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Review

Potential Role of Biochar on Capturing Soil Nutrients, Carbon Sequestration and Managing Environmental Challenges: A Review

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Abstract: Biochar (BC) properties and its influences within agricultural soil health and environmental ecosystems largely depend on feedstock, residence time and pyrolysis conditions. The organic and inorganic contaminants from soil can be removed using BC as an adsorbent. Additionally, soil amendment with BC is known to improve overall soil quality, microbial and enzymatic activities and soil organic carbon content with nutrient retention and availability. Moreover, one of the great impacts of BC is its capability to capture soil nutrients and sequestrate carbon. The physicochemical properties of biochar could be affected by the feedstocks and pyrolysis conditions (temperature, duration, activation method, etc.). This review paper summarizes the recent research studies on the composition of BC that controls carbon presence in soil, as well as BCs role in improving soil fertility and carbon sequestration, which has not been reported in detail yet. The main finding of the present work revealed that the high pyrolytic temperatures in BC production may have negative impacts on phyto-availability of essential nutrients. Depending on the feedstock raw material and pyrolysis process used for producing BC, it has different capacities for releasing nutrients in the soil. An economically feasible method of producing newly engineered biochar, with more controlled pyrolysis and C-based materials, for suitable agriculture needs to be developed. Further investigation should be carried out to optimize the production procedure and its application to local farming community for sustainable agriculture.

Keywords: biochar; carbon sequestration; feedstock; soil pollution; pyrolysis condition; soil remediation

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1. Introduction

Biochar (BC) has been a widely researched material due to its ability to be used in soil improvement and also as an adsorbent [1,2]. BC production is a sustainable process [3]; however, due to the multiplicity of potentially usable biomass sources, their physical and chemical properties can be very variable [4,5]. Physical and chemical properties, as well as production conditions, play an important role in functional properties such as adsorption characteristics, surface area, porosity, alkalinity and carbon content [6,7]. On the surface, there is an appreciable number of heteroatoms chemically linked to the hydrocarbon skeleton. At the base of the structure are unsaturated carbon atoms with high concentrations of electron pairs that play a strong role in the chemisorption of oxygen atoms, which represents a strong influence on the quality of the chemical surface of the BC [8,9].

The surface of the BC is also made up of acidic and basic radicals. Acids are associated with surfaces with large amounts of oxygen and have the property of anion exchange, whereas surfaces with low amounts of oxygen are responsible for basic characteristics and affect cation exchanges [10–12]. BC has a relatively large surface area, micropore volume, high CEC (cation exchange capacity), and abundant surface functional groups which make it a valuable amendment for remediating contaminated soils and improving soil health [13,14]. Many of the soil properties are affected by the application of BC, including an increase in pH of soil and CEC, changes in soil organic matter composition, improving mineralization (as a result of positive priming) and leaching of soil organic carbon [15–17]. Different management strategies, such as the application of soil additives including animal manure, composts, mulches, sewage sludge alone and integrated with inorganic chemicals, fertilizers, nano-materials, clay minerals, etc., are being used to enhance soil fertility in order to combat climate change [18,19]. However, most of these management strategies have little or no impact on the storage of soil carbon because rapid decomposition of OC (organic carbon) results in CO_2 emission, thereby losing their efficacy in maintaining carbon balance [20–23]. However, composts and sewage sludge may also come with phytopathogens, hazardous metals and potentially drugs/antibiotics [24]. The emissions of gases such as ammonia, methane and nitrous oxide may also be increased due to the application of composts and manures into the soil. Groundwater and surface water may be polluted by these gaseous compounds, contributing to climate change [25,26].

Application of a new class of biochar-based composites, also known as engineered/modified BC, into the soil can play a considerable role in the management of the environment and reduction of pollution of multi-metal contaminated soils [27]. Several studies showed that such BC can potentially act as a soil pH regulator, a carbon sink and aggregate soil particles, as well as helping to stabilize long-term heavy metals in polluted soils. Engineered-BC, which is similar to ordinary BC, is a solid carbonaceous and porous material obtained as a result of controlled pyrolysis of diverse biomass and C-based materials [28]. An engineered biochar's chemical composition is determined by the pyrolysis conditions, biomass and reaction atmosphere, as well as the metal oxides and nanometals it contains [29]. The engineered BC is relatively better than the ordinary BC when it comes to the greater surface area, effective functional groups and high adsorption strength and reactivity [30]. Hence, the design of improved supported metal oxide or nanometals can resolve the critical limitations and also feasibly enhance their soil properties. Researchers have extensively investigated the possibility of biochar-based composites as effective bio-adsorbents due to their peculiar physicochemical properties. Reactivity and sorption capacity is based on their fractions of carbonized or non-carbonized state [31].

According to several studies, there has been controversy surrounding the effect of temperature and feedstock used to produce BC on phyto-availability of nutrients and crop productivity [32–34]. Hussain et al. [35] found a wide range in crop yield index (−36%–31%) as well as in soil properties index (−21%–101%), after biochar application. Jeffery et al. [36] revealed that the difference may be attributed to the nature of the feedstock within the BC preparation process. Moreover, it has been reported that there was no significant response in terms of mineral nitrogen, plant productivity or nutrient update after BC application to soil [37]. In their work, Hussain et al. [35] summarised that the implementation of BCs can improve the crop yield planted in severely degraded lands with very low nutrient content but not fertile and healthy soils. In this regard, BCs could be utilized as an efficient bioremediation agent to the degraded and interfile soils. Hence, using BC, along with chemical fertilizer, as integrated application is required for a successful management strategy for improving crop productivity under different soil type variation [38–41]. However, not enough work was undertaken to investigate the outcomes of this approach [39–43]. Tammeorg et al. [42] found no improvement in wheat productivity after combined application of meat bone meal BC with chemical fertilizer.

Furthermore, BC properties and functions vary with the nature of feedstock and production environment [23,25,44–46]. So far, it appears that none of the literature has explored the BC composition-dependent impact on soil quality. Consequently, the present review will examine the BC composition-dependent impact in main domains, such as nutrient content and release, soil structure and environment-harming effects.

2. Effect of Biochar Amendment on Soil Fertility

The characteristics of BC are considerably different from those of feedstocks. In addition, these characteristics depend on pyrolysis conditions viz. oxygen, highest temperature, pressure, heating period and rate, etc. [47,48]. Amorphous aromatic compounds and graphene sheets can be found in Douglas fir bark made BC pyrolysis at 623 °C; furthermore, the incorporated elements in aromatic rings, oxygen (O), nitrogen (N), phosphorus (P) and sulphur (S) are found the most, which might be due to pyrolysis temperature and biomass type [49–51]. The heteroatoms present in BC aromatic rings may have a great influence on its surface, making it heterogeneous and reactive [52]. Cayuela et al. [53] revealed that the BC has a typical molar hydrogen-to-carbon ratio that was observed less than feedstock, which subsequently had shown polymerization and potential recalcitrance.

The application of BC as soil conditioner has the potential to enhance soil aeration, soil structure, water holding capacity, microbial biomass carbon, enzymatic activities, soil organic carbon (SOC) content [46,53–56] and nutrient retention and availability [56,57], which may reduce the nutrient leaching from soil surface to groundwater [58]. Table 1 summarizes the influence of BC amendment on soil properties. Many studies have shown that BC is an effective soil amendment, as described in Table 1, while Schmidt et al. [59], reported that there was reduced crop productivity after application of BC, which could be due to reduction in soil C mineralization or a decreased uptake of nutrient by the plant [60]. Conflicting results regarding crop yields in soils amended with BC probably reflects variables in BC and soil properties; for example, high pyrolytic temperatures (500–800 °C) may reduce phyto-availablity in nutrients by binding and lessening increments in adsorption capacities [61].

Table 1. Effect of biochar on soil fertility parameters.

Biochar Feedstock	Pyrolysis Temperature (°C)	Type of Soil	Impact on Soil Properties	Reference
Wheat straw	450	-	Higher sorption efficiency for pesticides.	[62]
Sewage sludge (100 g kg^{-1})	550	Acidic soil	Increased soil pH by + 34.1%; total carbon by + 818.2%; total nitrogen by + 550%	[63]
Willow wood	550	weathered soil	Increased nodulation by 18–24%; organic amendments by 9–25%.	[39]

Table 1. *Cont.*

Biochar Feedstock	Pyrolysis Temperature (°C)	Type of Soil	Impact on Soil Properties	Reference
Rice straw	300	Silt loam soil	Soil N_2O emission was affected by N fertilizer	[64]
Hay grass	400	Sandy soil	No effect on soil water retention or field saturated conductivity.	[65]
Rice straw	500	Sandy soil	Plant salt and drought stresses alleviation.	[66]
Bamboo	600	Mineral soil	Affected the biogeochemical cycles such as release of CH_4 and N_2O from the soil,	[67]
Walnut shell	900	Acidic soil	Efficient tetracycline and Cu (II) sorption on iron and zinc doped sawdust biochar.	[68]
Municipal biowaste	450–550	Anthrosol	Increased SOC (soil organic carbon) by +20.2%	[69]
Wheat straw	350–650	Clay texture	Increased water-stable aggregates, and highest available water content up to 39% and 166%.	[70]

3. Nutrients Available from Biochar

Lignocellulosic biomass is generally made up of a complex mixture of natural carbohydrate polymers known as cellulose and hemicellulose, in addition to lignin and small amounts of other substances, such as extractives (usually small organic molecules or polymers) and ash (inorganic) [71–73]. The composition of biomass plays an important role in the distribution of pyrolysis products [74]. Each material exhibits a particular characteristic when it is pyrolyzed due to the proportion of its constituent components, as each component is degraded at a specific temperature, forming different compounds. The biochar is composed of carbon, hydrogen and nitrogen and also carries some of the other essential plant elements such as potassium, calcium, magnesium and sodium.

Therefore, different feedstock types and/or pyrolysis conditions, such as temperature, can dramatically affect the properties of BC [75–77]. The effect of pyrolysis temperature and feedstock type on final properties of BC has been explored in many studies (Figure 1). In BCs prepared by relatively high pyrolysis temperatures, hydrogen (H) and oxygen (O) are significantly depleted but aromatic carbon (C) is greatly enhanced [78]. It has been reported that the biochar application increased total N, P availability and K up to 1.41-fold, 2.65-fold and 2.60-fold, respectively [79]. Its chemical recalcitrance and resistance to chemical and microbial decay in soil are thus greater [80]. Furthermore, BC pH increases with increasing pyrolysis temperature due to the increased amount of alkaline elements, ash salts and soluble and exchangeable cations [81]. The most distinguishing characteristic of BC is its porous structure with a high surface area. As a result, BC has a higher capacity to adsorb moisture and nutrients into the soil [80,82]. The increasing temperature has the opposite effect on concentrations of acidic functional groups, volatile matter, BC yield and cation exchange capacity (CEC) [83,84]. The type of material from which the BC is produced (known as feedstock), has a tremendous effect on the content of fixed carbon, TOC (total organic carbon) and mineral elements within the BC [85]. Numerous recent studies have examined this using BC from a wide range of sources and origins [86]. Few studies have been conducted on the pyrolytic conversion of industrial wastes in contrast to wastes of animal origin in order to ascertain the potential for environmental and agricultural applications. Biochar can be produced from a variety of feedstocks; similarly, BCs with a superior nutritional value can be made from organic wastes with a high nutrient content (Table 1).

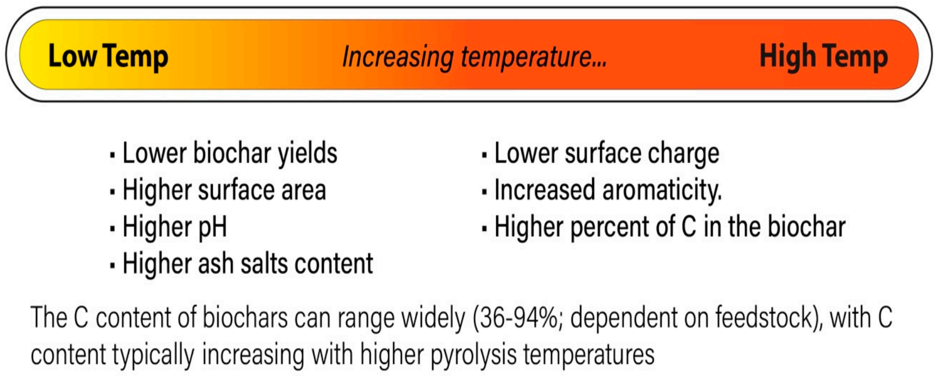

Figure 1. Effect of biochar feedstock and pyrolysis temperature on biochar properties.

The moisture content can have different effects on the final pyrolysis product, especially yield. High humidity levels lead to reduced yields [87]. Moisture content affects the temperature reduction inside the reactor, it reduces the reaction speed and also the process efficiency, because of the energy required for the vaporization of the water present in the biomass [88,89]. Generally, fast pyrolysis processes require a biomass with low moisture content, around 10%, so that the heating rate is not restricted by water evaporation [90]. The studies by Bulmău et al. [90] pointed out that the pyrolysis of wood with high percentages of moisture producing higher gas fractions, consequently meant lower production of liquid and solid fractions.

Another factor that significantly affects yield is the particle size of the biomass, due to the greater surface area available for thermal degradation, thus it facilitates the exit of condensable gases and vapors, which was be explained by Ryu et al. [91] with higher particle sizes. Lower volatilization rates lead to heat transfer between nearby particles.

Another factor dealing with particle size is the equality of particle sizes, since, if there are larger particles, they can favor the formation of spaces between the bed particles, as well as the development of preferential channels, which gives rise to fluctuations and heterogeneity in reactor temperature [92]. Therefore, the particle size must be as uniform as possible. Raj et al. [93] studied the yield of bio-oil using waste tires as biomass, varying the particle size in a range between 0.3 and 1.18 mm and obtaining higher bio-oil yields at low granulometry, also decreasing volume solid waste (coal). Haydary et al. [94] concluded in their study that particle size has a decisive effect on pyrolysis time. The combustion carried out at a temperature of 550 °C, with 5 mm particles, caused the decomposition of the biomass in times below 1 min, while in the combustion of 50 mm particles, the time was longer than 25 minutes. The larger the particle size, the greater the production of solid waste (coal), small particles are therefore preferred to maximize net yields [94,95]. Biomass residence time inside the reactor is also a parameter that can affect the pyrolysis yield. Studies report that in shorter time intervals, higher yields are obtained if compared to high residence times, as it prevents the bio-oil formed from remaining for a long time at high temperatures, enabling its cracking and decreasing the crude oil yield in pyrolysis [89]. Bulmău et al. [90] conducted a study of the behavior of residence time between 5 and 30 min, and observed a significant inverse relationship between residence time and income.

The temperature profile is the most important aspect of operational control for pyrolysis processes. The pyrolysis process together with the temperature produced by the reactor controls the main parameters, which are heating rate, minimum and maximum temperature and residence time. These factors contribute to the final quality of the product [95,96].

The final pyrolysis temperature is one of the parameters that has a clear effect on yields in relation to the production of bio-oil and biochar. High temperatures lead to reduced solid waste yield. Above the maximum temperatures generally employed in the pyrolysis process (>700 °C), the reactions generated cause further decomposition of the products generated and net yields are reduced [97].

Pyrolysis of waste materials to produce BC is thought to be an efficient way to encourage waste material recycling and value addition. In the pyrolysis process, waste materials are often decomposed at temperatures among 300 and 800 °C in partial or total absence of oxygen. According to Lehmann et al. [86], by thermally converting industrial or agricultural waste into BC (solid), fuel gas (CO, CO_2, H_2, CH_4, and other hydrocarbons) and bio-oil (liquid fuel), pyrolysis is now considered a viable alternative in the use of industrial or agricultural waste. The use of BC in soil conditioners, decontaminating environments and generation of electricity is also possible [98].

4. The Relationship between the Biochar Composition and Nutrient Release

Biochars (BCs) have been shown to have a positive effect on soil, plants and microbes due to the nutrients in their composition and/or their ability to absorb and retain nutrients [99,100]. However, nutrient leaching may have negative environmental effects; for example, the eutrophication effect on the surface and/or groundwaters. Mukherjee et al. [101] demonstrated that the nutrient content of BCs can range widely according to both biomass type and combustion conditions. About 15–20% of Ca, 10–60% of P, and ≈2% were readily leachable with distilled water from mallee wood BC as reported by Wu et al. [102]. The rate of the elements was varying depending on the temperature and the sampled portion of the plant. Char and soil type in which the BC is implemented influence significantly the plant-available nutrients released; for instance, column leachate from a Norfolk loamy soil supplemented with BC made from pecan shells made at 700 °C had less P (by about 35%), Ca, Mn and Zn than a soil that was not amended with BC [82]. Therefore, BC was assumed to exchange multivalent cations for superficially sorbed mono-valent cations. Asai et al. [103] observed N immobilization in the stable BC, due to the high C/N ratio of BC and N enmeshment. Hangs et al. [104], and Nguyen et al. [105] reported similar results. Experimentation over the short-term by Nelson et al. [106] provided evidence that N fertilization should be applied to soils amended with BC in order to improve their nitrogen status.

The result of successive batch extractions of BC, except for the N-rich ones, usually showed a minor release of N (Table 2). The nutrients released from BC to soil water varied with the types of feedstocks used. From the leachates from the BC products, the most abundant form of nitrogen was ammonium (NH_4), followed by organic nitrogen (ON). Nitrogen amount from nitrate ranged from 2% to 30% and number of organic nitrogen (ON) was up to 59%. According to Mukherjee and Zimmerman [107] reported that the dissolving organic carbon (OC), nitrogen (N) and phosphorus (P) in soil solution water are correlated with BC acid functional group density and volatile matter content.

Table 2. Proportion of DOC (dissolved organic carbon), total TKN (Kjeldahl nitrogen), and total P (phosphorous) in biochars.

Biochar	DOC	TKN	P	Reference
Oak-250	0.9	1.5	151	[107]
Oak-650	0.1	0.5	22	
Grass-250	1.7	5.3	117	
Grass-650	0.4	3	39	

5. Correlation between Biochars Physico-Chemical Properties and Nutrient Release

It is very likely that the surface area, porosity and ion exchange capacity of some BCs will affect their ability to sorb and possibly release organic matter (OM) or nutrients over time [15]. However, Mukherjee et al. [101] observed that the BC, CEC ranged from 0–70 cmolkg^{-1}, the latter being found in BC and developed at a lower temperature. Furthermore, the above results found that the aged BCs contained huge amounts of AEC (anion exchange capacity). In this sense, fresh BC should retain ammonia ($NH4^+$) and release exchangeable nitrate (NO_3^-) and phosphate ($PO4^{3-}$). Wu et al. [102] observed that there was no direct correlation between BET surface area and catalyst activity could be identified by the marked changes in the carbon structure. Nguyen et al. [105] stated that the BRT model supported the significant correlation among BC CEC and NH_4^+-N adsorption. The variation in lignin, cellulose and hemicellulose changed the physical properties of biochar, which in turn affected the nutrient release.

6. Application and Effect of Engineered Biochar

6.1. Effect on Soil Health and Carbon Content

Numerous food safety incidents can be attributed to soil pollution. Thus, soil remediation agents that are reliable and safe must be sought. Beesley et al. [108] and Park et al. [109] have suggested that BC can have a negative effect the mobility of some inorganic and organic soil pollutants.

Due to its large surface areas, oxygen-containing functional groups and CECs, BC has the ability to retain, stabilize and inactivate toxic heavy metals, and reduce the phytotoxicity and bioavailability of heavy metal ions in soil environment [110–112]. According to Beesley et al. [108], water-soluble carbon and highly alkaline pH could immobilize some elements. Rees et al. [113] observed that soil-heavy metal mobility is mainly regulated by increase in soil pH and soil intra-particle diffusion after BC implementation. After modification, BC products have excellent adsorption ability for both inorganic and organic pollutants. There is relatively little literature on engineered-BC (the biochar processed at varying temperature and conditions to improve the properties), compared to pristine-BC (carbonaceous biochar), when it comes to using it for the restoration of soil heavy metals. The particulate organic matter can interact in different types of soils, which may add variation to the nutrient availability or release. However, the ability to observe and apply these findings at a large scale is still lacking, despite some experiments being carried out in the laboratory. The production cost of engineered-BC, its stability, collection and regeneration process, as well as its possible environmental risks, requires additional investigation.

The Organic Carbon (OC) in biochar stability is mainly in soil. For example, wood biochar is more stable than rice residues [56]. Bird et al. [114] recorded that wood-derived BC is more carbon (C) stable due to its higher lignin content compared to crop residues. Kloss et al. [115] revealed the characteristics of biochar biomass at low pyrolysis temperature. Biochar's carbon stability is also affected by the temperature for pyrolysis, since it can alter the pro-portion of aliphatic and aromatic carbons and the amount of aromatic carbon (AC) that is condensed in BC [116–118]. When manufactured under elevated pyrolysis temperatures, BC contains a greater amount of aromatic carbon (AC) than when produced at low pyrolysis temperatures. Thus, low pyrolysis temperatures produce BC that shows lower soil degradability than high pyrolysis temperatures. It is crucial for BC to be stable in the soil, as it improves and maintains soil properties relevant to plant growth and production.

6.2. Effect of Engineered Biochar Amendment on Soil Quality and Environmental Parameters

Pyrolysis, raw materials and BC conversion methods determine the properties of engineered-BC [117]. Engineered-BC is manufactured using a different feedstock from agriculture and forestry. According to Mayer et al. [118], the effects of manufacturing conditions on engineered-BC are poorly understood. It is essential for the development of engineered-BCs to understand how long-term stability of pyrolyzed BCs is affected by production conditions and their characteristics [68]. As a result, the adsorption characteristics of engineered-BCs are mainly defined by the specific surface area, pore structure and surface functional groups. Therefore, various engineered-BCs have been developed in order to meet the various application demands. An engineered-BC adsorbent's performance can be affected by the characteristics of raw materials (feedstocks), BC preparation methods and process requirements [50]. By choosing certain feedstocks or altering the raw material chemically, physically or biologically, as well as through a physiochemical chemical-physical combination method, the pore structure of the carbonaceous adsorbent can be regulated to an extent (Figure 2).

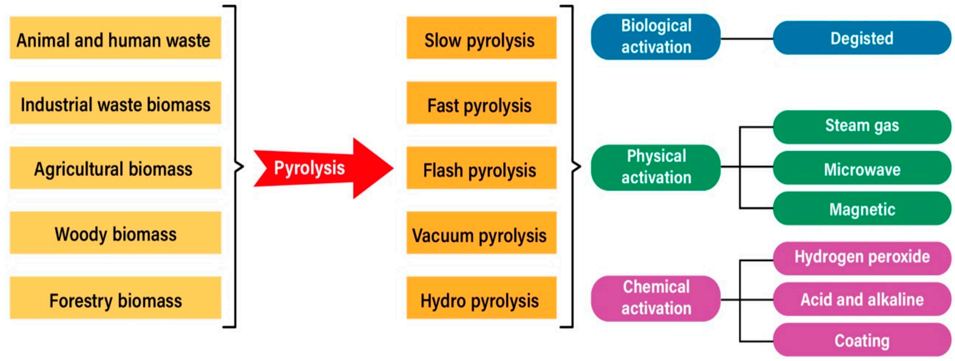

Figure 2. Typical engineered biochar production methods.

Ever-growing interest in the production and application of BC has led to the emergence of multidisciplinary scientific and engineering fields, especially in the field of environmental science. A BC is made from various feedstock materials and used to treat contaminated soil, particularly for agriculture. Engineered-BC plays a beneficial role in reducing environmental pollution due to its extensive applications in soils and the atmosphere.

Essentially, engineered-BCs are aged BCs with modifications made by chemical oxidation. Meanwhile, engineered-BCs will have significantly more oxygen functional groups after chemical oxidation [119,120]. The high content of anions, particularly those containing N^- or O^- functional groups, can increase the reactivity of BCs. In addition, it contains reactive functional groups alongside non-aromatic Carbon structures, which make up the bulk of the labile BC fraction and are vulnerable to biotic degradation in soil. Thus, engineered-BCs might be less stable during the early stages of aging than regular BCs, because of these factors (Figure 3). Duan et al. [121] reported that the contaminant removal performance of engineered-BCs was significantly increased after Fe_3O_4 modification. Additionally, they noted that BCs functions may be dramatically reduced as they age. Yaashikaa et al. [122] revealed that activating BC is another particular region for the growing utilization of BC for expelling specific pollutions; furthermore, the closed-loop systems to produce BC creates more opportunities, such as managing wastes and increasing resource proficiency in circular bio-economy.

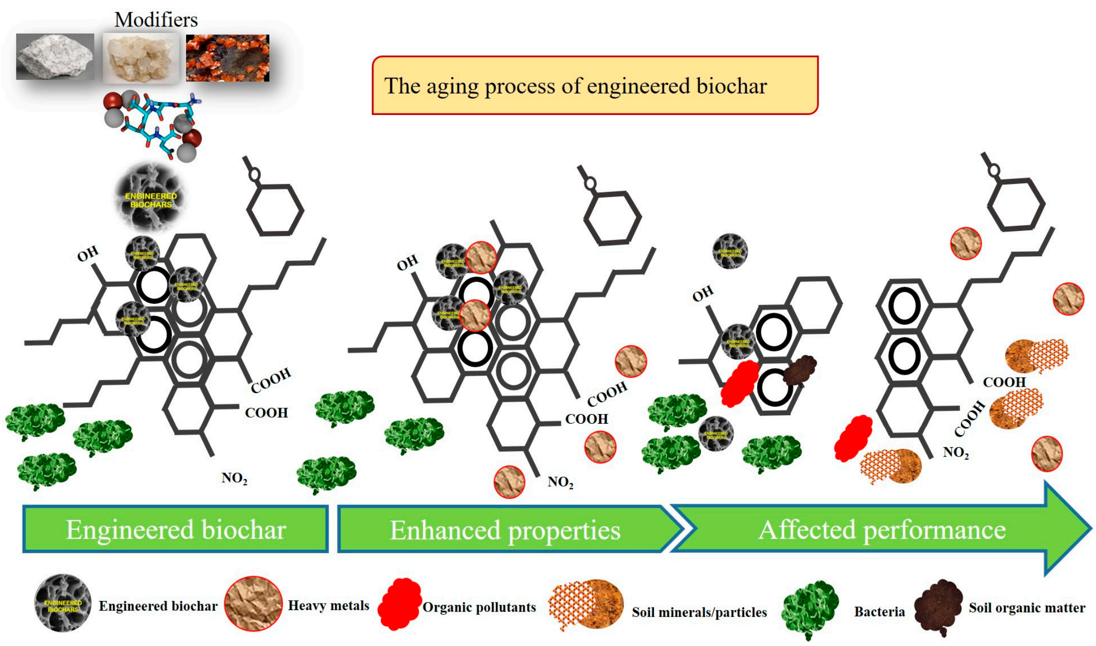

Figure 3. The contaminant removal performance of EngBC.

7. Limitations concerning the Use of Biochar as a Soil Amendment

Several limitations were reported of BCs implementation, although most of the studies demonstrated their beneficial aspects (Figure 4)**.** First, soil aging is notably affected by BC application resulting in soil aging inhibition. As a result, alternate addition of biomass to soil might be necessary for proper nutrient cycling; for example, it has been proven by Anyanwu et al. [123] that, in the long term, BC can have a negative effect on microbiota and earthworms in soil. In the same way, the aged-BC also limits underground root biomass of rice (*Oryza sativa*) and tomato (*Solanum lycopersicum*). In addition, BC can decrease soil thermal, coming from the low thermal diffusivity of BC [84]. On the other hand, popular findings show that the positive effects of BC are soil-specific.

Consequently, soil amendment performance by BC might change according to the types of soils [124,125]. Safaei Khorram et al. [126] reported an excessive weed growth (≈200%) after the application of BC at 15 tha^{-1} to lentil culture and concluded that over-application of BC might worsen weed control in a field. Vaccari et al. [127] observed that BC's effect on crops' productivities might change for different types of planted crops and the targeted part of the crop. In fact, the same study added that BC application at 14 tha^{-1} improved vegetative growth of tomato plants whereas productivity was not improved significantly [124]. Additionally, a delay in plants flowering was reported by Hol et al. [128] related to the BC application. Moreover, BC is selective in its ability to adsorb pollutants; for example, DDT (dichlorodiphenyltrichloroethane) pesticide uptake was not impeded by BC supplementation in soil [129]. We usually notice a higher ash content in BC produced under higher temperatures compared to the once produced under low temperatures. Therefore, negative effects were expected on crops grown in soil where high temperature derived BCs was applied [69]. Kim et al. [130] signalled another negative effect on BC capacity to adsorbed nitrogen and other essential nutrients, such as iron, which might impact plant growth performance. Moreover, BC can enter in competition with soil on nutrients available in BC-soil [131]. For example, if BC is applied along with phosphorus fertilizer in saline-sodic soil the precipitation/sorption reactions of phosphate could be facilitated. The phyto-availability of P (phosphorous) may decrease through this interaction [6]. When BC is applied to soil, it intervenes in the decomposition of OM (organic matter), which results in reducing fungi populations, namely Ascomycota and Basidiomycota, by 11 and 66%, respectively [132]. Furthermore, the source of BC-derived products is extremely important. As an example, coconut-husk-derived BC is highly effective at improving 90% of maize (*Zea mays*) biomass, while orange-bagasse-derived BC does not show much effect at a similar dose [133]. Jones and Quilliam [134] reported plant growth was negatively affected by contamination of the BC. Subsequently, BC production costs might be affected by the availability of feedstock. Shackley et al. [135] reported that an estimated 148–389 British pounds would be required to produce a ton of BC with all the additional expenses. On top of that, the regulatory issues and testing for the biomass feedstock could raise costs.

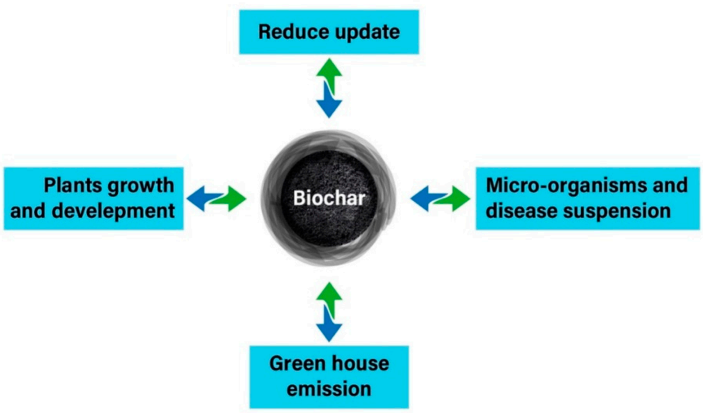

Figure 4. Effect of biochar amendment of soil in agricultural land (reduce updates like heavy metals,

pesticides; engineered nanomaterials and pharmaceuticals, for plants growth and biomass like germination and biomass, nitrogen utilization, water utilization, and also Micro-organisms and disease suspension, for Greenhouse emission like CO_2 and methane mitigation and increase N_2O emissions).

8. Progress in Biochar Production for Soil Carbon Sequestration and Soil Fertility Improvement

In simplest material context, BC is incompletely combusted organic matter (OM) that is applied to the soil. However, in recent years, these materials have attracted considerable attention due to goals that may be achievable through their production and end-use. A considerable proportion of the world's natural SOC (soil organic carbon) content comprises black carbon, a pool that is resistant to microbial degradation and was deposited from historic fires [136]. Augmenting this nearly ubiquitous pool with additional recalcitrant carbon has recently been the subject of much scientific research focused on soil improvement and carbon (C) sequestration, which has garnered notable support from some of the world's most well-known climate scientists and environmental advocates, such as Gore et al. [137], Flannery [138] and Hansen et al. [139]. Moreover, BC is a form of anthropogenic recalcitrant carbon produced for application to the soil that draws inspiration from the practices of pre-colonial native Amazonians who transformed some of the world's poorest soils into extremely fertile soils that remain productive into the present centuries, long after their production ceased [58]. This rediscovered concept represents both a stable form of C-rich SOM and a means to ameliorate degraded soils into fertile soils [140]. Carbon sequestration is achievable through a range of thermo-chemical conversion processes (Table 3), including pyrolysis, a process that produces BC as a by-product. Recalcitrant carbon, including particulates emitted by fossil fuel combustion, may represent up to 30% of all soil C globally [21]. Woolf et al. [141] reported that, by increasing BC production, net anthropogenic greenhouse gas (GHG) emissions could be reduced by as much as 12% through the substitution of pyrolysis oils and gases for fossil fuels.

Table 3. Biomass Pyrolytic Conversion Processes.

Process	Temperature (°C)	Heating Rate	End Products
Torrefaction	230–300	Very low	Biochar
Slow Pyrolysis	380–530	Low	Biochar, bio-oils, gas
Fast Pyrolysis	380–530	High	Bio-oils, relatively little biochar
Combustion	700–1400	Very high	Gas
Gasification	>750	Very high	Gas

The future of BC to enhance the fertility of soils varies accordingly. Innovation in BC manufacturing technology can improve its effectiveness in promoting soil carbon storage and soil fertility. Furthermore, BC implementation was carried out to assess the soil fertility status, carbon sequestration and crop production improvement [142]. Corn stover and rice husk BCs were derived by slow pyrolysis from rice husk (RHBC) at 650 °C and from corn stover (CSBC) at 550 °C, respectively. As a negative control to know the effect of temperature on BC production, unpyrolyzed rice husks and corn stover were applied as soil amendments under CIE (controlled incubation environment) for 107 days. In soils treated with BC, CO_2 emissions were decreased, and TOC (total organic carbon), WHC (water holding capacity) and CEC (cation exchange capacity) increased. After BCs application, soil fertility was improved and eggplant crop growth (height, leaf number fresh and dry weight) was enhanced. Additionally, carbon mitigation and long-term sequestration were experimented in soil and found that both chars could be used for carbon sequestration and soil application.

Teodoro et al. [143] biochar co-application with compost has more potential to increase compost process than compost alone, as a result it can maintain the provision of available nutrients, reduce the metal mobility in soil and improve conditions for plant establishment. Murtaza et al. [144] stated that the BC amendment can reduce the bulk density of soil, increased soil porosity, infiltration rate, microbial activity, pH level and water holding capacity. However, it varied according to soil texture and, concurrently, BC addition sometimes could have adverse impacts on soil characteristics that appear in the form of crop productivity loss. Joseph et al. [145] stated that BC properties and its effects within agricultural ecosystems fundamentally depend on biomass and pyrolysis conditions, the metaanalysis results showed that P and SOC increased by 4.6 times and 17–39%, whereas they reduced the non-CO_2 greenhouse gas emissions from sandy acidic soil by 12–50% with addition of BC. Asadi et al. [146] revealed that the rice husk biochar (RHB) has potential to reduce nitrate leaching and greenhouse gas (CH_4, CO_2 and N_2O) emissions from paddy soil, it might be due to characteristics of RHB depends on pyrolysis heating rate and residence time. Allohverdi et al. [147] reported some fundamental challenges within agricultural practices comprise the improvement of water retention and microbiota in soils, as well as boosting the efficacy of fertilizers. Furthermore, BC is a nutrient-rich material produced from biomass and gaining attention for soil additive has the potential to improve soil health, crop production and capture carbon emission. Simiele et al. [148] found an increase of up to twofold root length, root surface area, and root, stem and leaf biomasses with application of BC at 20% application rate as compared with control. Hussain [149] revealed that maximum mustard dry biomass was observed with application of green coconut-modified biochar than control treatment.

9. Perspectives and Challenges

Many studies have suggested that BCs can be used as a promising soil amendment for fertility improvement and carbon sequestration in soils. However, several perspectives should be taken into account to ensure its efficacy and its cost-effectiveness, particularly in the following areas:

(1) The development of BC should concede the optimization of the production conditions based on the suitable implementation rates for the improvement of soil fertility, nutrient availability to plants and carbon sequestration. This standardization could help to maximize the efficiency of BC implementation and to minimize any potential environmental drawbacks. The optimization of BC production should include several parameters, such as quality of raw materials (feedstock), temperature for pyrolysis and pre or post treatment of BC. More studies are needed to elucidate the relationship between all those parameters, along with their performance in soils. Establishing a standard model for the development of efficient BC is still challenging, mostly because it remains a challenge to specific applications in different kinds of soils, crops and environments.

(2) Developing a prediction for the decaying period of BC in the field under differing cropping patterns is one of the main challenging milestones. The degradation of BC can be studied in two ways: using the stable phase of BC in soil, which is expected to persist in soil for thousands of years, and comparing its characteristics to labile phase in soil, which will decompose more rapidly. It is important to demonstrate BC stability in the soil at the field level. Field experiments conducted over time are crucial for this aspect.

(3) Understanding the plant roots-microbe-soil-BC interactions within the rhizosphere is also a crucial investigation pathway. This will elucidate the biogeochemical cycling of nutrients and release dynamics in BC-amended soil environments.

(4) Studies should also consider the determination of the adsorption and the desorption capacities of BCs to soil nutrients for predicting the phyto-availability of nutrients and the slow release of nutrients to plants in the BC-soil complex environment. These adsorption–desorption capacities might change according to the type of BC. Thus, different types of BCs should be tested by implementing them in different types of soil habitats with various properties and different crop genotype.

10. Conclusions

The BC can help in maintaining the soil health in sustainable manner. The stability of BC in the soil is essential for crop production since it improves, fixes and maintains soil properties. However, Further studies are needed to determine how raw materials used in BC production are related to its ability to produce soil nutrients, especially regarding the new advancements in BC production processes. The research should be focussed on BC development standardization, BC decay prediction, BC interactions with different parts of the rhizosphere (roots, microbes, and soils) and BC adsorption—desorption capacities so that the BC can be used as an efficient alternative to conventional fertilization and even a solution to carbon sequestration. Long-term studies are needed to investigate the impact of activated BCs with low-cost and environment-friendly nanomaterials/minerals on mineralizable-N, soil health and sustainable crop production.

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References

1. He, L.; Zhong, Z.; Yang, H. Effects on soil quality of biochar and straw amendment in conjunction with chemical fertilizers. *J. Integr. Agr.* **2017**, *16*, 704–712. [CrossRef]
2. Moreira, M.T.; Noya, I.; Feijoo, G. The prospective use of biochar as adsorption matrix–A review from a lifecycle perspective. *Bioresour. Technol.* **2017**, *246*, 135–141. [CrossRef] [PubMed]
3. Waqas, M.; Nizami, A.S.; Aburiazaiza, A.S.; Barakat, M.A.; Ismail, I.M.I.; Rashid, M.I. Optimization of food waste compost with the use of biochar. *J. Environ. Manag.* **2018**, *216*, 70–81. [CrossRef] [PubMed]
4. Yavari, S.; Malakahmad, A.; Sapari, N.B.; Yavari, S. Sorption properties optimization of agricultural wastes-derived biochars using response surface methodology. *Process Saf. Environ. Prot.* **2017**, *109*, 509–519. [CrossRef]
5. Colantoni, A.; Evic, N.; Lord, R.; Retschitzegger, S.; Proto, A.R.; Gallucci, F.; Monarca, D. Characterization of biochars produced from pyrolysis of pelletized agricultural residues. *Renew. Sustain. Energy Rev.* **2016**, *64*, 187–194. [CrossRef]
6. Xu, X.; Wu, Z.; Dong, Y.; Zhou, Z.; Xiong, Z. Effects of nitrogen and biochar amendment on soil methane concentration profiles and diffusion in a rice-wheat annual rotation system. *Sci. Rep.* **2016**, *6*, 38688. [CrossRef]
7. Shen, Z.; Zhang, Y.; Jin, F.; McMillan, O.; Al-Tabbaa, A. Qualitative and quantitative characterisation of adsorption mechanisms of lead on four biochars. *Sci. Total Environ.* **2017**, *609*, 1401–1410. [CrossRef]
8. Yang, K.; Jiang, Y.; Yang, J.; Lin, D. Correlations and adsorption mechanisms of aromatic compounds on biochars produced from various biomass at 700 C. *Environ. Pollut.* **2018**, *233*, 64–70. [CrossRef]
9. de Caprariis, B.; De Filippis, P.; Hernandez, A.D.; Petrucci, E.; Petrullo, A.; Scarsella, M.; Turchi, M. Pyrolysis wastewater treatment by adsorption on biochars produced by poplar biomass. *J. Environ. Manag.* **2017**, *197*, 231–238. [CrossRef]
10. Reddy, P.M.K.; Krushnamurty, K.; Mahammadunnisa, S.K.; Dayamani, A.; Subrahmanyam, C. Preparation of activated carbons from bio-waste: Effect of surface functional groups on methylene blue adsorption. *Int. J. Environ. Sci. Technol.* **2015**, *12*, 1363–1372. [CrossRef]
11. Brewer, C.E.; Unger, R.; Schmidt-Rohr, K.; Brown, R.C. Criteria to select biochars for field studies based on biochar chemical properties. *Bioenerg. Res.* **2011**, *4*, 312–323. [CrossRef]
12. Shen, W.; Li, Z.; Liu, Y. Surface chemical functional groups modification of porous carbon. *Recent Patents Chem. Eng.* **2008**, *1*, 27–40. [CrossRef]
13. Fu, Y.; Rong, M.; Yang, K.; Yang, A.; Wang, X.; Gao, Q.; Liu, D.; Murphy, A.B. Calculated rate constants of the chemical reactions involving the main byproducts SO_2F, SOF_2, SO_2F_2 of SF_6 decomposition in power equipment. *J. Phys. D Appl. Phys.* **2016**, *49*, 155502. [CrossRef]
14. Pratt, K.; Moran, D. Evaluating the cost-effectiveness of global biochar mitigation potential. *Biomass Bioenerg.* **2010**, *34*, 1149–1158. [CrossRef]

15. Fahad, S.; Chavan, S.B.; Chichaghare, A.R.; Uthappa, A.R.; Kumar, M.; Kakade, V.; Pradhan, A.; Jinger, D.; Rawale, G.; Yadav, D.K.; et al. Agroforestry Systems for Soil Health Improvement and Maintenance. *Sustainability* **2022**, *14*, 14877. [CrossRef]
16. Singh, B.P.; Cowie, A.L. Long-term influence of biochar on native organic carbon mineralisation in a low-carbon clayey soil. *Sci. Rep.* **2014**, *4*, 3687. [CrossRef]
17. Mitchell, P.J.; Simpson, A.J.; Soong, R.; Simpson, M.J. Shifts in microbial community and water-extractable organic matter composition with biochar amendment in a temperate forest soil. *Soil Biol. Biochem.* **2015**, *81*, 244–254. [CrossRef]
18. Bibi, S.; Ullah, S.; Hafeez, A.; Khan, M.N.; Javed, M.A.; Ali, B.; Din, I.U.; Bangash, S.A.K.; Wahab, S.; Wahid, N.; et al. Exogenous Ca/Mg quotient reduces the inhibitory effects of PEG induced osmotic stress on *Avena sativa* L. *Braz. J. Biol.* **2022**, *84*, e264642. [CrossRef]
19. Yasmeen, S.; Wahab, A.; Saleem, M.H.; Ali, B.; Qureshi, K.A.; Jaremko, M. Melatonin as a Foliar Application and Adaptation in Lentil (Lens culinaris Medik.) Crops under Drought Stress. *Sustainability* **2022**, *14*, 16345. [CrossRef]
20. Lehmann, J. A handful of carbon. *Nature* **2007**, *447*, 143–144. [CrossRef]
21. Schmidt, T.M.; Do, M.T.H.; Dacey, D.; Lucas, R.; Hattar, S.; Matynia, A. Melanopsin-positive intrinsically photosensitive retinal ganglion cells: From form to function. *J. Neurosci.* **2011**, *31*, 16094–16101. [CrossRef] [PubMed]
22. Paustian, K.; Lehmann, J.; Ogle, S.; Reay, D.; Robertson, G.P.; Smith, P. Climate-smart soils. *Nature* **2016**, *532*, 49–57. [CrossRef]
23. Agegnehu, G.; Srivastava, A.K.; Bird, M.I. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Appl. Soil Ecol.* **2017**, *119*, 156–170. [CrossRef]
24. Thakur, A.; Singh, S.; Dulta, K.; Singh, N.; Ali, B.; Hafeez, A.; Vodnar, D.C.; Marc, R.A. Nutritional evaluation, phytochemical makeup, and antibacterial and antioxidant properties of wild plants utilized as food by the Gaddis, a tribe in the Western Himalayas. *Front. Agron.* **2022**, *4*, 1010309. [CrossRef]
25. Akram, N.A.; Saleem, M.H.; Shafiq, S.; Naz, H.; Farid-ul-Haq, M.; Ali, B.; Shafiq, F.; Iqbal, M.; Jaremko, M.; Qureshi, K.A. Phytoextracts as Crop Biostimulants and Natural Protective Agents—A Critical Review. *Sustainability* **2022**, *14*, 14498. [CrossRef]
26. Afridi, M.S.; Ali, S.; Salam, A.; César Terra, W.; Hafeez, A.; Ali, B.; AlTami, M.S.; Ameen, F.; Ercisli, S.; Marc, R.A.; et al. Plant Microbiome Engineering: Hopes or Hypes. *Biology* **2022**, *11*, 1782. [CrossRef]
27. Naz, R.; Khan, M.K.; Hafeez, A.; Fazil, M.; Khan, M.N.; Ali, B.; Javed, M.A.; Imran, M.; Shati, A.A.; Alfaifi, M.Y.; et al. Assessment of phytoremediation potential of native plant species naturally growing in a heavy metal-polluted industrial soils. *Braz. J. Biol.* **2022**, *84*, e264473. [CrossRef]
28. Shen, M.; Zhang, Y.; Zhu, Y.; Song, B.; Zeng, G.; Hu, D.; Wen, X.; Ren, X. Recent advances in toxicological research of nanoplastics in the environment: A review. *Environ. Pollut.* **2019**, *252*, 511–521. [CrossRef]
29. Shen, T.; Zhou, T.; Long, G.; Jiang, J.; Wang, S.; Zhang, C. Reinforced Self-Attention Network: A Hybrid of Hard and Soft Attention for Sequence Modeling. In Proceedings of the Twenty-Seventh International Joint Conference on Artificial Intelligence (IJCAI), Stockholm, Sweden, 13–19 July 2018; pp. 4345–4352.
30. O'Connor, D.; Peng, T.; Zhang, J.; Tsang, D.C.; Alessi, D.S.; Shen, Z.; Bolan, N.S.; Hou, D. Biochar application for the remediation of heavy metal polluted land: A review of in situ field trials. *Sci. Total Environ.* **2018**, *619*, 815–826. [CrossRef]
31. Yu, H.; Chin, M.; Yuan, T.; Bian, H.; Remer, L.A.; Prospero, J.M.; Omar, A.; Winker, D.; Yang, Y.; Zhang, Y. The fertilizing role of African dust in the Amazon rainforest: A first multiyear assessment based on data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations. *Geophys. Res. Lett.* **2015**, *42*, 1984–1991. [CrossRef]
32. Saini, A.; Manuja, S.; Kumar, S.; Hafeez, A.; Ali, B.; Poczai, P. Impact of Cultivation Practices and Varieties on Productivity, Profitability, and Nutrient Uptake of Rice (Oryza sativa L.) and Wheat (Triticum aestivum L.) Cropping System in India. *Agriculture* **2022**, *12*, 1678. [CrossRef]
33. Saleem, A.; Zulfiqar, A.; Ali, B.; Naseeb, M.A.; Almasaudi, A.S.; Harakeh, S. Iron Sulfate (FeSO4) Improved Physiological Attributes and Antioxidant Capacity by Reducing Oxidative Stress of Oryza sativa L. Cultivars in Alkaline Soil. *Sustainability* **2022**, *14*, 16845. [CrossRef]
34. Yasin, M.; Anwar, F.; Noorani, H.; Muhammad, S.; Mahmood, A.; Javed, T.; Ali, B.; Alharbi, K.; Saleh, I.A.; Abu-Harirah, H.A. Evaluating Non-Composted Red Cotton Tree (Bombax ceiba) Sawdust Mixtures for Raising Okra (Abelmoschus esculentus (L.) Moench) in Pots. *Agronomy* **2023**, *13*, 97. [CrossRef]
35. Hussain, S.; Khan, F.; Cao, W.; Wu, L.; Geng, M. Seed priming alters the production and detoxification of reactive oxygen intermediates in rice seedlings grown under sub-optimal temperature and nutrient supply. *Front. Plant Sci.* **2016**, *7*, 439. [CrossRef]
36. Jeffery, S.; Abalos, D.; Prodana, M.; Bastos, A.C.; Van Groenigen, J.W.; Hungate, B.A.; Verheijen, F. Biochar boosts tropical but not temperate crop yields. *Environ. Res. Lett.* **2017**, *12*, 053001. [CrossRef]
37. Biederman, L.A.; Harpole, W.S. Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenerg.* **2013**, *5*, 202–214. [CrossRef]
38. Fageria, N.K.; Baligar, V.C. Enhancing nitrogen use efficiency in crop plants. *Adv. Agr.* **2005**, *88*, 97–185.
39. Agegnehu, G.; Bass, A.M.; Nelson, P.N.; Bird, M.I. Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Sci. Total Environ.* **2016**, *543*, 295–306. [CrossRef]
40. Brantley, K.E.; Savin, M.C.; Brye, K.R.; Longer, D.E. Nutrient availability and corn growth in a poultry litter biochar-amended loam soil in a greenhouse experiment. *Soil Use Manag.* **2016**, *32*, 279–288. [CrossRef]

41. Ali, F.; Amin, M.; Cobanoglu, C. An integrated model of service experience, emotions, satisfaction, and price acceptance: An empirical analysis in the Chinese hospitality industry. *J. Hospit. Market. Manag.* **2016**, *25*, 449–475. [CrossRef]
42. Tammeorg, P.; Simojoki, A.; Mäkelä, P.; Stoddard, F.L.; Alakukku, L.; Helenius, J. Short-term effects of biochar on soil properties and wheat yield formation with meat bone meal and inorganic fertiliser on a boreal loamy sand. *Agric. Ecosys. Environ.* **2014**, *191*, 108–116. [CrossRef]
43. Gul, S.; Whalen, J.K. Biochemical cycling of nitrogen and phosphorus in biochar-amended soils. *Soil Biol. Biochem.* **2016**, *103*, 1–15. [CrossRef]
44. Khura, T.; Sundaram, P.K.; Lande, S.D.; Kushwaha, H.L.; Chandra, R. Biochar for climate change mitigation and ameliorating soil health—A review. *J. AgriSearch* **2015**, *2*, 1–6.
45. Xie, T.; Reddy, K.R.; Wang, C.; Yargicoglu, E.; Spokas, K. Characteristics and applications of biochar for environmental remediation: A review. *Crit. Rev. Environ. Sci. Technol.* **2015**, *45*, 939–969. [CrossRef]
46. Igalavithana, A.D.; Lee, S.-E.; Lee, Y.H.; Tsang, D.C.; Rinklebe, J.; Kwon, E.E.; Ok, Y.S. Heavy metal immobilization and microbial community abundance by vegetable waste and pine cone biochar of agricultural soils. *Chemosphere* **2017**, *174*, 593–603. [CrossRef] [PubMed]
47. Kalinke, C.; Oliveira, P.R.; Oliveira, G.A.; Mangrich, A.S.; Marcolino-Junior, L.H.; Bergamini, M.F. Activated biochar: Preparation, characterization and electroanalytical application in an alternative strategy of nickel determination. *Anal. Chim. Acta* **2017**, *983*, 103–111. [CrossRef] [PubMed]
48. Gonzaga, M.I.S.; Matias, M.I.D.A.S.; Andrade, K.R.; de Jesus, A.N.; da Costa Cunha, G.; de Andrade, R.S.; de Jesus Santos, J.C. Aged biochar changed copper availability and distribution among soil fractions and influenced corn seed germination in a copper-contaminated soil. *Chemosphere* **2020**, *240*, 124828. [CrossRef]
49. Suliman, W.; Harsh, J.B.; Abu-Lail, N.I.; Fortuna, A.-M.; Dallmeyer, I.; Garcia-Perez, M. Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties. *Biomass Bioenerg.* **2016**, *84*, 37–48. [CrossRef]
50. Tripathi, M.; Sahu, J.N.; Ganesan, P. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renew. Sustain. Energ. Rev.* **2016**, *55*, 467–481. [CrossRef]
51. Zhu, X.; Chen, B.; Zhu, L.; Xing, B. Effects and mechanisms of biochar-microbe interactions in soil improvement and pollution remediation: A review. *Environ. Pollut.* **2017**, *227*, 98–115. [CrossRef]
52. Abdul, R.N.F.; Abdul, R.N.S. The effect of biochar application on nutrient availability of soil planted with MR219. *J. Microb Biochem Technol.* **2017**, *9*, 583–586.
53. Cayuela, M.L.; Jeffery, S.; van Zwieten, L. The molar H: Corg ratio of biochar is a key factor in mitigating N2O emissions from soil. *Agri. Ecosys. Environ.* **2015**, *202*, 135–138. [CrossRef]
54. Ma, N.; Zhang, L.; Zhang, Y.; Yang, L.; Yu, C.; Yin, G.; Doane, T.A.; Wu, Z.; Zhu, P.; Ma, X. Biochar improves soil aggregate stability and water availability in a mollisol after three years of field application. *PLoS ONE* **2016**, *11*, e0154091. [CrossRef] [PubMed]
55. Awad, Y.M.; Wang, J.; Igalavithana, A.D.; Tsang, D.C.; Kim, K.-H.; Lee, S.S.; Ok, Y.S. Biochar effects on rice paddy: Meta-analysis. *Adv. Agr.* **2018**, *148*, 1–32.
56. Ahmad, M.; Ishaq, M.; Shah, W.A.; Adnan, M.; Fahad, S.; Saleem, M.H.; Khan, F.U.; Mussarat, M.; Khan, S.; Ali, B.; et al. Managing Phosphorus Availability from Organic and Inorganic Sources for Optimum Wheat Production in Calcareous Soils. *Sustainability* **2022**, *14*, 7669. [CrossRef]
57. Umar, U.d.; Ahmed, N.; Zafar, M.Z.; Rehman, A.; Naqvi, S.A.H.; Zulfiqar, M.A.; Malik, M.T.; Ali, B.; Saleem, M.H.; Marc, R.A. Micronutrients Foliar and Drench Application Mitigate Mango Sudden Decline Disorder and Impact Fruit Yield. *Agronomy* **2022**, *12*, 2449. [CrossRef]
58. Lehmann, J.; Skjemstad, J.; Sohi, S.; Carter, J.; Barson, M.; Falloon, P.; Coleman, K.; Woodbury, P.; Krull, E. Australian climate–carbon cycle feedback reduced by soil black carbon. *Nat. Geosci.* **2008**, *1*, 832–835. [CrossRef]
59. Schmidt, J.; Schulz, E.; Michalzik, B.; Buscot, F.; Gutknecht, J.L. Carbon input and crop-related changes in microbial biomarker levels strongly affect the turnover and composition of soil organic carbon. *Soil Biol. Biochem.* **2015**, *85*, 39–50. [CrossRef]
60. Ippolito, J.A.; Laird, D.A.; Busscher, W.J. Environmental benefits of biochar. *J. Environ. Qual.* **2012**, *41*, 967–972. [CrossRef]
61. Chatterjee, R.; Sajjadi, B.; Chen, W.-Y.; Mattern, D.L.; Hammer, N.; Raman, V.; Dorris, A. Effect of pyrolysis temperature on physicochemical properties and acoustic-based amination of biochar for efficient CO_2 adsorption. *Front. Energ. Res.* **2020**, *8*, 85. [CrossRef]
62. Liu, H.; Xu, F.; Xie, Y.; Wang, C.; Zhang, A.; Li, L.; Xu, H. Effect of modified coconut shell biochar on availability of heavy metals and biochemical characteristics of soil in multiple heavy metals contaminated soil. *Sci. Total Environ.* **2018**, *645*, 702–709. [CrossRef] [PubMed]
63. Khan, N.A.; Hasan, Z.; Jhung, S.H. Adsorptive removal of hazardous materials using metal-organic frameworks (MOFs): A review. *J. Hazard. Mater.* **2013**, *244*, 444–456. [CrossRef] [PubMed]
64. Feng, Z.; Zhu, L. Impact of biochar on soil N_2O emissions under different biochar-carbon/fertilizer-nitrogen ratios at a constant moisture condition on a silt loam soil. *Sci. Total Environ.* **2017**, *584*, 776–782. [CrossRef] [PubMed]
65. Jeffery, S.; Meinders, M.B.; Stoof, C.R.; Bezemer, T.M.; van de Voorde, T.F.; Mommer, L.; van Groenigen, J.W. Biochar application does not improve the soil hydrological function of a sandy soil. *Geoderma* **2015**, *251*, 47–54. [CrossRef]
66. Naeem, M.A.; Khalid, M.; Arshad, M.; Ahmad, R. Yield and nutrient composition of biochar produced from different feedstocks at varying pyrolytic temperatures. *Pak. J. Agric. Sci.* **2014**, *51*, 75–82.

67. Liu, P.; Liu, W.J.; Jiang, H.; Chen, J.J.; Li, W.W.; Yu, H.Q. Modification of bio-char derived from fast pyrolysis of biomass and its application in removal of tetracycline from aqueous solution. *Biores. Technol.* **2012**, *121*, 235–240. [CrossRef]
68. Wang, B.; Gao, B.; Fang, J. Recent advances in engineered biochar productions and applications. *Critic. Rev. Environ. Sci. Technol.* **2017**, *47*, 2158–2207. [CrossRef]
69. Butnan, S.; Deenik, J.L.; Toomsan, B.; Antal, M.J.; Vityakon, P. Biochar characteristics and application rates affecting corn growth and properties of soils contrasting in texture and mineralogy. *Geoderma* **2015**, *237*, 105–116. [CrossRef]
70. Ghorbani, M.; Amirahmadi, E.; Neugschwandtner, R.W.; Konvalina, P.; Kopecký, M.; Moudrý, J.; Perná, K.; Murindangabo, Y.T. The impact of pyrolysis temperature on biochar properties and its effects on soil hydrological properties. *Sustainability* **2022**, *14*, 14722. [CrossRef]
71. Rechberger, M.V.; Kloss, S.; Rennhofer, H.; Tintner, J.; Watzinger, A.; Soja, G.; Lichtenegger, H.; Zehetner, F. Changes in biochar physical and chemical properties: Accelerated biochar aging in an acidic soil. *Carbon* **2017**, *115*, 209–219. [CrossRef]
72. Dong, C.; Zhang, Z.; Lu, Q.; Yang, Y. Characteristics and mechanism study of analytical fast pyrolysis of poplar wood. *Energ. Convers. Manag.* **2012**, *57*, 49–59. [CrossRef]
73. Carrier, M.; Loppinet-Serani, A.; Denux, D.; Lasnier, J.-M.; Ham-Pichavant, F.; Cansell, F.; Aymonier, C. Thermogravimetric analysis as a new method to determine the lignocellulosic composition of biomass. *Biomass Bioenerg.* **2011**, *35*, 298–307. [CrossRef]
74. Giudicianni, P.; Cardone, G.; Ragucci, R. Cellulose, hemicellulose and lignin slow steam pyrolysis: Thermal decomposition of biomass components mixtures. *J. Anal. Appl. Pyrol.* **2013**, *100*, 213–222. [CrossRef]
75. Mimmo, T.; Panzacchi, P.; Baratieri, M.; Davies, C.A.; Tonon, G. Effect of pyrolysis temperature on miscanthus (Miscanthus × giganteus) biochar physical, chemical and functional properties. *Biomass Bioenerg.* **2014**, *62*, 149–157. [CrossRef]
76. Li, L.; Lai, C.; Huang, F.; Cheng, M.; Zeng, G.; Huang, D.; Li, B.; Liu, S.; Zhang, M.; Qin, L. Degradation of naphthalene with magnetic bio-char activate hydrogen peroxide: Synergism of bio-char and Fe–Mn binary oxides. *Water Res.* **2019**, *160*, 238–248. [CrossRef]
77. Zhang, X.; Gao, B.; Zheng, Y.; Hu, X.; Creamer, A.E.; Annable, M.D.; Li, Y. Biochar for volatile organic compound (VOC) removal: Sorption performance and governing mechanisms. *Biores. Technol.* **2017**, *245*, 606–614. [CrossRef]
78. Heitkötter, J.; Marschner, B. Interactive effects of biochar ageing in soils related to feedstock, pyrolysis temperature, and historic charcoal production. *Geoderma* **2015**, *245*, 56–64. [CrossRef]
79. Karimi, A.; Moezzi, A.; Chorom, M.; Enayatizamir, N. Application of biochar changed the status of nutrients and biological activity in a calcareous soil. *J. Soil Sci. Plant Nutr.* **2020**, *20*, 450–459. [CrossRef]
80. Li, L.; Tang, H.; Hu, Y. The effect of thickness on the mechanics of nanobeams. *Int. J. Eng. Sci.* **2018**, *123*, 81–91. [CrossRef]
81. 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*, 601–611. [CrossRef]
82. Das, J.P.; Marek, I. Enantioselective synthesis of all-carbon quaternary stereogenic centers in acyclic systems. *Chemic. Communic.* **2011**, *47*, 4593–4623. [CrossRef] [PubMed]
83. Novak, J.M.; Lima, I.; Xing, B.; Gaskin, J.W.; Steiner, C.; Das, K.C.; Ahmedna, M.; Rehrah, D.; Watts, D.W.; Busscher, W.J. Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. *Ann. Environ. Sci.* **2009**, *3*, 195–206.
84. Ferjani, A.I.; Jeguirim, M.; Jellali, S.; Limousy, L.; Courson, C.; Akrout, H.; Thevenin, N.; Ruidavets, L.; Muller, A.; Bennici, S. The use of exhausted grape marc to produce biofuels and biofertilizers: Effect of pyrolysis temperatures on biochars properties. *Renew. Sustain. Energ. Rev.* **2019**, *107*, 425–433. [CrossRef]
85. Zhao, L.; Cao, X.; Zheng, W.; Wang, Q.; Yang, F. Endogenous minerals have influences on surface electrochemistry and ion exchange properties of biochar. *Chemosphere* **2015**, *136*, 133–139. [CrossRef] [PubMed]
86. Lehmann, J.; Kuzyakov, Y.; Pan, G.; Ok, Y.S. Biochars and the plant-soil interface. *Plant Soil* **2015**, *395*, 1–5. [CrossRef]
87. Saeed, S.; Ullah, A.; Ullah, S.; Noor, J.; Ali, B.; Khan, M.N.; Hashem, M.; Mostafa, Y.S.; Alamri, S. Validating the Impact of Water Potential and Temperature on Seed Germination of Wheat (Triticum aestivum L.) via Hydrothermal Time Model. *Life* **2022**, *12*, 983. [CrossRef]
88. Jacobson, K.; Maheria, K.C.; Dalai, A.K. Bio-oil valorization: A review. *Renew. Sustain. Energ. Rev.* **2013**, *23*, 91–106. [CrossRef]
89. Bridgwater, A.V. Review of fast pyrolysis of biomass and product upgrading. *Biomass Bioenerg.* **2012**, *38*, 68–94. [CrossRef]
90. Bulmău, C.; Mărculescu, C.; Badea, A.; Apostol, T. Pyrolysis parameters influencing the bio-char generation from wooden biomass. *Univ. Politeh. Buchar. Sci. Bull. Ser. C Electr. Eng.* **2010**, *72*, 29–38.
91. Ryu, C.; Yang, Y.B.; Khor, A.; Yates, N.E.; Sharifi, V.N.; Swithenbank, J. Effect of fuel properties on biomass combustion: Part I. Experiments—Fuel type, equivalence ratio and particle size. *Fuel* **2006**, *85*, 1039–1046. [CrossRef]
92. Warnecke, R. Gasification of biomass: Comparison of fixed bed and fluidized bed gasifier. *Biomass Bioenerg.* **2000**, *18*, 489–497. [CrossRef]
93. Raj, R.E.; Kennedy, Z.R.; Pillai, B.C. Optimization of process parameters in flash pyrolysis of waste tyres to liquid and gaseous fuel in a fluidized bed reactor. *Energy Convers. Manag.* **2013**, *67*, 145–151. [CrossRef]
94. Haydary, J.; Jelemenskỳ, L.; Gašparovič, L.; Markoš, J. Influence of particle size and kinetic parameters on tire pyrolysis. *J. Anal. Appl. Pyrolys.* **2012**, *97*, 73–79. [CrossRef]
95. Zhang, Q.; Chang, J.; Wang, T.; Xu, Y. Review of biomass pyrolysis oil properties and upgrading research. *Energy Convers. Manag.* **2007**, *48*, 87–92. [CrossRef]

96. Zaror, C.A.; Pyle, D.L. The pyrolysis of biomass: A general review. *Proc. Indian Acad. Sci. Sect. C Eng. Sci.* **1982**, *5*, 269–285. [CrossRef]
97. Garcia-Perez, M.; Wang, X.S.; Shen, J.; Rhodes, M.J.; Tian, F.; Lee, W.-J.; Wu, H.; Li, C.-Z. Fast pyrolysis of oil mallee woody biomass: Effect of temperature on the yield and quality of pyrolysis products. *Ind. Eng. Chem. Res.* **2008**, *47*, 1846–1854. [CrossRef]
98. 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]
99. Lehmann, J.; Rillig, M.C.; Thies, J.; Masiello, C.A.; Hockaday, W.C.; Crowley, D. Biochar effects on soil biota–a review. *Soil Biol. Biochem.* **2011**, *43*, 1812–1836. [CrossRef]
100. Hammes, K.; Schmidt, M.W. Changes of Biochar in Soil. In *Biochar for Environmental Management*; Routledge: Oxfordshire, UK, 2012; pp. 201–214.
101. Mukherjee, A.; Zimmerman, A.; Harris, W. Surface chemistry variations among a series of laboratory-produced biochars. *Geoderma* **2011**, *163*, 247–255. [CrossRef]
102. Wu, G.; Nelson, M.; Ma, S.; Meng, H.; Cui, G.; Shen, P.K. Synthesis of nitrogen-doped onion-like carbon and its use in carbon-based CoFe binary non-precious-metal catalysts for oxygen-reduction. *Carbon* **2011**, *49*, 3972–3982. [CrossRef]
103. Asai, H.; Samson, B.K.; Stephan, H.M.; Songyikhangsuthor, K.; Homma, K.; Kiyono, Y.; Inoue, Y.; Shiraiwa, T.; Horie, Y. Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield. *Field Crop. Res.* **2009**, *111*, 81–84. [CrossRef]
104. Hangs, R.D.; Ahmed, H.P.; Schoenau, J.J. Influence of willow biochar amendment on soil nitrogen availability and greenhouse gas production in two fertilized temperate prairie soils. *Bioenergy Res.* **2016**, *9*, 157–171. [CrossRef]
105. 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]
106. Nelson, N.O.; Agudelo, S.C.; Yuan, W.; Gan, J. Nitrogen and phosphorus availability in biochar-amended soils. *Soil Sci.* **2011**, *176*, 218–226. [CrossRef]
107. Mukherjee, A.; Zimmerman, A.R. Organic carbo107n and nutrient release from a range of laboratory-produced biochars and biochar–soil mixtures. *Geoderma* **2013**, *193*, 122–130. [CrossRef]
108. Beesley, L.; Moreno-Jiménez, E.; Gomez-Eyles, J.L.; Harris, E.; Robinson, B.; Sizmur, T. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environ. Pollut.* **2011**, *159*, 3269–3282. [CrossRef] [PubMed]
109. Park, S.I.; Gocheva, I.; Okada, S.; Yamaki, J. Electrochemical properties of $NaTi_2$ $(PO_4)_3$ anode for rechargeable aqueous sodium-ion batteries. *J. Electrochem. Soc.* **2011**, *158*, A1067. [CrossRef]
110. Ma, J.; Saleem, M.H.; Yasin, G.; Mumtaz, S.; Qureshi, F.F.; Ali, B.; Ercisli, S.; Alhag, S.K.; Ahmed, A.E.; Vodnar, D.C.; et al. Individual and combinatorial effects of SNP and NaHS on morpho-physio-biochemical attributes and phytoextraction of chromium through Cr-stressed spinach (Spinacia oleracea L.). *Front. Plant Sci.* **2022**, *13*, 973740. [CrossRef]
111. Ma, J.; Saleem, M.H.; Ali, B.; Rasheed, R.; Ashraf, M.A.; Aziz, H.; Ercisli, S.; Riaz, S.; Elsharkawy, M.M.; Hussain, I.; et al. Impact of foliar application of syringic acid on tomato (Solanum lycopersicum L.) under heavy metal stress-insights into nutrient uptake, redox homeostasis, oxidative stress, and antioxidant defense. *Front. Plant Sci.* **2022**, *13*, 950120. [CrossRef]
112. Ma, J.; Ali, S.; Saleem, M.H.; Mumtaz, S.; Yasin, G.; Ali, B.; Al-Ghamdi, A.A.; Elshikh, M.S.; Vodnar, D.C.; Marc, R.A.; et al. Short-term responses of Spinach (Spinacia oleracea L.) to the individual and combinatorial effects of Nitrogen, Phosphorus and Potassium and silicon in the soil contaminated by boron. *Front. Plant Sci.* **2022**, *13*, 983156. [CrossRef]
113. Rees, F.; Sterckeman, T.; Morel, J.L. Root development of non-accumulating and hyperaccumulating plants in metal-contaminated soils amended with biochar. *Chemosphere* **2016**, *142*, 48–55. [CrossRef]
114. Bird, M.I.; Wurster, C.M.; de Paula Silva, P.H.; Bass, A.M.; De Nys, R. Algal biochar–production and properties. *Biores. Technol.* **2011**, *102*, 1886–1891. [CrossRef] [PubMed]
115. Kloss, S.; Zehetner, F.; Dellantonio, A.; Hamid, R.; Ottner, F.; Liedtke, V.; Schwanninger, M.; Gerzabek, M.H.; Soja, G. Characterization of slow pyrolysis biochars: Effects of feedstocks and pyrolysis temperature on biochar properties. *J. Environ. Qual.* **2012**, *41*, 990–1000. [CrossRef] [PubMed]
116. Usman, A.R.; Abduljabbar, A.; Vithanage, M.; Ok, Y.S.; Ahmad, M.; Ahmad, M.; Elfaki, J.; Abdulazeem, S.S.; Al-Wabel, M.I. Biochar production from date palm waste: Charring temperature induced changes in composition and surface chemistry. *J. Anal. Appl. Pyrolysis.* **2015**, *115*, 392–400. [CrossRef]
117. Shen, Z.; Som, A.M.; Wang, F.; Jin, F.; McMillan, O.; Al-Tabbaa, A. Long-term impact of biochar on the immobilisation of nickel (II) and zinc (II) and the revegetation of a contaminated site. *Sci. Total Environ.* **2016**, *542*, 771–776. [CrossRef]
118. Mayer, Z.A.; Eltom, Y.; Stennett, D.; Schröder, E.; Apfelbacher, A.; Hornung, A. Characterization of engineered biochar for soil management. *Environ. Prog. Sustain. Energy* **2014**, *33*, 490–496. [CrossRef]
119. Wang, R.-Z.; Huang, D.-L.; Liu, Y.-G.; Zhang, C.; Lai, C.; Zeng, G.-M.; Cheng, M.; Gong, X.-M.; Wan, J.; Luo, H. Investigating the adsorption behavior and the relative distribution of Cd^{2+} sorption mechanisms on biochars by different feedstock. *Biores. Technol.* **2018**, *261*, 265–271. [CrossRef]
120. Hadjittofi, L.; Pashalidis, I. Uranium sorption from aqueous solutions by activated biochar fibres investigated by FTIR spectroscopy and batch experiments. *J. Radioanal. Nucl. Chem.* **2015**, *304*, 897–904. [CrossRef]
121. Duan, W.; Oleszczuk, P.; Pan, B.; Xing, B. Environmental behavior of engineered biochars and their aging processes in soil. *Biochar* **2019**, *1*, 339–351. [CrossRef]

122. Yaashikaa, P.R.; Kumar, P.S.; Varjani, S.; Saravanan, A.A. Critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. *Biotechnol. Rep.* **2020**, *28*, e00570. [CrossRef]
123. 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. Safety* **2018**, *153*, 116–126. [CrossRef]
124. Zhu, Q.; Wu, J.; Wang, L.; Yang, G.; Zhang, X. Effect of biochar on heavy metal speciation of paddy soil. *Water Air Soil Pollut.* **2015**, *226*, 429. [CrossRef]
125. Sarraf, M.; Vishwakarma, K.; Kumar, V.; Arif, N.; Das, S.; Johnson, R.; Janeeshma, E.; Puthur, J.T.; Aliniaeifard, S.; Chauhan, D.K.; et al. Metal/Metalloid-Based Nanomaterials for Plant Abiotic Stress Tolerance: An Overview of the Mechanisms. *Plants* **2022**, *11*, 316. [CrossRef]
126. Safaei Khorram, M.; Fatemi, A.; Khan, M.A.; Kiefer, R.; Jafarnia, S. Potential risk of weed outbreak by increasing biochar's application rates in slow-growth legume, lentil (*Lens culinaris* Medik.). *J. Sci. Food Agric.* **2018**, *98*, 2080–2088. [CrossRef] [PubMed]
127. Vaccari, F.P.; Maienza, A.; Miglietta, F.; Baronti, S.; Di Lonardo, S.; Giagnoni, L.; Lagomarsino, L.; Pozzi, A.; Pusceddu, E.; Ranieri, R. Biochar stimulates plant growth but not fruit yield of processing tomato in a fertile soil. *Agric. Ecosys. Environ.* **2015**, *207*, 163–170. [CrossRef]
128. Hol, W.H.G.; Vestergård, M.; ten Hooven, F.; Duyts, H.; van de Voorde, T.F.J.; Bezemer, T.M. Transient negative biochar effects on plant growth are strongest after microbial species loss. *Soil Biol. Biochem.* **2017**, *115*, 442–451. [CrossRef]
129. Denyes, M.J.; Rutter, A.; Zeeb, B.A. Bioavailability assessments following biochar and activated carbon amendment in DDT-contaminated soil. *Chemosphere* **2016**, *144*, 1428–1434. [CrossRef]
130. Kim, S.; Lee, J.; Kang, J.S.; Jo, K.; Kim, S.; Sung, Y.-E.; Yoon, J. Lithium recovery from brine using a λ-MnO_2/activated carbon hybrid supercapacitor system. *Chemosphere* **2015**, *125*, 50–56. [CrossRef]
131. Joseph, S.; Kammann, C.I.; Shepherd, J.G.; Conte, P.; Schmidt, H.-P.; Hagemann, N.; Rich, A.M.; Marjo, C.E.; Allen, J.; Munroe, P. Microstructural and associated chemical changes during the composting of a high temperature biochar: Mechanisms for nitrate, phosphate and other nutrient retention and release. *Sci. Total Environ.* **2018**, *618*, 1210–1223. [CrossRef]
132. Zheng, J.; Chen, J.; Pan, G.; Liu, X.; Zhang, X.; Li, L.; Bian, R.; Cheng, K.; Jinwei, Z. Biochar decreased microbial metabolic quotient and shifted community composition four years after a single incorporation in a slightly acid rice paddy from southwest China. *Sci. Total Environ.* **2016**, *571*, 206–217. [CrossRef]
133. Gonzaga, M.I.S.; Mackowiak, C.; de Almeida, A.Q.; Wisniewski Jr, A.; de Souza, D.F.; da Silva Lima, I.; de Jesus, A.N. Assessing biochar applications and repeated *Brassica juncea* L. production cycles to remediate Cu contaminated soil. *Chemosphere* **2018**, *201*, 278–285. [CrossRef] [PubMed]
134. Jones, D.; Quilliam, R. Metal contaminated biochar and wood ash negatively affect plant growth and soil quality after land application. *J. Hazard. Mater.* **2014**, *276*, 362–370. [CrossRef] [PubMed]
135. Shackley, S.; Hammond, J.; Gaunt, J.; Ibarrola, R. The feasibility and costs of biochar deployment in the UK. *Carbon Manag.* **2011**, *2*, 335–356. [CrossRef]
136. Krull, E.; Lehmann, J.; Skjemstad, J.; Baldock, J.; Spouncer, L. The Global Extent of black C in Soils: Is it Everywhere. In *Grasslands: Ecology, Management and Restoration*; Nova Science Publishers, Inc.: New York, NY, USA, 2008; pp. 13–17.
137. Gore, A.; Nixon, C.; Slattery, J. *Our choice: A Plan to Solve the Climate Crisis*; Bloomsbury: London, UK, 2009.
138. Flannery, T. *Now or Never: Why we Must Act Now to End Climate Change and Create a Sustainable Future*; Open Road+ Grove/Atlantic: New York, NY, USA, 2009.
139. Hansen, V.; Müller-Stöver, D.; Munkholm, L.J.; Peltre, C.; Hauggaard-Nielsen, H.; Jensen, L.S. The effect of straw and wood gasification biochar on carbon sequestration, selected soil fertility indicators and functional groups in soil: An incubation study. *Geoderma* **2016**, *269*, 99–107. [CrossRef]
140. Lehmann, H.-T. *Panorama of Postdramatic Theatre, Postdramatic Theatre*; Routledge: Oxfordshire, UK, 2006; pp. 69–107.
141. Woolf, D.; Amonette, J.E.; Street-Perrott, F.A.; Lehmann, J.; Joseph, S. Sustainable biochar to mitigate global climate change. *Nat. Commun.* **2010**, *1*, 1–9. [CrossRef]
142. Salam, A.; Afridi, M.S.; Javed, M.A.; Saleem, A.; Hafeez, A.; Khan, A.R.; Zeeshan, M.; Ali, B.; Azhar, W.; Ulhassan, Z.; et al. Nano-Priming against Abiotic Stress: A Way Forward towards Sustainable Agriculture. *Sustainability* **2022**, *14*, 14880. [CrossRef]
143. Teodoro, M.; Trakal, L.; Gallagher, B.N.; Šimek, P.; Soudek, P.; Pohořelý, M.; Beesley, L.; Jačka, L.; Kovář, M.; Seyedsadr, S.; et al. Application of co-composted biochar significantly improved plant-growth relevant physical/chemical properties of a metal contaminated soil. *Chemosphere* **2020**, *242*, 125255. [CrossRef]
144. Murtaza, G.; Ahmed, Z.; Usman, M.; Tariq, W.; Ullah, Z.; Shareef, M.; Iqbal, H.; Waqas, M.; Tariq, A.; Wu, Y.; et al. Biochar induced modifications in soil properties and its impacts on crop growth and production. *J. Plant Nutr.* **2021**, *44*, 1677–1691. [CrossRef]
145. Joseph, S.; Cowie, A.L.; Van Zwieten, L.; Bolan, N.; Budai, A.; Buss, W.; Cayuela, M.L.; Graber, E.R.; Ippolito, J.A.; Kuzyakov, Y.; et al. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy* **2021**, *13*, 1731–1764. [CrossRef]
146. Asadi, H.; Ghorbani, M.; Rezaei-Rashti, M.; Abrishamkesh, S.; Amirahmadi, E.; Chengrong, C.H.; Gorji, M. Application of rice husk biochar for achieving sustainable agriculture and environment. *Rice Sci.* **2021**, *28*, 325–343. [CrossRef]
147. Allohverdi, T.; Mohanty, A.K.; Roy, P.; Misra, M. A review on current status of biochar uses in agriculture. *Molecules* **2021**, *26*, 5584. [CrossRef] [PubMed]

148. Simiele, M.; Argentino, O.; Baronti, S.; Scippa, G.S.; Chiatante, D.; Terzaghi, M.; Montagnoli, A. Biochar Enhances Plant Growth, Fruit Yield, and Antioxidant Content of Cherry Tomato (Solanum lycopersicum L.) in a Soilless Substrate. *Agriculture* **2022**, *12*, 1135. [CrossRef]
149. Hussain, T.; Ahmed, S.R.; Lahori, A.H.; Mierzwa-Hersztek, M.; Vambol, V.; Khan, A.A.; Rafique, L.; Wasia, S.; Shahid, M.F.; Zengqiang, Z. In-situ stabilization of potentially toxic elements in two industrial polluted soils ameliorated with rock phosphate-modified biochars. *Environ. Pollut.* **2022**, *309*, 119733. [CrossRef] [PubMed]