. Study on potassium releasing activity of silicate bacteria. *J. Microbiol.* **1999**, *2*, 43–51.
155. Zhang, W.L.; Li, G.H.; Gao, W.D. Effect of biomass charcoal on soil character and crop yield. *Chin. Sci. Bull.* **2009**, *25*, 153–157.
156. Jílková, V.; Angst, G. Biochar and compost amendments to a coarse-textured temperate agricultural soil lead to nutrient leaching. *Appl. Soil Ecol.* **2022**, *173*, 104393. [CrossRef]
157. Quilliam, R.S.; Marsden, K.A.; Gertler, C.; Rousk, J.; DeLuca, T.H.; Jones, D.L. Nutrient dynamics, microbial growth and weed emergence in biochar amended soil are influenced by time since application and reapplication rate. *Agric. Ecosyst. Environ.* **2012**, *158*, 192–199. [CrossRef]
158. Hilber, I.; Bastos, A.C.; Loureiro, S.; Soja, G.; Marsz, A.; Cornelissen, G.; Bucheli, T.D. The different faces of biochar: Contamination risk versus remediation tool. *J. Environ. Eng. Landsc. Manag.* **2017**, *25*, 86–104. [CrossRef]
159. Xing, J.; Li, L.C.; Li, G.B.; Xu, G.R. Feasibility of sludge-based biochar for soil remediation: Characteristics and safety performance of heavy metals influenced by pyrolysis temperatures. *Ecotoxicol. Environ. Saf.* **2019**, *180*, 457–465. [CrossRef]
160. 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. Quantifying the Total and Bioavailable Polycyclic Aromatic Hydrocarbons and Dioxins in Biochars. *Environ. Sci. Technol.* **2012**, *46*, 2830–2838. [CrossRef]
161. Lyu, H.; He, Y.; Tang, J.; Hecker, M.; Liu, Q.; Jones, P.D.; Codling, G.; Giesy, J.P. Effect of pyrolysis temperature on potential toxicity of biochar if applied to the environment. *Environ. Pollut.* **2016**, *218*, 1–7. [CrossRef]
162. Buss, W.; Masek, O.; Graham, M.; Wüstc, D. Inherent organic compounds in biochar-Their content, composition and potential toxic effects. *J. Environ. Manag.* **2015**, *156*, 150–157. [CrossRef]
163. Luo, J.; Lin, L.; Liu, C.; Jia, C.; Chen, T.; Yang, Y.; Shen, M.; Shang, H.; Zhou, S.; Huang, M.; et al. Reveal a hidden highly toxic substance in biochar to support its effective elimination strategy. *J. Hazard. Mater.* **2020**, *399*, 123055. [CrossRef]
164. Wang, X.; Li, C.; Li, Z.; Yu, G.; Wang, Y. Effect of pyrolysis temperature on characteristics, chemical speciation and risk evaluation of heavy metals in biochar derived from textile dyeing sludge. *Ecotoxicol. Environ. Saf.* **2019**, *168*, 45–52. [CrossRef]
165. Shen, X.; Zeng, J.; Zhang, D.; Wang, F.; Li, Y.; Yi, W. Effect of pyrolysis temperature on characteristics, chemical speciation and environmental risk of Cr, Mn, Cu, and Zn in biochars derived from pig manure. *Sci. Total Environ.* **2020**, *704*, 135283. [CrossRef]
166. Sørmo, E.; Silvani, L.; Thune, G.; Gerber, H.; Schmidt, H.P.; Smebye, A.B.; Cornelissen, G. Waste timber pyrolysis in a medium-scale unit: Emission budgets and biochar quality. *Sci. Total Environ.* **2020**, *718*, 137335. [CrossRef]
167. Godlewska, P.; Ok, Y.S.; Oleszczuk, P. The dark side of black gold: Ecotoxicological aspects of biochar and biochar-amended soils. *J. Hazard. Mater.* **2021**, *403*, 123833. [CrossRef]
168. Kończak, M.; Gao, Y.Z.; Oleszczuk, P. Carbon dioxide as a carrier gas and biomass addition decrease the total and bioavailable polycyclic aromatic hydrocarbons in biochar produced from sewage sludge. *Chemosphere* **2019**, *228*, 26–34. [CrossRef]
169. Tomczyk, B.; Siatecka, A.; Bogusz, A.; Oleszczuk, P. Ecotoxicological assessment of sewage sludge-derived biochars-amended soil. *Environ. Pollut.* **2021**, *275*, 116484. [CrossRef]
170. Zhao, L.; Zhao, Y.H.; Nan, H.Y.; Yang, F.; Qiu, H.; Xu, X.Y.; Cao, X.D. Suppressed formation of polycyclic aromatic hydro-carbons (PAHs) during pyrolytic production of Fe-enriched composite biochar. *J. Hazard. Mater.* **2020**, *382*, 121033. [CrossRef]
171. Devi, P.; Saroha, A.K. Effect of pyrolysis temperature on polycyclic aromatic hydrocarbons toxicity and sorption behaviour of biochars prepared by pyrolysis of paper mill effluent treatment plant sludge. *Bioresour. Technol.* **2015**, *192*, 312–320. [CrossRef]
172. Chen, X.; Yang, L.; Myneni, S.C.B.; Deng, Y. Leaching of polycyclic aromatic hydrocarbons (PAHs) from sewage sludge-derived biochar. *Chem. Eng. J.* **2019**, *373*, 840–845. [CrossRef]
173. Anjum, R.; Krakat, N.; Reza, M.T.; Klocke, M. Assessment of mutagenic potential of pyrolysis biochars by Ames Salmonella/mammalian-microsomal mutagenicity test. *Ecotoxicol. Environ. Saf.* **2014**, *107*, 306–312. [CrossRef]
174. Meng, J.; Wang, L.; Zhong, L.; Liu, X.; Brookes, P.C.; Xu, J.; Chen, H. Contrasting effects of composting and pyrolysis on bioavailability and speciation of Cu and Zn in pig manure. *Chemosphere* **2017**, *180*, 93–99. [CrossRef]

175. Amoakwah, E.; Arthur, E.; Frimpong, K.A.; Lorenz, F.N.; Rahman, M.A.; Nziguheba, G.; Islam, K.R. Biochar amendment impacts on microbial community structures and biological and enzyme activities in a weathered tropical sandy loam. *Appl. Soil Ecol.* **2022**, *172*, 104364. [CrossRef]
176. Ren, T.; Feng, H.; Xu, C.; Xu, Q.; Fu, B.; Azwar, E.; Wei, Y.; Lam, S.S.; Liu, G. Exogenous application and interaction of biochar with environmental factors for improving functional diversity of rhizosphere's microbial community and health. *Chemosphere* **2022**, *294*, 133710. [CrossRef]
177. Andrés, P.; Rosell-Melé, A.; Colomer-Ventura, F.; Denef, K.; Cotrufo, M.F.; Riba, M.; Alcañiz, J.M. Belowground biota re-sponses to maize biochar addition to the soil of a Mediterranean vineyard. *Sci. Total Environ.* **2019**, *660*, 1522–1532. [CrossRef]
178. Li, Q.; Lei, Z.; Song, X.; Zhang, Z.; Ying, Y.; Peng, C. Biochar amendment decreases soil microbial biomass and increases bacterial diversity in Moso bamboo (*Phyllostachys edulis*) plantations under simulated nitrogen deposition. *Environ. Res. Lett.* **2018**, *13*, 044029. [CrossRef]
179. Nan, Q.; Hu, S.; Qin, Y.; Wu, W. Methane oxidation activity inhibition via high amount aged biochar application in paddy soil. *Sci. Total Environ.* **2021**, *796*, 149050. [CrossRef]
180. Han, Y.X.; Douds, D.D., Jr.; Boateng, A.A. Effect of biochar soil-amendments on Allium porrum growth and Arbuscular mycorrhizal fungus colonization. *J. Plant Nutr.* **2015**, *39*, 1654–1662. [CrossRef]
181. Stefaniuk, M.; Oleszczuk, P.; Bartmiński, P. Chemical and ecotoxicological evaluation of biochar produced from residues of biogas production. *J. Hazard. Mater.* **2016**, *318*, 417–424. [CrossRef]
182. Anyanwu, I.N.; Alo, M.N.; Onyekwere, A.M.; Crosse, J.D.; Nworie, O.; Chamba, E.B. Influence of biochar aged in acidic soil on ecosystem engineers and two tropical agricultural plants. *Ecotoxicol. Environ. Saf.* **2018**, *153*, 116–126. [CrossRef]
183. Zhang, F.; Zhang, G.; Liao, X. Negative role of biochars in the dissipation and vegetable uptake of polycyclic aromatic hydrocarbons (PAHs) in an agricultural soil: Cautions for application of biochars to remediate PAHs-contaminated soil. *Ecotoxicol. Environ. Saf.* **2021**, *213*, 112075. [CrossRef]
184. Zhang, Q.; Saleem, M.; Wang, C. Effects of biochar on the earthworm (*Eisenia foetida*) in soil contaminated with and/or without pesticide mesotrione. *Sci. Total Environ.* **2019**, *671*, 52–58. [CrossRef]
185. Bielská, L.; Škulcová, L.; Neuwirthová, N.; Cornelissen, G.; Hale, S.E. Sorption, bioavailability and ecotoxic effects of hydrophobic organic compounds in biochar amended soils. *Sci. Total Environ.* **2018**, *624*, 78–86. [CrossRef]
186. Baronti, S.; Alberti, G.; Vedove, G.D.; Di Gennaro, F.; Fellet, G.; Genesio, L.; Miglietta, F.; Peressotti, A.; Vaccari, F.P. The Biochar Option to Improve Plant Yields: First Results from Some Field and Pot Experiments in Italy. *Ital. J. Agron.* **2010**, *5*, 3–12. [CrossRef]
187. Hale, S.E.; Jensen, J.; Jakob, L.; Oleszczuk, P.; Hartnik, T.; Henriksen, T.; Okkenhaug, G.; Martinsen, V.; Cornelissen, G. Short-Term Effect of the Soil Amendments Activated Carbon, Biochar, and Ferric Oxyhydroxide on Bacteria and Invertebrates. *Environ. Sci. Technol.* **2013**, *47*, 8674–8683. [CrossRef]
188. Gascó, G.; Cely, P.; Paz-Ferreiro, J.; Plaza, C.; Méndez, A. Relation between biochar properties and effects on seed germination and plant development. *Biol. Agric. Hortic.* **2016**, *32*, 237–247. [CrossRef]
189. Palansooriya, K.N.; Ok, Y.S.; Awad, Y.M.; Lee, S.S.; Sung, J.-K.; Koutsospyros, A.; Moon, D.H. Impacts of biochar application on upland agriculture: A review. *J. Environ. Manag.* **2019**, *234*, 52–64. [CrossRef]
190. Gao, X.; Cheng, H.-Y.; Del Valle, I.; Liu, S.; Masiello, C.A.; Silberg, J.J. Charcoal Disrupts Soil Microbial Communication through a Combination of Signal Sorption and Hydrolysis. *ACS Omega* **2016**, *1*, 226–233. [CrossRef]
191. Du, Z.L.; Hu, A.B.; Wang, Q.D.; Ai, J.; Zhang, W.J.; Liang, Y.; Cao, M.X.; Wu, H.J.; Han, D.S. Molecular composition and biotoxicity effects of dissolved organic matters in sludge-based carbon: Effects of pyrolysis temperature. *J. Hazard. Mater.* **2022**, *424*, 127326. [CrossRef]
192. Ding, J.; Zhu, D.; Hong, B.; Wang, H.T.; Li, G.; Ma, Y.B.; Tang, Y.T.; Chen, Q.L. Long-term application of organic fertilization causes the accumulation of antibiotic resistome in earthworm gut microbiota. *Environ. Int.* **2019**, *124*, 145–152. [CrossRef]
193. Xiao, R.; Ali, A.; Xu, Y.; Abdelrahman, H.; Li, R.; Lin, Y.; Bolan, N.; Shaheen, S.M.; Rinklebe, J.; Zhang, Z. Earthworms as candidates for remediation of potentially toxic elements contaminated soils and mitigating the environmental and human health risks: A review. *Environ. Int.* **2022**, *158*, 106924. [CrossRef]
194. Han, J.; Huang, Y.; Meng, J.; Fan, C.; Yang, F.; Tan, H.; Zhang, J. Exposure of earthworm (*Eisenia fetida*) to rice straw biochar: Ecotoxicity assessments for soil-amended programmes. *Sci. Total Environ.* **2021**, *794*, 148802. [CrossRef]
195. Shi, Z.; Yan, J.; Ren, X.; Wen, M.; Zhao, Y.; Wang, C. Effects of biochar and thermally treated biochar on *Eisenia fetida* survival, growth, lysosomal membrane stability and oxidative stress. *Sci. Total Environ.* **2021**, *770*, 144778. [CrossRef]
196. Méndez, A.; Gómez, A.; Paz-Ferreiro, J.; Gascó, G. Effects of sewage sludge biochar on plant metal availability after application to a Mediterranean soil. *Chemosphere* **2012**, *89*, 1354–1359. [CrossRef]
197. Visioli, G.; Conti, F.D.; Menta, C.; Bandiera, M.; Malcevschi, A.; Jones, D.L.; Vamerali, T. Assessing biochar ecotoxicology for soil amendment by root phytotoxicity bioassays. *Environ. Monit. Assess.* **2016**, *188*, 1–11. [CrossRef]
198. Ren, N.N.; Tang, Y.Y.; Li, M. Mineral additive enhanced carbon retention and stabilization in sewage sludge-derived biochar. *Process Saf. Environ. Prot.* **2018**, *115*, 70–78. [CrossRef]
199. Alves, B.S.Q.; Zelaya, K.P.S.; Colen, F.; Frazão, L.A.; Napoli, A.; Parikh, S.J.; Fernandes, L.A. Effect of sewage sludge and sugarcane bagasse biochar on soil properties and sugar beet production. *Pedosphere* **2021**, *31*, 572–582. [CrossRef]

200. Chagas, J.K.M.; de Figueiredo, C.C.; da Silva, J.; Paz-Ferreiro, J. The residual effect of sewage sludge biochar on soil availa-bility and bioaccumulation of heavy metals: Evidence from a three-year field experiment. *J. Environ. Manag.* **2021**, *279*, 111824. [CrossRef]
201. Gonzaga, M.I.S.; Mackowiak, C.; de Almeida, A.Q.; Wisniewski, A.; de Souza, D.F.; da Silva Lima, I.; de Jesus, A.N. As-sessing biochar applications and repeated *Brassica juncea* L. production cycles to remediate Cu contaminated soil. *Chemosphere* **2018**, *201*, 278–285. [CrossRef]
202. Tian, Y.F.; Cui, L.; Lin, Q.M.; Li, G.T.; Zhao, X.R. The sewage sludge biochar at low pyrolysis temperature had better im-provement in urban soil and turf grass. *Agronomy* **2019**, *9*, 156. [CrossRef]
203. Hossain, M.K.; Strezov, V.; Nelson, P.F. Comparative assessment of the effect of wastewater sludge biochar on growth, yield and metal bioaccumulation of cherry tomato. *Pedosphere* **2015**, *5*, 680–685. [CrossRef]
204. Yang, C.Y.; Liu, J.J.; Lu, S.G. Pyrolysis temperature affects pore characteristics of rice straw and canola stalk biochars and biochar-amended soils. *Geoderma* **2021**, *397*, 115097. [CrossRef]
205. Zhang, X.Y.; Gu, P.X.; Liu, X.Y.; Huang, X.; Wang, J.Y.; Zhang, S.Y.; Ji, J.H. Effect of crop straw biochars on the remedia-tion of Cd-contaminated farmland soil by hyperaccumulator *Bidens pilosa* L. *Ecotoxicol. Environ. Saf.* **2021**, *219*, 112332. [CrossRef]
206. Palansooriya, K.N.; Sang, M.K.; Igalavithana, A.D.; Zhang, M.; Hou, D.Y.; Oleszczuk, P.; Sung, J.; Ok, Y.S. Biochar alters chemical and microbial properties of microplastic-contaminated soil. *Environ. Res.* **2022**, *209*, 112807. [CrossRef]
207. Qin, J.L.; Qian, S.Y.; Chen, Q.C.; Chen, L.; Yan, L.L.; Shen, G.Q. Cow manure-derived biochar: Its catalytic properties and influential factors. *J. Hazard. Mater.* **2019**, *371*, 381–388. [CrossRef]
208. Xu, Y.G.; Bai, T.X.; Yan, Y.B.; Ma, K.R. Influence of sodium hydroxide addition on characteristics and environmental risk of heavy metals in biochars derived from swine manure. *Waste Manag.* **2020**, *105*, 511–519. [CrossRef]
209. Xu, Y.G.; Qu, W.; Sun, B.Y.; Peng, K.; Zhang, X.Z.; Xu, J.M.; Gao, F.; Yan, Y.B.; Bai, T.X. Effects of added calcium-based additives on swine manure derived biochar characteristics and heavy metals immobilization. *Waste Manag.* **2021**, *123*, 69–79. [CrossRef]
210. Hossain, M.Z.; Bahar, M.M.; Sarkar, B.; Donne, S.W.; Wade, P.; Bolan, N. Assessment of the fertilizer potential of biochars produced from slow pyrolysis of biosolid and animal manures. *J. Anal. Appl. Pyrolysis* **2021**, *155*, 105043. [CrossRef]
211. Kiran, Y.K.; Barkat, A.; Cui, X.; Feng, Y.; Pan, F.; Tang, L.; Yang, X.E. Cow manure and cow manure-derived biochar ap-plication as a soil amendment for reducing cadmium availability and accumulation by *Brassica chinensis* L. in acidic red soil. *J. Integr. Agric.* **2017**, *16*, 725–734. [CrossRef]
212. Wang, F.; Jin, L.T.; Guo, C.N.; Min, L.J.; Zhang, P.; Sun, H.W.; Zhu, H.K.; Zhang, C.P. Enhanced heavy metals sorption by modified biochars derived from pig manure. *Sci. Total Environ.* **2021**, *786*, 147595. [CrossRef]