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Review

The Impacts of Biochar-Assisted Factors on the Hydrophysical Characteristics of Amended Soils: A Review

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Abstract: Biochar is known as a well-developed porous carbonaceous material with multifunctional abilities that can enhance the physical properties of soils. However, the lack of certainty about the consequences of biochar application to soils has limited its acceptability. Application of biochar can lead to a series of changes in the physical functions of soil, which are crucial in both agricultural and environmental management. The type of feedstock, pyrolysis conditions, size of particles, and rate of amendments are responsible for biochar effectiveness. Concurrently, the physical characteristics of soil, such as particle-size distribution, can intensify the impacts. Beside the physical attributes, the chemical components and interactions between biochar and the soil interface may play an important role. The chemical properties, such as the value of electrical conductivity, pH and zeta potential, are the remarkable parameters in the hydrophysical behavior. The summary proposes that biochar has a great contribution In enhancing the definite range of aggregation formation, reduction of compaction and shear strength frequency and/or intensity, improvement of microorganisms activity, and abundance. Simultaneously, biochar plays a devastating role by filling the pores, blocking the water flow pathways, and inhibiting macro fauna growth. Particle size of biochar as a major factor, and surface functional groups as a minor factor, affect the performance of biochar in improving the hydrophysical properties of amended soils. The increment in the dosage of biochar application is not promising to enhance the physical properties of soils. Therefore, it is necessary to find a balance between the consumption of biochar and promotion of the soil-water dynamic. This review provides an overview of fastidious perspectives on how to achieve an efficient and sustainable use of biochar in hydrophysical properties.

Keywords: biochar; pyrolysis condition; porosity; aggregation formation; hydraulic conductivity; compaction

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1. Introduction

In recent years, anthropogenic problems threaten environmental health, especially human life. Menaces, such as rapid population growth, lack of agriculture production, soil degradation, soil pollution, air, water, greenhouse gas emissions, expanding rate of waste production, and other problems, urgently need a sustainable solution. The solution should be focused on environmentally friendly substances with the ability to utilize resources comprehensively, such as biochar [1–6].

Biochar, as a carbonaceous, porous, and aromatic material, has origin-related properties which derive from a wide range of feedstock after pyrolysis is performed under a controlled temperature in no or limited oxygen conditions. Biochar contains a variety of surface functional groups, nutritional value, and a small fraction of easily degradable components. Biochar could increase the chemical properties of soils and include cation-exchange capacity and pH. In recent years, Biochar studies have focused on small- (laboratory, greenhouse), and large-scale (field) experiments with a focus on environmental protection, enriching agriculture production, industry wastes treatment, etc. Alongside the chemical and physical benefits of biochar in soil, water flux and moisture distribution in the soil's profile are major concerns because biochar creates a redistribution of nutrients, co-transport/facilitated transport of contaminant at the presence of biochar, and the transport of biochar particles individually [7,8].

An improved soil–plant–water environment may be caused by the application of biochar in the soil, which can be a benefit for magnifying the particle-surface area, pore rearrangement, and enhancing microstructural stability [9]. However, there are numerous studies showing that no significant changes have been observed in the water retention and moisture characteristics in soil by the application of biochar [10,11]. This is because of the loss of inter-particle cementation, which partially occurs at a given pore-water pressure by adding biochar to soil [12]. Generally, the soil's water retention improves by increasing the water retained in pores by capillary force, due to application of biochar. Additionally, the water-holding capacity of biochar strongly depends on the total pore volume, which plays an important role compared to the surface area, surface functional groups and porosity structure [4,6].

Several unique properties of biochar include a low bulk density and large surface area, and a highly porous structure can change the chemical and biological properties of soils [2,13]. The direct effect of biochar in the chemistry of soil solution and the habitation of the microbial community has been demonstrated wisely and mentioned, which can be positive or negative. Accordingly, the indirect effect of biochar application could be explained in complex interactions in the soil profile. Several physical properties are affected by the application of biochar, such as porosity, saturated hydraulic conductivity, and aggregation formation. The shape and size distribution of pores and canals, saturated hydraulic conductivity, compaction/penetration, pH, ionic strength, types of ions and zeta potential, constituents and texture of soil, application rate, and the surface properties of biochar are major factors in water flow regimes [14,15]. The specific objectives of this review are as follows: (i) the effects of adding biochar on the hydrophysical properties of soil; (ii) assessing the interaction of biochar with the soil's chemical, physical and biological properties; and (iii) addressing future research directions regarding biochar and soil types from an environmental-management perspective.

2. Pore Connectivity and Pore Size Distribution

The alteration in pore distribution, and irregularity in pore shapes are repercussions of applying biochar to soils, resulting in the complexity of pore structure. The addition of biochar may enhance the formation of narrow and medium pores. It is believed that rearrangement of inter-aggregate pore space is enhanced in biochar amended soils [16,17]. In contrast, the increment of tortuosity in soil media could happen because of pores filling with biochar particles, thus impacting the inter-pore and intra-pore space in the soil profile [18,19]. Although the biochar can increase the inter-porosity, mean pore radii can decrease by 25% [20–22]. Studies have showed that the application of biochar significantly impacts the distribution of pores with a diameter between 0.0003 to 0.03 μm in the amended soils, but by referring to the permanent wilting point, only the pores more than 0.2 μm are useful for plants' roots [10,21–23]. The pores > 30 μm in diameter are a path to water transition and are not useful for plants directly.

By considering soil type, biochar may alter the soil's pore-size distribution by direct and indirect intervention in the soil aggregate stability or changes in the current pore space [9]. Enhancements in the macroaggregate formation can help to improve the mesopores (0.2 to 56 μm) contents, which can retain more available water whereby macropores generally facilitate soil drainage and aeration, and are suitable for flood stress [24–26]. Additionally, adding biochar could change the wettability conditions and fluid-migration pattern due to changes in the pore-throat radius and pore connectivity [27,28].

The increasing of mesopores (0.2 to 29 μm in diameter) by the application of biochar is indicated in other studies. These studies showed that the application of biochar to the expansive clayey soil considerably enhanced the porosity of the soil (ranging from 0.003 to 360 μm), and especially improved the formation of mesopores (6 to 45 μm), but had no significant effect on crytopores (<0.1 μm) [25–28].

2.1. Effect of Biochar's Particle Size

Many studies have indicated that the total porosity of amended soils directly depends on the rate and size of the biochar particles [29–80]. The small particles of biochar do not have adequate effects on different pore sizes. Additionally, the smaller size of biochar could reduce the volume of some pores, rather than increase the volume of larger pores. The smaller particles (0.05–1.00 mm) of biochars can increase the gravimetric water-holding capacity more than larger particles (2–4 mm) in coarse textured soils [29]. The application of unsieved biochar to soils results in the formation of pores of at least 300 to 3000 μm, especially the formation of pores > 1200 μm [10,24]. Distinguishing the sensitivity (impressive pores size) of adding biochar requires sufficient knowledge of particles from both media, including type of soil, as well as the structure, rate, type and size of applied biochar [30].

By adding different sizes of biochar particles to the soil, the pore-size distribution is affected differently. In a complex combination of soil aggregate and biochar particles sizes, only the pores with a specific range of diameter are impacted, while the rest of the range may have opposite changes or even remain unaltered [23]. Size and dosage effectiveness on the porosity, tortuosity and Ks are shown in Figure 1.

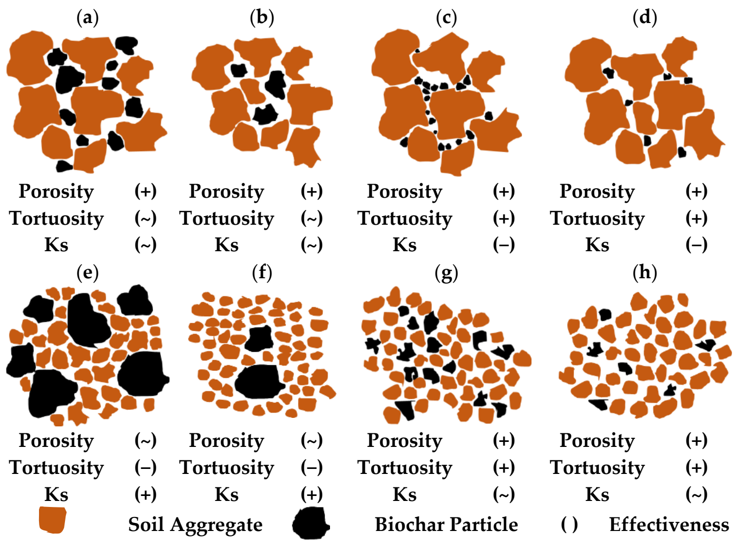

Figure 1. Conceptual diagram illustrating the effects of size and dosage of biochar particles in coarse- (top row) and fine-textured soil (bottom row), by large (**a**,**b**,**e**,**f**) and fine particle size (**c**,**d**,**g**,**h**), at a high (**a**,**c**,**e**,**g**) and low dosage (**b**,**d**,**f**,**h**) on the porosity, tortuosity and hydraulic conductivity of soils. The letters of +, —, and ~, mean positive, negative and conditional effectiveness, respectively. The diagram was developed based on the published literature (Major et al., 2010 [36]; Glab et al., 2016 [30]; Obia et al., 2016 [23]; Verheijen et al., 2019 [29]; Li et al., 2017 [32]; Githinji, 2013; Herath et al., 2013 [39]; Barnes et al., 2014 [57]; Liu et al., 2016 [58]; Sorrenti et al., 2016 [59]; Dokoohaki et al., 2017 [49]; Esmaeelnejad et al., 2017 [18]; Wang et al., 2020 [37]; Chen et al., 2021 [31]; Hussain et al., 2021 [60]).

The nano size of particles would change the distribution of the soil pore structure, and consequently, the degree of anisotropy and fractal dimension could be affected as a result. Additionally, the results revealed that the application of nano-sized particles can increase the Ks of sandy-loam soil besides the decline of cumulative infiltration values in mixed layers. The rate of application of nano particles indirectly manipulates the surface energy of soil particles, negatively, and the water repellency, positively [31,32].

2.2. Effect of Feedstock Type

The pore distribution is affected by biochar size more than biochar type, as a consequence of aggregate formation. The variation of pore size distribution in amended soil is initially affected by biochar inter-porosity, followed by the impact of biochar on pore geometry and distribution via two main pathways. The rearrangement of soil-biochar particles and the enhancement of aggregation formation may determine the final result of impact on the pore distribution [32–34]. Additionally, the settlement of biochar particles in macropores directly affects the physical properties of amended soils, such as pore geometry [24,33,34]. The internal pore size in biochar particles has a wide range from <2 nm up to >365 μm based on feedstock type and pyrolysis condition [2,33]. Biochar produced from rice straw, rice husk, wheat straw, maize straw and bamboo could enhance the macroaggregate (>5 mm) after three consecutive crops plantations. Increasing the macropores in soils (greater than 30 μm) was due to the application of straw biochar, compared to woody or waste sludge biochar [35].

2.3. Effect of Pyrolysis Condition

The porosity of rice husk at two pyrolysed temperatures is higher than woodchip and dairy manure biochar, although the surface area ranking was, respectively, woodchip > rice husk > dairy manure at high temperatures (700 °C) and dairy manure > rice husk > woodchip biochar at low temperatures (300 °C) [36]. The low and high temperature pyrolyzed, corn stover biochars increased the frequencies of macropores at Alfisols and mesopores at Andisols, and was enough to enhance the drainage in poorly drained Alfisols [39]. Adding biochar that was produced at a high temperature enhanced the porosity of soils more than biochar pyrolyzed at low temperature [11,37,38].

3. Water Movement and Soil Media

3.1. Saturated Hydraulic Conductivity

Changing the pore size distribution and improving the binding of soil aggregate to other soil constituents, as well as limiting or reducing the mobility of water in some types of soils, causes biochar to potentially impact the Ks values [39–55]. The Ks alterations after the application of biochar in soils can be divided into positive, negative, and no significant changes. Generally, differences between the median size of biochar particles and the medium size of soil particles govern the final impact on the value of Ks [39,49,56–59]. The interstitial biochar-soil particle space and pores of biochar particles are responsible for water flux in the soil profile. So, if the application of biochar increases the tortuosity or diminishes the pore-void space, then the Ks decreases compared to the bare soil [57]. The meta-analysis of the hydro-physical properties in amended soils revealed that if the biochar application causes an increase in inter-porosity, then Ks increases simultaneously; additionally, a decrease in the inter-porosity value declines regardless of soil texture and the size of biochar particles [20,21]. Factually, every influential variation in the skewness of pore size distribution happened by biochar application, which could change the connectivity of air clusters, distribution and diameter of water-occupied pores, and therefore, water flux in the soil profile.

3.1.1. Soil Texture

Regardless of the type of biochar, the type of soil definitely explains the outcomes of the application of biochar (Table 1). The double-edged effects of biochar can be observed in different soils. The different types of movements in particles and aggregates lead to obstruction of water flow through soil pores. Overall, the reduction of Ks in coarse textured soils is explained by an increase in tortuosity that is caused by decreasing of macropores, and clogging of pores. The reduction of Ks in coarse textured soils is different if impacted by finer or coarser particles. At finer particles, the pore filling, increasing of tortuosity, and reduction of pore-throat size are the main effects of decreases of Ks, but at coarse particles, the reduction of Ks is associated with increasing of tortuosity due to bimodal size distribution (Table 1) [57,58]. Additionally, strong capillary and adsorptive forces can prohibit water molecules from moving as fast as before [57–62]. The chemical compounds on the surface of biochar particles, mainly have a negative effect on plasticity index, specific gravity, and Ks in pure-sandy textures [63].

Table 1. The changes in the effect of biochar addition on total porosity and saturated hydraulic conductivity as a function of soil texture.

Soil Texture	Feedstock Type	Pyrolysis Temp (°C)/ Rate (°C min^{-1})	Experiment Scale	Application Dosage	IOP *	IOKs **	Ref
Clay	Wood residue	—	Column	4, 8, 16 t ha^{-1}	+	+	[39]
	Sugercane bagasse	600	Lysimeter	3%	+	+	[40]
	Biosolids	600	Lysimeter	1%	–	–	[40]
	Sugercane bagasse	400, 600, 800	Column	1, 3, 5%	+	+	[41]
	Hard wood pellet	500	Column	1, 2, 5%	+	+	[64]
	Pine wood chips	500	Column	1, 2, 5%	+	+	[64]
	Hard wood chips	500	Column	1, 2, 5%	+	+	[64]
	Oat hulls	500	Column	1, 2, 5%	+	+	[64]
	Hardwood	500	Field	2.5, 5%	0	+	[42]
	Herbaceous shrub	500	Column	2.5, 5, 10%	0	+	[42]
	Peanut shell	500	Column	0, 5, 20%	+	+	[43]
Clay loam	Mesquite wood	400/6	Column	10%	+	+	[57]
	Hard wood	450	Column	0.50%		+	[65]
	Wood chip	525	Pot	3%	+	+	[40]
	Miscanthus grass	450/15	Pot	25 t ha^{-1}	0	0	[44]
	Wheat straw	450	Field	2.5, 5, 10, 20, 30, 40 t ha^{-1}	+	+	[45]
	Beech wood	—	Field	0, 24, 72 t ha^{-1}	+	+	[46]
Loam	Switch grass	375–475	Field	1%	+		[47]
	Hard wood pellet	500	Column	1, 2, 5%	0	0	[64]
	Pine wood chips	500	Column	1, 2, 5%	0	0	[64]
	Hard wood chips	500	Column	1, 2, 5%	0	0	[64]
	Oat hulls	500	Column	1, 2, 5%	0	0	[64]
	Grape stalks	600	Column	2, 5%		–	[62]
	Dairy manure	300, 500, 700	Column	5%	+	(+700)	[48]
	Wood chip	300, 500, 700	Column	5%	+	(+700)	[48]
Loamy (Fine)	Hardwood charcol	—	Column	5, 10, 20 g kg^{-1} soil	+	0	[49]

Table 1. *Cont.*

Soil Texture	Feedstock Type	Pyrolysis Temp (°C)/ Rate (°C min^{-1})	Experiment Scale	Application Dosage	IOP *	IOKs **	Ref
Loamy sand	Maize (whole plant)	750/20	Column, Field	1, 2.5, 5%	+	0	[73]
	Woodchips	750	Column	2%	+	+	[50]
	Digestate corn	750	Column	2%	+	+	[50]
	Peanut hulls	500	Column	0, 25, 50, 75, 100%	+	–	[56]
	Pine	550	Column	2, 4, 6%	–	(~)	[21]
Organic rich soil	Mesquite wood	400/6	Column	10%	–	–	[57]
Sand	Beechwood	550/15	Column, Field	0, 1, 2.5, 5%	+	0	[73]
	Grassland species	400	Column, Field	1, 5, 20, 50	0	0	[11]
	Mesquite wood	400 -/5	Column	2%	+	+	[34]
	Miscanthus straw pellet	550, 700	Column, Field	10 t ha^{-1}	0	0	[51]
	Oil seed rape	550, 700	Column, Field	10 t ha^{-1}	0	0	[51]
	Rice husk	550, 700	Column, field	10 t ha^{-1}	0	0	[51]
	Sewage sludge	550, 700	Column, field	10 t ha^{-1}	0	0	[51]
	Wheat straw pellet	550, 700	Column, field	10 t ha^{-1}	0	0	[51]
	Softwood pellet	550, 700	Column, Field	10 t ha^{-1}	0	0	[51]
	Cotton	300, 400, 500	Pot	5%	+	–	[53]
	Swine manure	300, 400, 500	Pot	5%	+	–	[53]
	Eucalyptus	300, 400, 500	Pot	5%	+	–	[53]
	Sugarcane filtercake	300, 400, 500	Pot	5%	+	–	[53]
	Black locust	300, 400, 500	Column	10, 20 t ha^{-1}	0	–	[54]
	Switch grass	500	Pot	0, 5, 10, 15, 20, 25%	+	+	[55]
	Pine	450, 550	Column		+	–	[68]
	Poplar	450, 550	Column		+	–	[68]
Sand (coarse)	Hard wood pellet	500	Column	1, 2, 5%	+	–	[64]
	Pine wood chips	500	Column	1, 2, 5%	+	–	[64]
	Hard wood chips	500	Column	1, 2, 5%	+	–	[64]
	Oat hulls	500	Column	1, 2, 5%	+	–	[64]
Sand (fine)	Wood chip	500–600	Column	20, 50, 100 g kg^{-1} soil	+	–	[61]
	Miscanthus grass	450/15	Pot	25 t ha^{-1}	0	0	[44]
	Hard wood pellet	500	Column	1, 2, 5%	+	–	[64]
	Pine wood chips	500	Column	1, 2, 5%	+	–	[64]
	Hard wood chips	500	Column	1, 2, 5%	+	–	[64]
	Oat hulls	500	Column	1, 2, 5%	+	–	[64]
	Mesquite wood	500	Column	5, 10, 15%	–	–	[52]
Sand (silica sand)	Pine	550	Column	2, 4, 6%	+	(~)	[21]
Sandy clay loam	Hardwood	500	Column	0, 3, 6%	+	+	[74]

Table 1. *Cont.*

Soil Texture	Feedstock Type	Pyrolysis Temp (°C)/ Rate (°C min^{-1})	Experiment Scale	Application Dosage	IOP *	IOKs **	Ref
Sandy loam	Wood chip	500–600	Column	20, 50, 100 g kg^{-1} soil	+	-	[61]
	Corn cob	500–550	Field	10, 20 t ha^{-1}	+	+	[75]
	Wood chip	550/10	Column	2%	+	−	[18]
	Wood chip	350/10	Column	2%	+	−	[18]
	Acacia green waste	—	Field	47 t ha^{-1}		+	[10]
	Switch grass	375-475	Field	1%	+		[47]
	Powered wood charcol	—	Column	0, 0.5, 1.5, 2.5, 5%		−	[76]
	Pine	550	Column	2, 4, 6%	+	−	[21]
	Grape stalks	600	Column	2, 5%		−	[62]
	Mesquite wood	400/6	Column	10%	−	−	[57]
	Wheat straw	525	Pot	3%	+	+	[40]
Silt loam	Corn stover	350/36	Column	1.13, 1.50 t ha^{-1}	+	+	[39]
	Corn stover	550/51	Column	1.00, 1.33 t ha^{-1}	0	(+350)	[39]
	Pine	550	Column	2, 4, 6%	0	+	[21]
	Vineyard-pruning	525, 400	Pot	3%	+	+	[40]
	Beech wood	—	Field	0, 24, 72 t ha^{-1}	+	+	[46]
	Wheat straw	450	Column	27 t ha^{-1}	0	0	[79]
Silty clay	Apple branch	450	Column, Field	0, 1, 2, 4%	+	+	[77]
	Diary manure	500/10	Pot	2%		0	[78]
Silty clay loam	Wood chip	500–600	Column	20, 50, 100 g kg^{-1} soil	+	+	[61]
	Switch grass	375–475	Field	1%	+		[47]
Silty sand (compacted)	Mesquite wood	500	Column	5, 10, 15%	+	+	[52]

(—) No data; * Impact on the total porosity of soil; ** Impact on the saturated hydraulic conductivity; Note: The indicators of (+), (−), (0) and (~) represents of positive, negative, not significant, and conditionally impact.

Biochar particles in clay or heavy textured soils could have a greater positive impact on soil Ks than their slightly negative effects on sandy and light textured soils (Table 1) [39,56–58]. The mediate percentage of biochar application (1 or 2%) to clay–loam soil may cause an increase of Ks [64]. In acidic, clayey soils, such as the African highlands, the application of oak and corn biochar did not affect the soil Ks, but instead decreased the relative Ks. The higher ratio of adsorption of Na and K in corn biochar led to more decreases in relative Ks than oak biochar [65]. Through comparing the soil types, biochar can be seen to have positive effects on hydraulic properties in certain soils more than others, which are closely associated with the type of biochar and soil. By the application of high- and low-temperature pyrolysis of corn stover to soils, the change of physical properties was more evident in Alfisol than Andisol, which increased the Ks in Alfisol; however, low-temperature pyrolyzed biochar could increase the Ks in Andisol [39].

3.1.2. Biochar Characteristics

An increase in total porosity is indicated as the main reason for the increase in Ks, and pore reduction or clogging of intra-pores has been reported as major factors in decreasing Ks (Table 1) [60]. The bimodal, particle-size distribution may have been caused by the application of the coarser biochar particles that lead to more compact packing, tortuosity and lower values of Ks (Figure 1). As an imperative fact, the increment in porosity by the application of biochar does not mean an increase of Ks. It can be due to the filling of the pores by biochar particles and a significant reduction of the pore-throat's size [18]. However, some studies have shown that the application of biochar can change the structure of amended soil and increase the soil pores (>300 μm), even up to 164% after one year (3% w/w), but has no significant effect on the value of Ks compared to un-amended soil (application rate 1% and 3% w/w) [37].

The large size of biochar particles may have no significant effect on water retention in coarse-textured soil, which is caused by a lack of suction [66]. As the difference effects various biochar-particle sizes, the biochar significantly reduced the Ks of subsoil (0.17 ± 0.07 cm h^{-1}) per a percent of added biochar in sandy-loam soil, which could be due to the clogging of soil pores by particles, or a collapse in the soil structure near water saturation [67]. Additionally, the grinding of biochar reduces Ks more than the original biochar because of destroyed pore structure. The redox activity properties of nano-sized biochar's can impact the aggregation or coagulation of particles in pores, as well [68].

The type of feedstock has a greater impact than the pyrolysis condition on the soil's functional properties (Table 1) [69]. The addition of biochar to desert soil from woody, rice husk and manure feedstock, pyrolyzed at low and high temperatures, decreased Ks significantly compared to no added soil [36]. Water penetration dynamics may be enhanced significantly by the application of sludge-produced biochar through influencing the capillary-rise process, compared to the production of vegetable feedstock [69]. The wettability of the inner and outer surfaces of biochar can be different significantly, which is a subset of biochar type and pyrolysis conditions [69,70].

The depth and dosage of biochar application have the influence on water infiltration rate (Table 1) [71]. Additionally, the method of mixing biochar into soil may influence the Ks. Adding single layers of biochar to sandy soil increases the Ks, but when the same biochar is mixed with whole soil, it leads to a reduction of Ks [68].

The aging process has a substantial influence on imbibition in soil after the application of biochar [59]. After one year of applying different biochar to soils, the contact angle of water decreased, testifying the hydrophobicity of the initial biochar that disappeared after one year [69]. With the elapsing time since the application of biochar, there was no particular trend in Ks variation, but the reduction in the value of the contact angle happened at both low- and high-temperature pyrolyzed biochars [36,69].

The effect of hydrophobicity/hydrophilicity of the pores are fundamental features in water permeability in nano and micropores [70]. Larger portions of water molecules interact with the wall of pores. Therefore, the friction effect increases by decreasing pore size [72]. Hydrophobic pores impede water permeability to achieve high values. Furthermore, the hydrophobicity of biochar could affect water entering into its internal structure. The positive, water-entry pressure of hydrophobic biochar (produced at <400 °C), inhibits water molecules from entering intra-pores. The water flow in pores reduces if the hydrostatic pressure is less than the water entry pressure [22,58]. In some cases, hydrophobicity can occur by fungal colonization in local spots where nutrient availability is induced by biochar presence [73]. Additionally, if the soil has the ability to oxide the biochar surface faster via chemical and biological reactions, then, over time, the intensity of the exhibited O-containing functional groups improves, and the water holding potentials change in favor of Ks [59].

The volumetric flux of water is negatively related to the hydrophilic–hydroxyl group concentration. Hence, the hydrogen-bond interactions between water molecules and the hydroxyl group decrease the water-diffusion rate [72,74]. In the nano-channels, the water viscosity is anisotropic and has a non-monotonic variation. The reduction in the velocity of water may be caused by hydrogen-bond networks, which are in close relation with the density of both hydroxyl- and carboxyl-surface functional groups [72]. The large, steric, geometric structure of carboxyl groups has a negative impact on water transport in pores and channels. In contrast, H atoms can promote water transport because of their low-resistance steric structure. When the surface-charge density increases on biochar particles, it could lead to the dipoles of water molecules reorienting, with oxygen atoms facing the positively charged surfaces [80].

Meanwhile, the application of biochar decreases the Ks until the plant's root system grows and spreads. After the plant's system is established, the presence of biochar acts as a promoter to the plant's root. The results conclude that the combination of biochar and plant may cause greater Ks than soils with only plant or biochar. As a long-term impact of biochar application on the growth of plants, such as grass, Ks may increase 200 times more, compared to soil without either plant or biochar [81].

3.1.3. Blocking, and Restraining

As the biochar particles become micro- and/or nano-sized, the O-containing surface-functional groups and mineral components increase, but aromatic clusters decrease [19]. Additionally, the formation of large biochar aggregates in soil pores is plausible and directly related to solution chemistry in pores. The aggregation is positively associated with the density of functional groups and the degree of oxidation on the biochar surface that are functions of the van der Waals attraction; electrostatic repulsion [82,83]. The presence of divalent cations may enhance aggregation in biochar-amended, fine-textured soils through double-layer compression and cation binding. The presence of Ca^{2+}, Mg^{2+} and Al^{3+} on the surface of nano-sized biochar particles can lead them to be deposited onto a medium surface, but via the adsorption of Na^{+} on the surface of particles, charge reversal happens, and the transport of nanoparticles enhances the soil medium, unless exposed to much higher concentrations, rather than more highly charged exchangeable cations [84]. Strongly attaching nonpolar components to the surface of biochar particles can also decrease their mobility and decrease the zeta potential of the surface [84]. Small particles of biochar can clog the large, water-conducting pores and form bottlenecks, which can lead to an initial reduction in Ks [85]. Micro-sized, biochar particles retention may be referred to their surface-charge heterogeneity and particle straining. By decreasing the particle size, the influence of straining and surface charge becomes insignificant in nanoparticles retention [85,86]. Additionally, a lower pyrolysis temperature of biochar particles has a high affinity to movement in the soil profile, due to a greater, repulsive, acid–base interaction [86]. Pore blocking transitioned to ripening by increasing the ionic-strength level. Additionally, instantaneously blocking the channels and main paths of transient water in soil can lead to the hammer effect [87]. This phenomenon happens by settling down of suspended particles in a solution, or the coagulation of biochar/soil particles [85].

3.2. Evaporation

Soil-moisture variation is fundamental to managing pressing nature concerns, from agricultural to environmental issues, etc., and is a key factor to determining the functionality of ecosystems. Water availability and surface-energy balance governs the ecosystem productivity that is directly associated with water movement in the soil profile. Evaporation, as a main route of soil-moisture loss, is a catenary-physical process, which is regulated by the internal capillary flow of the soil structure [88]. Biochar acts as a substantial storage of water and promotes water movement because of its ability to develop the total porosity and pore-size distribution in amended soils. Generally, it was found that the treatment of soils by biochar lead to a reduction of cumulative evaporation, compared to non-treated soils [88]. However, research indicates that the results of using the biochar application on evaporation are closely associated to soil texture, and the size of biochar particles [71,89]. Additionally, high-dosage application of biochar may promote the entire process of evaporation, due to preserving soil-hydraulic dynamics [88]. Research results show that the addition of biochar can manipulate micropores in soils and, consequently, decrease the evaporation rate; although, the cumulative evaporation increases by enhancing the diffusion-limited, vapor-transport stage of evaporation. However, the decisive role of biochar on evaporation are determined by its particle size and dosage. Increments in the dosage of coarse-sized biochar (2–0.25 mm) could cause a reduction of cumulative evaporation via increasing fine-sized biochar, which, in turn, increases the evaporation (<0.25 mm) [89,90]. Additionally, the deeper mixing of biochar can inhibit evaporation more than simply adding biochar to the surface of soils [90]. Studies reveal that woody biochar has less impact on evaporation than other types of biomass due to the variation of structures [68,91,92]. Additionally, the application of biochar can change the albedo, storage, and reflection capacity of soils. These changes could, respectively, control the temperature gradient in soils. Additionally, the temperature of amended soils are associated with the dosage and size of added biochar. The temperature-gradient flow is the main factor of water-vapor production in soils [93–95].

3.3. Infiltration

Water infiltration is one of the most crucial functions that prevents the formation of run-off in the lands. A higher rate of biochar could lower the cumulative infiltration [71,95]. Applying biochar to coarse-textured soil decreased the water-infiltration rate; however, applying various types of biochar (less than 2 mm size) significantly increased the infiltration rate in compacted soils and subsoils [96,97]. Furthermore, the application of biochar particles (<0.25 mm) significantly minimizes the large pores (>20 μm) number and prevents incremental changes in the infiltration rate [98]. The deeper mixing of biochar can reduce infiltration further [88,90]. Interaction among the biochar-particle size, dosage of application and application pattern is another influencing factor on the infiltration process in amended soils [90]. The infiltration rate and cumulative infiltration could be influenced by type, size and dosage of biochar [97,99]. Additionally, a decreasing infiltration rate is due to decrease of the crack index in the surface layer [100], whereas the finer microstructure increases due to adding biochar to soils, and water-retention capacity increases due to a reduction in the transfer of water in the soil profile [100]. The significant impact of biochar on the volumetric-water content of soils, results in a decreased infiltration rate when increasing the dosage, which could be explained by adding more intra-pores via biochar particles. Similarly, adding non-sieved biochar significantly decreases the infiltration rate, in contrast to adding a sieved biochar showing a < 0.25 mm improvement. Additionally, the biochar-related chemical changes in amended soil may be an important factor regarding infiltration-rate variation [101]. The indirect effect of biochar addition on an aggregation formation, also promotes the soil-infiltration rate. The formation of aggregates can help to maintain the preferred pathway for water entrance and movement. Similarly, the soil covers became more efficient, and inhibit water infiltration and percolation [98].

4. Compaction/Shrinkage (C/S)

4.1. Shear Strength

Biochar reduces water loss in the soil profile during desiccation periods. The relatively high-moisture content in biochar-amended soil causes a reduction in cracking-equivalent width, fractional dimension, area density, connectivity index and, in general, cracking propagates more slowly than in control soil [102,103].

The area density of cracking in biochar-amended soils has a positive relation to the amount of added biochar, alongside the wet and dry cycles, but the proportional-shrinkage zone does not follow the same pattern. Increments in the biochar application rate leads to a reduction in the shrinkage-characteristics slope [102]. The shape of the shrinkage-characteristic curve is significantly changed by the application of biochar, wet and dry cycles, and soil texture, which has been reported in several studies [17,103]. It seems the application of biochar, depending on rate and type, has a direct influence on the void and water-filled space. A normal, shrinkage-characteristic curve contains structural-, proportional-, residual-, and zero-shrinkage zones, which, by adding biochar, disturbs these zones [12,102].

Biochar can enhance the rigidity of coarse texture and prevent the rapid loss of water from the soil body [17]. The constant-rate stage, declining-rate stage and residual-rate stage are evaporation processes, and the application of biochar enforces change in all sections. The constant-rate stage of evaporation is responsible for desiccation-crack formations [103,104]. The application of biochar to pure-sand and silty-sand media can increase shear-strength and load-bearing capacity in both soils. The main factors of shear strength in soil include cohesion and the angle of internal friction [63].

At artificial conditions, such as contributions of biochar and clay that are mostly used for land fill establishment, shear strength increased with biochar content. The increment in cohesion leads to the greater values of the shear strength in the biochar- and clay-mixed materials, while reducing the angle of internal friction [105]. From an engineering perspective, the contribution of biochar with the expansive soils to cover landfills or slopes, results in important differences that happen in relation to swelling characteristics. Increasing the biochar could eventuate the decreasing swelling characteristics [106]. The swelling-ability reduction of expansive soils could happen when water content entering the soil is limited. Adsorption, flocculation and cation exchange between biochar and clay particles reduced the thickness of the diffused double-layer and limited the free water content in the pores [106].

The multifaceted effects of the application of biochar on swelling behavior could be different even at clayey soils. It seems that the application of biochar to soils with a low-expansion capacity significantly increases the swelling; however, in soils with no-load swelling behavior, the application of biochar did not affect their swelling [107]. Water sensitivity of the expansive soil is reduced because of the contraction of clay minerals in the presence of biochar particles. Hydrophilic minerals in the expansive soils had the smallest crystal spacing and the smallest peak area based on XRD results, because of the presence of biochar [106].

It seems biochar could change the cracking behavior of soils by mitigating pore water salinity and reducing the thinner-surface crack. Biochar could enhance the CaO and MgO content of expansive soil while Na_2O and K_2O decreases [106,108]. Differentiation of biochar's affinity to soil-soluble minerals can facilitate the leaching of ions from solution in soil pores. The biochar, which is produced from agricultural feedstock, can promote Ca^{2+} and K^+ leaching in soil, whereas sugarcane biochar increases the leaching of Na^+. The effects of disturbance arise from soil-solution chemistry due to reduction of water retention capacity of soil after leaching. The reduction and exchange of ions may be changed due to the thickness of the double-diffusion layer and pore-water pressure. This interruption happens because of the biochar and improves expansive-soil properties [106,108]. The presence of biochar particles in the soil profile may frustrate the flocculation process of expanding clays and the collapsing of clods, thereby disordering the chemistry of soil solution in wet and dry periods. There was no evidence, until the publishing of this paper, about how surface functional groups in the outer and inner space of biochar particles impact swelling.

4.2. Desiccation

Biochar can play a critical role in overcoming the problem of multiple risks arising due to cracks and the shrinkage potential in soils, and can also mitigate soil impoverishment. Desiccation cracking can inhibit due to the application of biochar through the reduction of the tensile strength between soil particles and tensile stress on the soil surface, which occupy the shrinkage space and growth of repulsive forces between soil particles [109]. Additionally, the development of tensile stress can cause the desiccation of cracks. Biochar can also act in a healing capacity and can improve soil quality. For example, biochar enhances the resistance of soil to desiccation cracking, promotes the formation of narrow and short cracks, and becomes more resistant to cracking under dry and wet cycles [109].

Because of biochar's ability to hold water, the evaporation rate decreases even at a low rate of biochar application and, consequently, the existence of water in pores and narrow cracks, induced the formation of annular cracks. Changes in the soil-crack development process, as a result of applied biochar, could decrease the surface-crack ratio and average crack in soils [109,110].

Increasing the rate of application leads to an increase in the shear-strength parameters, such as cohesion and the angle of internal friction [110]. Biochar may dominate the shapes of cracks by changing the formation of slurry in clayey soils. The orthogonal-crack pattern is dominant in thick slurries, while thin slurries have a non-orthogonal crack pattern. The mechanisms of slurry formation in biochar-amended soils needs further investigation.

4.3. Types of Feedstock

Research has shown that woody biochar is more efficient than manure-based biochar to reduce cracks. Woody biochar has more angularity and a better shape edge that promotes and reinforces the interlocking of particles in soil, and could maintain larger water quantities than other biochars [108,111]. This could be due to the cohesion- and internal-friction angle of biochar particles, which are directly associated with their surface morphology [111]. As an example, adding water–hyacinth biochar decreases the peak of the crack-intensify factor but the wheat–straw biochar has less effect on the reduction of cracks [97,108,112]. Additionally, application of woody, herbaceous and diary manure-produced biochar at low and high temperatures led to a reduction in tensile strength and cohesion, due to an increase in the plasticity index [113], but observed no significant effect on the internal-friction angle [38]. The influence of adding wheat–straw biochar was prominent on the decreasing coefficient of the linear extensibility of the clayey soil after 180 days of incubation, compared to woodchip- and waste water-sludge biochars. Additionally, the tensile strength decreased approximately 50% by the application of wheat–straw biochar, while waste-sludge biochar decreased by only 30 percent [113].

4.4. Size of Particle

Studies show that coarse particles of biochar have a lesser effect on the soil's hydro-physical characteristics than fine particles. Fine particles create more opportunities for contact between particles, which help in the formation of soil aggregates, while simultaneously increasing the water retention in the soil [103], which, with the increase in the distance between clay particles and biochar, the capillary force first increases and then decreases [103,105]. Fine grained biochar looks more susceptible to crack formations [111]. It is generally accepted that the application of biochar significantly reduces the compressibility of clayey soil, and this is easier to achieve via the application of fine biochar [107]. As an example, the application of fine biochar (<0.25 mm) has stricter contact with soils, and inhibits desiccation cracking more than coarse biochar [103]. Generally, by increasing the size of the biochar particles, the contact between biochar and soil particles then transition from close contact to loose contact, regardless of biochar dosage [103].

4.5. Dosage of Biochar

The increment in the dosage of the applied biochar may lead to an increase in the settlement rate of clayey soils [107]. The dosage of biochar could also have a negative effect on the compressive strength of the aggregates [114]. If the application has been taken densely, then the evaporation rate and crack progression will be further reduced, compared to a non-dense application [108]. More investigations have revealed that the formation of cracks, coefficient of linear extensibility, and the tensile and shear strength of soils may be impacted by the application of biochar.

In clayey soils, the presence of biochar at a low content (such as 2%), reduces the narrow and wide cracks compared to reference soils, but increases the narrow cracks at a high content of application (such as 6%). A small content of biochar increases the integrity of soil due to the establishment of channels which transfer water to the surface, thereby prohibiting narrow cracks from occurring [108].

The presence of biochar in the soil causes disruption in aggregate-size distribution. The formation of macroaggregate, reduction of microaggregate destruction, and rearrangement of aggregate, changes the pores that are responsible for water retention. By changing the distribution of pores, microstructural heterogeneity, and the intensity of suction, capillary-induced, local stress has a positive impact [9,115].

Research indicates that woody biochar can cause high-water-retention content in compacted, biochar-amended soil, as well as a low-evaporation rate and low-crack intensity factor [29,108]. A higher content of biochar in such soils leads to the intensification of variations [108]. At undrained conditions, by the application of biochar to the compacted soils, the shear-strength value decreased, especially by the presence of high-clay content. The decrease of shear strength could be due to the lubricating effect from the higher content of water [110]. Via the compaction of amended soils, or a dense use of biochar, the probability of decreasing biochar–biochar particle distance increases, which has the largest capillary forces among other particle–particle capillary forces [105].

However, the knowledge about water penetration into the pores of biochar particles within a hydrophobic nature is limited. In many cases, the water entrance to a pore needs some fundamental conditions. Apart the minimum radii for water entry in pores, the shape and structure of pores are critical, which can lead to the encapsulating of water in porous materials with narrow channels (diameter ~7.5 Å) [70]. In the hydrophobic surface, the water angle can rise up to 144.7 degrees. Additionally, water can be entrapped in hydrophobic channels in a wire-like shape [116].

Water molecules can be sorbed to the biochar surface via two main mechanisms, including physical sorption through π interactions, and chemical sorption by hydrogen bonds on the carboxyl and hydroxyl groups, or hydration interactions with cations [62]. The total oxygen-containing functional groups on the surface of biochar can govern water holding and the evaporation-rate behavior. The hydrophobicity of biochar particles affects the flow rate of water in canals and pores, especially at the throats of the amended soils. The hydrophilicity indicates the amounts of water being absorbed by the surface functional groups (OH and COOH) [97]. The intensive swelling ability and reduction in Ks in coarse-textured soils are the result of bonding water molecules to the O-H- and C-O-H-surface functional groups of biochar through polar-hydrogen bonds based on FTIR spectroscopy curves [62].

By adding the biochar and wet/dry cycles together, the stability of aggregates increased in a significantly different way from the negative impacts of other amendments, such as straw. Repeated wet and dry cycles advance the porosity in the soil profile and improve water flux in both fine-sand and sandy-loamy silt soils [12]. The results show that adding biochar particles to soil in excessive quantities could be the factor dominating the internal soil strength, but at a commensurate amount, biochar increased the particle to particle bonding in soil media [61,114]. In paddy soils, where the dry and wetting cycles are more severe (such as rice cultivated soils), biochar can protect soil-quality indexes.

Biochar can alleviate drought conditions by improving soil's hydro-physical properties, including soil structure and water retention [26], and by influencing crack-formation behavior, biochar can prohibit changes in the flow-regime transition from matrix flow to preferential flow mostly by preserving soil aggregates. Additionally, biochar may alter the microstructure of soil that effects cracking behavior in the topsoil. The cracks initiate at the surface and then propagate, laterally, and downward, gradually. As the evaporation process continues at dry periods, cracks transit into the networks due to coalescence and bifurcation. By reducing the intensity and rate of evaporation, crack expansions will be limited due to biochar. Additionally, the presence of biochar impacts the dynamics of crack closure during wet periods [103].

5. Aggregation Formation and Stability

The presence of biochar particles could directly affect the soil's chemical, physical, and biological characteristics. However, phenomena like dispersion, dissolution, deposition, and transportation of biochar particles in the soil profile may inevitably modify the whole process in porous media in biochar-amended soils [117,118]. As an important geochemical process, aggregation governs chemical-, physicochemical-, and physical-behaved ions in the soil profile, which play a fundamental role in soil quality and environmental health. Research showed that in biochar-amended soils, physicochemical associations between biochar particles and natural minerals of soil, cause an increase in soil–aggregate stability [119]; however, the incorporation of homo-aggregates and hetero-aggregates (macro and microaggregate) may be decreased by adding biochar [120,121].

The mechanical resilience of aggregates could improve biochar-amended soils that result in an improvement of soil structure and aeration, and enhance the recovering ability from the myriad of mechanical stresses imposed under arable systems [114]. The application of biochar may not cause a significant change in soil aggregate stability, but it causes a remarkable affect in the amount of macroaggregate (>2 mm) in soil. The formation of macroaggregate is directly related to the concentration of aggregate-associated soil organic carbon which may increase after application of biochar (approximately 1-fold) [115,117,120]. The increment of dosage of biochar is not a promising reason to increase water stability of aggregates. The linear increase of biochar application leads to a nonlinear increase in aggregate stability (>0.25 mm) [115,117]. In some cases, types of biochar may reveal opposite effects in different soils. This means that adding a specific type of biochar to a soil might increase aggregation stability and, simultaneously, have inverse effects on other soils. These inverse effects can be observed in other hydraulic properties of biochar-amended soils [39]. Additionally, research conducted regarding the effects that the combination of organisms, chemical fertilizers and biochar have on aggregation stability in soils, provides positive results as reported by the analysis of data [121].

5.1. Time of Application

Research showed that the aging process has a directly significant effect on aggregate class and stability in soils after biochar application. By increasing the time, the stability of macroaggregates increases versus short-term application, where only microaggregate stability improves significantly [104,122]. The long-term application of biochar to red soil, revealed that the percentage of aggregate destruction and soil-fractal dimension decreased, and the breakage of macroaggregates reduced significantly [32,59]. The studies showed that woody biochar can improve aggregate stability approximately four-fold greater than other types [40,123]. However, results showed that straw biochar was more effective in the long-term application than woody biochar in the improvement of soil-aggregate stability [40].

5.2. The Fauna of Soil

The relation between biochar and soil organisms brings multifaceted benefits. Biochar can provide a more favorable environment and suitable habitat for an organism's growth and activity in soils, due to its specific area and porosity, regardless of the biochar type and size. Simultaneously, the variety and abundance of organisms can improve soil characteristics, including soil agglomeration and aggregate stability. The primary agents of aggregate stabilization, especially in healthy soils, are microorganisms. Enhancing a microorganism's activity in soils as a corollary reaction to the released nutrients of biochar, the interactions between biochar and microorganisms are crucial for improving the physical characteristics of amended soils. There is a positive correlation between microbiological indexes with soil–aggregate stability, such as microbial–metabolic coefficient > microbial biomass > basal respiration.

The biochar may emit substrates, which include volatile organic carbons, and polyaromatic-hydrocarbon constituents, and may release mineral–nutrient elements, which significantly accelerate an organism's growth. The application of biochar has a major effect on the C/N ratio and soil pH; both have a undeniable impact on the microbial community of soils [124,125], and as a consequence, aggregate-size redistribution may be controlled by the soil–microbial community [126]. However, biochar would promote the proliferation of fungi hyphae because of the high C/N ratio, which is important for improving the stability of soil aggregates [127]. Both fungi and bacteria, regarding to their type and abundance, facilitate the formation of aggregation by forming clay-polyvalent, metal–organic complexes. Although, micro-aggregation happens by the cementing of silt-clays or fine-soil particles through chemical–inorganic compounds [121,128,129], and is followed by the formation of macroaggregate through the binding of stable microaggregate by living biomass (fungi hyphae that improves and roots) or their exudations [121,130], the deposition of extracellular polysaccharides and aromatic-humic constituents are acting as a glue in the soil to form larger aggregates. The content and mean diameter of aggregate increase by the application of biochar [115]. The activities of living organisms in soils enhance aggregate formation, especially aggregates that are influenced by the type and abundance of organisms.

The presence of biochar can improve soil–nutrient sufficiency; thus, the exudation of plant roots decreases, and the components of roots exudate, such as polysaccharides decline [121]. As a comparison of plant types, under the presence of biochar, monocotyledons plants produce stronger effects on aggregate stability than dicotyledonous plants [23]. Additionally, the shape of the root could have an impact on the effects of the applied biochar. Aggregate stability is enhanced further by the fibrous roots compared to the tuberous roots [117]. Furthermore, the stability of aggregates in soils under soybean crops increased further than the maize crops by adding biochar (approximately two-fold) [23].

Rhizodeposits can bind microaggregates to form macroaggregates. The association affinity of biochar particles for natural minerals in soil is assuredly expected. On the other hand, natural minerals in soil can cover the inner pores and outer surface of biochar particles [128]. These associations have an impact on stabilizing soil organic carbon, and the oxidation resistance of biochar and transformation of soil-organic matter [119]. Figure 2 shows the detailed map of the direct and indirect effects of biochar application in the formation of macroaggregates, which was induced by microaggregates combining together and aggregate-seed formations.

To interpret the contradictory results regarding the effects of adding biochar on the ratio of bacteria to fungi, it can be explained that if the addition of biochar is effective on the changes in soil parameters, then depending on the type of bacteria and fungi, it can improve or weaken the abundance of the microbial community. Among these parameters, it can be mentioned that the pH of soil and rhizodeposits are the important factors in growing the dominant community of soil organisms. Therefore, microbial-promoted aggregation is affected by changes in the dominant microbial communities of the soil with the application of biochar, which will certainly change over time. Hyphae growth from fungi between soil constituents and among microaggregates improves the aggregation-formation mechanism.

The combination of biochar, plant roots, and plant growth promoting bacteria (PGPB), can encourage the aggregate formation by expanding root growth in the rhizosphere [131,132]. Additionally, the exoenzymes activities of bacteria could promote the binding of soils, both organic and inorganic constituents. So, if the application of biochar is focused on increasing microbial communities that have high-exoenzymes activities, then soil aggregation increases significantly when related to microbes with low-exoenzymes activities [132]. Additionally, the high ratio of Gram-positive to Gram-negative bacteria could facilitate the accumulation of soil organic carbon in soil [129,131].

The long-term application of biochar increased the functionality of bacteria, but could still decrease the diversity of bacteria by influencing the soil pH and unbalancing the nutrients, especially in a combination with chemical fertilizers [125,133]. According to the soil, applying biochar could enhance the relation and behavior of bacteria and fungi in soils based on the sequestration of soil organic matter. The mean diameter of aggregates further improves while applying chemical fertilizers to biochar before adding to soils [134]. The application of organic fertilizers to biochar-amended soils has a substantial impact on aggregation formation [135]. These two types of fertilizers could promote the growth, diversity and abundance of living organisms greater than when only biochar is used in the soil. The consequences result in the expedition and multiplication of the aggregation formation, and produces a positive alteration in aggregate stability [135,136].

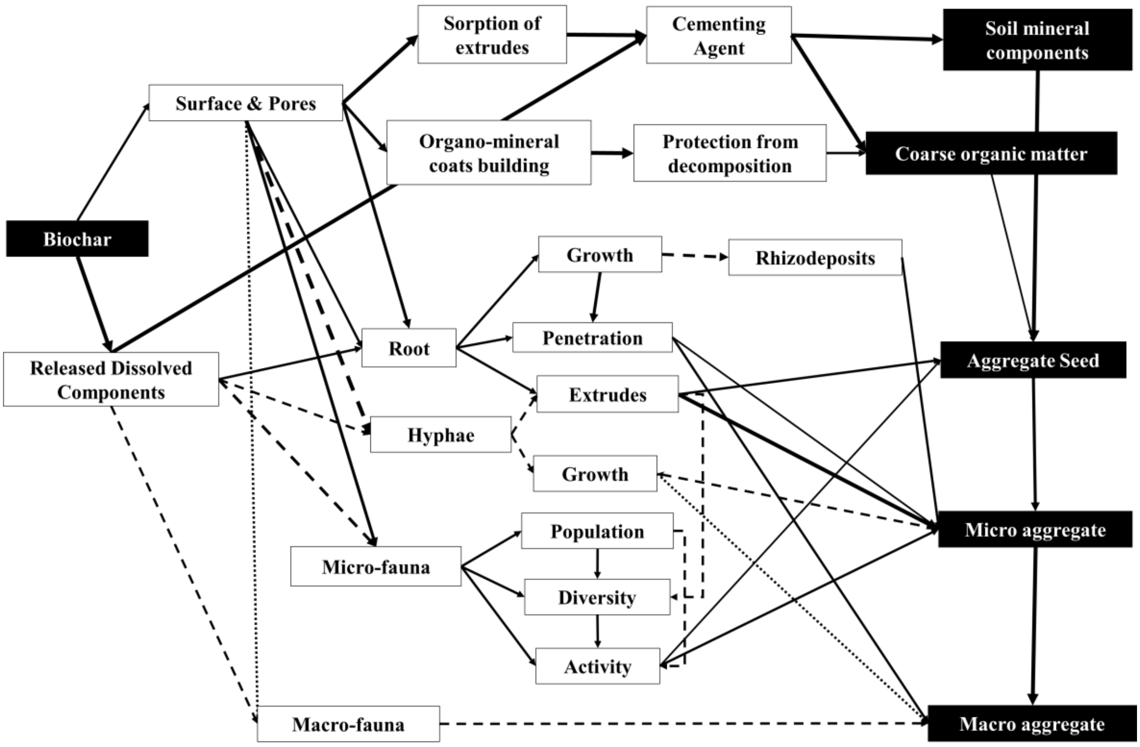

Figure 2. A detailed map describing direct and indirect effects of biochar application on aggregation. I: surface and pores of biochar, and II: released dissolved components. Plain, Dashed, and Dotted lines represent the positive, conditional, and inverse effects of biochar, respectively. The white and black boxes represent influencing processes and the biochar particles presence respectively. Note that the diagram was a brief explanation of macroaggregate (>250 µm) formation induced by microaggregate (53–250 µm), which is formed from aggregate seeds (<53 µm) due to the biochar application to soils.

The ratio of bacteria/fungi could decrease by the application of chemical fertilizer to biochar-applied soils; however, the assessment of the optimal amount of biochar and chemical fertilizers in agricultural soil is essential. Furthermore, the changing of a microbial community may induce over time through changing the properties of biochar, such as physical structure, labile fractions, and aromatic moieties [104,137]. However, physical structures are less influenced by phylotype variation, especially in macroaggregates [130]. Additionally, the application of biochar helps bacteria compete with fungi and lead to a decrease of aggregation stability due to less fungal entangling in aggregates [121,132].

5.3. Electrical Conductivity

Three types of compounds, inorganic, organic, and organo-inorganic, play a predominant role in enhancing the aggregation of soils. Sesquioxides figure prominently in microaggregate formation, while macroaggregate formation greatly depends on organic matter. Biochar could release soluble forms of low-organic molecules besides the formation of humic substances. The interaction of these substances, with iron oxides or silicates, forms binding agents, which promote aggregation [32]. As a fringe beneficence, the alleviation of electrical conductivity can improve aggregation stability. Long-term applications of biochar causes a direct relation between the electrical conductivity of applied soils and aggregation stability. The addition of biochar can increase the electrical conductivity by adding soluble salts. The water soluble salts could shrink the diffused double-layers of colloids and promote flocculation. The efficiency of aggregation mechanisms improves in the flocculated state [40]. Additionally, aromatic C fraction of biochar has a negative impact on soil aggregation stability [138]. Adding biochar to soil can interrupt the ratio of aliphatic to aromatic C, alkyl C to alkyl C/O, and hydrophobic C to hydrophilic C towards the increase in soil aggregate stability by increasing the hydrophobicity of aggregates [14]. Studies indicate that aggregate stability can be improved by adding biochar to soil because of the reduction in the internal forces of net-repulsive soil. The application of biochar may strengthen electrostatic repulsive and van der Waals attraction in soils [139].

5.4. Micro/Macro Aggregate

The trend of variation of aggregate stability has no significant relation to the increase of biochar percent [123]; but, in contrast, some researchers showed that adding biochar would induce particle rearrangement via two mechanisms: bonding non-cohesive soil particles, and oxidation of the surface at the biochar-soil particles interphase [61]. It is critical to choose the right biochar dosage in various soils, especially in light-textured soils. Additionally, the application of low or high dosages of biochar, sometimes, has diverse effects on aggregate stability [38]. In the sandy soil, the aggregate content significantly decreased in aggregates >0.5 mm, and increased in aggregates < 0.25 mm [71]. However, in heavy-textured soils with high content of swelling clay, the macroaggregates (>0.25 mm) increased significantly, while the microaggregates (<0.25 mm) were reduced by the application of biochar [25,115]. At loam soil, in the field conditions, the application of five types of high-temperature pyrolyzed biochars had diverse effects on aggregate stability; the percentage of soil aggregates decreased at <0.5 mm diameter, and increased at >5 mm, and had no significant effect on 0.5–2 mm. The effect of biochars on the aggregates with a 2–5 mm diameter was mostly negative [38].

5.5. Seedling of Aggregate

Homo- or hetero-aggregation of natural minerals and biochar particles depends on the pH of the solution that could lead to coagulation. The interaction between mineral and biochar particles depends on the type of biochar and/or minerals, and aquatic environment conditions, especially pH [140–142]. The soil's natural minerals, such as goethite and hematite, may slightly adsorb to the surface of the biochar particles in different ways, and settle or deposit in the soil profiles or on the biochar particles. The kaolinite and montmorillonite showed less affinity to make the interaction via biochar particles at different pH levels versus goethite or hematite [141–143].

These variations of surface-functional groups of biochar particles led to fundamental differences in the stability of aggregates that are created by micro and nanoparticles [86]. Aggregates which are created by micro- and nano-biochar particles produced from plant feedstock are more stable than dairy manure at a higher ionic strength [19]. Studies have revealed that high-ionic strength could retain biochar particles in porous media, especially in low-temperature pyrolyzed biochar. Additionally, biochars' colloid mobility can decrease by an increment in ionic strength [19,144].

Two opposite repulsion forms, homo and hetero repulsion, may occur in soil solution containing biochar and natural-mineral particles. The electrostatic hetero repulsion causes to the greater particle dispersion which is called the steric effect. The steric hindrance may be caused by functional groups at the surface of a biochar particle, in which any modification of the functional groups leads to a variation in the steric effect amount [128,145]. The zeta potential of systems, which contain both types of particles, is more negative than suspensions with a single type of particle [128,145].

5.6. Zeta Potential

The zeta potential provides an assessment of colloidal stability in soil solutions. Negative or positive values of this parameter are directly associated with the charge of the particle's surface. The conditions of the pyrolysis process, type of feedstock, mixed-soil properties (such as pH, EC, etc.), and the chemistry of the soil solution, determine the final values of zeta potential. The studies reported that the sorption of organic and inorganic ions onto the surface of biochar particles, through strong interactions such as bonding, Lewis acid-base, π-π electron donor acceptor, or weak, electrostatic–repulsive interactions, can alter the absolute value of zeta potential of biochar, and, consequently, the increments in the aggregation process [145,146].

The application of biochar with more alkalinity than target soil may lead to an increase of solution pH, which causes the detachment of cations from the surface of particles and less aggregate stability [147,148]. However, the speciation of the coated or sorbed materials is highly pH dependent and can affect the transport of biochar to the deeper zone [118]. The zeta potential of particles may be protected by the pH of the solution, and the coverage of adsorbed ions. The presence of divalent cations may enhance aggregation in biochar-amended, fine-textured soils through double-layer compression and cation binding [82,146]. Anion adsorption could have different effects on low- or high-temperature pyrolyzed biochars. The final amount of adsorbed anions on the surface of biochar particles governs the values of the zeta potential [144,149]. By increasing the sorption amount of anions, the hydrodynamic diameter increased gradually. The larger hydrodynamic diameter of particles causes less ability for movement [144]. Additionally, loss of negatively charged, oxygen-containing functional groups after the adsorption of anions on the biochar surface, which have zero charge ranged between 6.8–8.5, is a major factor in increasing the zeta potential of biochar particles [144,149]. Modifying biochar particles with sulfamethazine causes the pH dependent behavior of particles, which reduces the surface charge to a shielding charge that increases the charge at pH = 10. These phenomena cause electrostatic repulsion between biochar particles and soil particles under alkaline conditions, leading to significant differences in particle transport and a chance of agglomeration [146]. As a summary, it seems that the results regarding the improvement of aggregate-stability factor is in a close association with soil Ks, and the creation of accommodation pore properties results in amended soils.

6. Conclusions and Directions of Future Study

6.1. Conclusions

How soil structures respond to the application of biochar is one of the more thought-provoking subjects in recent investigations in the field of developing biochar consumption. The application of biochar can have impactful effects on the hydrophysical properties, and the stability of the soil structure.

The main reason for the changes in the soil pores after the application of biochar is due to the rearrangement of soil particles and the biochar particles attachment or deposition to/among these particles. The decisive shape of the pore-size distribution curve, which reflects the state of changes, is different in various soils, and directly depends on the biochar type, apart from the shape and size of its particles. The tortuosity and pore connectivity are the most affected factors by the application of biochar, which directly influences the moisture movement of water in the forms of liquid, or vapor in the soil–porous media. The alteration in pore distribution and changes in the microstructural stability of pores, appear after the application of biochar in soils. The most effective attribute of biochar application is the redistribution of moisture. The saturated hydraulic conductivity in soils is dominated by biochar attributes, including type, size and dosage. The biochar particle size of equal or greater size than soil particles has positive effects on the water dynamic in pores.

The application of biochar mainly affects the infiltration and evaporation stages. The ability of biochar to prevent the soil from rapidly losing water makes it a reliable amendment to improving storage humidity and crack formation in soils. The biochar effectiveness on shear strength and crack formation in different soils are directly associated with cohesion and the angle of internal friction. However, swelling behavior in clay-rich soils is related to the hydrophobicity of biochar particles that explains the impact of the chemical and physical properties of biochar. Additionally, it seems that the size of the biochar particles is more important in coarse-textured soils, whereas the high-surface area is more important in fine-textured soils.

It is considerable that the ineluctable effects of biochar are associated with chemical properties and biological activities of amended soils. These attributes can induce or hinder the hydrophysical behavior of amended soils. Formation and stability of aggregates are controlled by changes in biological, chemical and physical status. If the changes are maintained by the application of biochar in the soil leading to an increase in biological activities, subsequently, this will increase the extrudes, which are responsible for the formation or the stability of soil aggregates. The presence of microorganisms, and also the extrudes resulting from their activities along with the activity of other organisms in amended soils, reflect the win-win process in improving soil structure. Moreover, the stability of soil aggregates or their size distribution is directly related to the type of feedstock, pyrolysis conditions, and the size and dosage of biochar particles. The formation and stability of micro/macroaggregates are indicators for evaluating the biochar application results.

Finally, an excessive application of biochar is not a reliable way to improve the hydrophysical properties of soil. The application of biochar and the complex reactions that it creates via its interaction with soil properties, cause the ambiguous behaviors of biochar in soils with different textures.

6.2. Directions of Future Study

Given the crucial characteristics of biochar and the involved properties of amended soil in water flux discussed in this review, we recommend the following areas for further research:

(i) Assess long-term and large-scale monitoring of the effects of size and dosage of biochar application on the aggregate formation and stability by different methods. Future studies should be conducted to examine the mechanisms of the multi-functional factor's effects on soil-hydrophysical properties. The fundamental properties of biochar, such as the availability of inter pores and channels of biochar particles, and types and abundance of surface functional groups, change by elapsing time. Additionally, the rearrangements of aggregates and the possibility of changes in pores and canals may be induced by time. Additionally, the variation of laboratory methods, which provide the data from field conditions, must be calibrated, especially on measuring aggregate stability.

(ii) Develop comprehensive guidelines for the application of biochar in different soils based on the purpose of addition as necessary. Soil's physicochemical properties vary, basically, because of both its constituents and structures. It is necessary to introduce guidelines for adding biochar to different soils based on the purpose of addition. The behavior of biochar can be manipulated by the depth of application and spreading methods. The chance of biochar contribution in different depths is directly related to soil type and is under the influence of biochar properties.

(iii) Strengthen the research on the effects of adding biochar on various soil textures. Studies have been conducted on the effects of adding biochar or its interactions on the properties of soils, mostly in light-textured soils. The lack of studies about the effects of biochar addition on hydrophysical properties of heavy- or medium-textured soils, with different regimes of moisture, should be resolved by future research. The complicated interaction between biochar, clay, silt, and organic matter must be verified in both arid and humid regions.

(iv) There is a possibility of intensifying or mitigating the changes in soil hydrophysical properties by adding modified biochar. In particular, via surface functional groups or promoting biological activities of modified biochar, which are different from pristine biochar. The pore structures of biologically activated biochar are being investigated recently, but there is a need for further clarification regarding the interactions of living organisms and biochar on hydrophysical properties. Additionally, the positive or negative mechanisms of modified functional groups on water flux in amended soils should be developed, thus supporting future engineered biochar application.

(v) Leveraging 3D imaging methods to study pore structures, and relevant mechanisms of pore filling by particles, should be strengthened. The topology of the pore network is a fundamental parameter for water flux in the soil profile. The application of biochar to soil, or the movement of its particle, could impact the microstructure of pores. In future studies, we should explore how mechanisms impact when adding biochar on particle relocation in a soil profile. Identifying the optimum dosage, size and type of biochar added to soil to improve soil hydrophysical properties should be prioritized, in order to reduce the leaching of pollutants or facilitate transport by particles.

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References

1. Shakoor, A.; Arif, M.S.; Shahzad, S.M.; Farooq, T.H.; Ashraf, F.; Altaf, M.M.; Ahmed, W.; Tufail, M.A.; Ashraf, M. Does biochar accelerate the mitigation of greenhouse gaseous emissions from agricultural soil?—A global meta-analysis. *Environ. Res.* **2021**, *202*, 111789. [CrossRef] [PubMed]
2. Danesh, P.; Niaparast, P.; Ghorbannezhad, P.; Ali, I. Biochar production: Recent developments, applications, and challenges. *Fuel* **2022**, *337*, 126889. [CrossRef]
3. Wang, T.; Liu, H.; Duan, C.; Xu, R.; Zhang, Z.; She, D.; Zheng, J. The eco-friendly biochar and valuable bio-oil from caragana korshinskii: Pyrolysis preparation, characterization, and adsorption applications. *Materials* **2020**, *13*, 3391. [CrossRef] [PubMed]
4. Rayhanitabar, A.; Farhadi, E.; Ramezanzadeh, H.; Oustan, S. Effect of pyrolysis temperature and feedstock sources on physico-chemical characteristics of biochar. *J. Agric. Sci. Technol.* **2020**, *22*, 547–561.
5. Xu, H.; Cai, A.; Wu, D.; Liang, G.; Xiao, J.; Xu, M.; Colinet, G.; Zhang, W. Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by biochar c:n ratio and soil pH: A global meta-analysis. *Soil Tillage Res.* **2021**, *213*, 105125. [CrossRef]
6. Zhang, Y.; Ren, M.; Tang, Y.; Cui, X.; Cui, J.; Xu, C.; Qie, H.; Tan, X.; Liu, D.; Zhao, J.; et al. Immobilization on anionic metal(loid)s in soil by biochar: A meta-analysis assisted by machine learning. *J. Hazard. Mater.* **2022**, *438*, 129442. [CrossRef] [PubMed]
7. Sasidharan, S.; Torkzaban, S.; Bradford, S.A.; Kookana, R.; Page, D.; Cook, P.G. Transport and retention of bacteria and viruses in biochar-amended sand. *Sci. Total Environ.* **2016**, *548–549*, 100–109. [CrossRef]
8. Liu, Y.; Zhang, X.; Xu, Y.; Liu, Q.; Ngo, H.H.; Cao, W. Transport behaviors of biochar particles in saturated porous media under dc electric field. *Sci. Total Environ.* **2023**, *856*, 159084. [CrossRef]
9. Hartley, W.; Riby, P.; Waterson, J. Effects of three different biochars on aggregate stability, organic carbon mobility and micronutrient bioavailability. *J. Environ. Manag.* **2016**, *181*, 770–778. [CrossRef]
10. Hardie, M.; Clothier, B.; Bound, S.; Oliver, G.; Close, D. Does Biochar Influence Soil Physical Properties and Soil Water Availability? *Plant Soil* **2013**, *376*, 347–361. [CrossRef]
11. Jeffery, S.; Meinders, M.B.J.; Stoof, C.R.; Bezemer, T.M.; van de Voorde, T.F.J.; Mommer, L.; van Groenigen, J.W. Biochar application does not improve the soil hydrological function of a sandy soil. *Geoderma* **2015**, *251–252*, 47–54. [CrossRef]
12. Ajayi, A.E.; Holthusen, D.; Horn, R. Changes in microstructural behaviour and hydraulic functions of biochar amended soils. *Soil Tillage Res.* **2016**, *155*, 166–175. [CrossRef]
13. Kazemi Shariat Panahi, H.; Dehhaghi, M.; Ok, Y.S.; Nizami, A.S.; Khoshnevisan, B.; Mussatto, S.I.; Aghbashlo, M.; Tabatabaei, M.; Lam, S.S. A comprehensive review of engineered biochar: Production, characteristics, and environmental applications. *J. Clean. Prod.* **2020**, *270*, 122462. [CrossRef]
14. Jeffery, S.; van de Voorde, T.F.J.; Harris, W.E.; Mommer, L.; Van Groenigen, J.W.; De Deyn, G.B.; Ekelund, F.; Briones, M.J.I.; Bezemer, T.M. Biochar application differentially affects soil micro-, meso-macro-fauna and plant productivity within a nature restoration grassland. *Soil Biol. Biochem.* **2022**, *174*, 108789. [CrossRef]

15. Tang, H.; Chen, M.; Wu, P.; Faheem, M.; Feng, Q.; Lee, X.; Wang, S.; Wang, B. Engineered biochar effects on soil physicochemical properties and biota communities: A critical review. *Chemosphere* **2023**, *311*, 137025. [CrossRef] [PubMed]
16. Major, J.; Lehmann, J.; Rondon, M.; Goodale, C. Fate of soil-applied black carbon: Downward migration, leaching and soil respiration. *Glob. Chang. Biol.* **2010**, *16*, 1366–1379. [CrossRef]
17. Villagra-Mendoza, K.; Horn, R. Effect of biochar addition on hydraulic functions of two textural soils. *Geoderma* **2018**, *326*, 88–95. [CrossRef]
18. Esmaeelnejad, L.; Shorafa, M.; Gorji, M.; Hosseini, S. mossa. Impacts of woody biochar particle size on porosity and hydraulic conductivity of biochar-soil mixtures: An incubation study. *Commun. Soil Sci. Plant Anal.* **2017**, *48*, 1710–1718. [CrossRef]
19. Song, B.; Chen, M.; Zhao, L.; Qiu, H.; Cao, X. Physicochemical property and colloidal stability of micron- and nano-particle biochar derived from a variety of feedstock sources. *Sci. Total Environ.* **2019**, *661*, 685–695. [CrossRef]
20. Edeh, I.G.; Mašek, O.; Buss, W. A meta-analysis on biochar's effects on soil water properties—New insights and future research challenges. *Sci. Total Environ.* **2020**, *714*, 136857. [CrossRef]
21. Yan, Y.; Akbar Nakhli, S.A.; Jin, J.; Mills, G.; Willson, C.S.; Legates, D.R.; Manahiloh, K.N.; Imhoff, P.T. predicting the impact of biochar on the saturated hydraulic conductivity of natural and engineered media. *J. Environ. Manag.* **2021**, *295*, 113143. [CrossRef] [PubMed]
22. Edeh, I.G.; Mašek, O. The role of biochar particle size and hydrophobicity in improving soil hydraulic properties. *Eur. J. Soil Sci.* **2021**, *73*, 13138. [CrossRef]
23. Obia, A.; Mulder, J.; Martinsen, V.; Cornelissen, G.; Børresen, T. In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. *Soil Tillage Res.* **2016**, *155*, 35–44. [CrossRef]
24. Dokoohaki, H.; Miguez, F.E.; Laird, D.; Horton, R.; Basso, A.S. Assessing the biochar effects on selected physical properties of a sandy soil: An analytical approach. *Commun. Soil Sci. Plant Anal.* **2017**, *48*, 1387–1398. [CrossRef]
25. Lu, S.G.; Sun, F.F.; Zong, Y.T. Effect of rice husk biochar and coal fly ash on some physical properties of expansive clayey soil (vertisol). *Catena* **2014**, *114*, 37–44. [CrossRef]
26. Kim, Y.J.; Hyun, J.; Yoo, S.Y.; Yoo, G. The role of biochar in alleviating soil drought stress in urban roadside greenery. *Geoderma* **2021**, *404*, 115223. [CrossRef]
27. Ghanbarian, B.; Hunt, A.G.; Skaggs, T.H.; Jarvis, N. Upscaling soil saturated hydraulic conductivity from pore throat characteristics. *Adv. Water Resour.* **2017**, *104*, 105–113. [CrossRef]
28. Ghorbani, M.; Neugschwandtner, R.W.; Konvalina, P.; Asadi, H.; Kopecky, M.; Amirahmadi, E. Comparative effects of biochar and compost applications on water holding capacity and crop yield of rice under evaporation stress: A two-years field study. *Paddy Water Environ.* **2023**, *21*, 47–58. [CrossRef]
29. Verheijen, F.G.A.; Zhuravel, A.; Silva, F.C.; Amaro, A.; Ben-Hur, M.; Keizer, J.J. The influence of biochar particle size and concentration on bulk density and maximum water holding capacity of sandy vs sandy loam soil in a column experiment. *Geoderma* **2019**, *347*, 194–202. [CrossRef]
30. Głąb, T.; Palmowska, J.; Zaleski, T.; Gondek, K. Effect of biochar application on soil hydrological properties and physical quality of sandy soil. *Geoderma* **2016**, *281*, 11–20. [CrossRef]
31. Chen, X.; Duan, M.; Zhou, B.; Cui, L. Effects of biochar nanoparticles as a soil amendment on the structure and hydraulic characteristics of a sandy loam soil. *Soil Use Manag.* **2021**, *38*, 836–849. [CrossRef]
32. Li, Q.; Jin, Z.; Chen, X.; Jing, Y.; Huang, Q.; Zhang, J. Effects of biochar on aggregate characteristics of upland red soil in subtropical China. *Environ. Earth Sci.* **2017**, *76*, 372. [CrossRef]
33. Petersen, C.T.; Hansen, E.; Larsen, H.H.; Hansen, L.V.; Ahrenfeldt, J.; Hauggaard-Nielsen, H. Pore-size distribution and compressibility of coarse sandy subsoil with added biochar. *Eur. J. Soil Sci.* **2016**, *67*, 726–736. [CrossRef]
34. Liu, Z.; Dugan, B.; Masiello, C.A.; Gonnermann, H.M. Biochar particle size, shape, and porosity act together to influence soil water properties. *PLoS ONE* **2017**, *12*, e0179079. [CrossRef]
35. Sun, F.; Lu, S. Biochars improve aggregate stability, water retention, and pore-space properties of clayey soil. *J. Soil Sci. Plant. Nutr.* **2013**, *177*, 26–33. [CrossRef]
36. Zhang, L.; Jing, Y.; Chen, G.; Wang, X.; Zhang, R. Improvement of physical and hydraulic properties of desert soil with amendment of different biochars. *J. Soils Sediments* **2019**, *19*, 2984–2996. [CrossRef]
37. Wang, K.; Zhang, X.; Sun, C.; Yang, K.; Zheng, J.; Zhou, J. Biochar application alters soil structure but not soil hydraulic conductivity of an expansive clayey soil under field conditions. *J. Soils Sediments* **2020**, *21*, 73–82. [CrossRef]
38. Yang, C.D.; Lu, S.G. Effects of five different biochars on aggregation, water retention and mechanical properties of paddy soil: A field experiment of three-season crops. *Soil Tillage Res.* **2021**, *205*, 104798. [CrossRef]
39. Asai, H.; Samson, B.K.; Stephan, H.M.; Songyikhangsuthor, K.; Homma, K.; Kiyono, Y.; Inoue, Y.; Shiraiwa, T.; Horie, T. Biochar Amendment techniques for upland rice production in northern laos. *Field Crop. Res.* **2009**, *111*, 81–84. [CrossRef]
40. Chen, Y.; Shinogi, Y.; Taira, M. Influence of biochar use on sugarcane growth, soil parameters, and groundwater quality. *Soil Res.* **2010**, *48*, 526. [CrossRef]
41. Kameyama, K.; Miyamoto, T.; Shiono, T. Influence of biochar incorporation on TDR-based soil water content measurements. *Eur. J. Soil Sci.* **2013**, *65*, 105–112. [CrossRef]
42. Obia, A.; Mulder, J.; Hale, S.E.; Nurida, N.L.; Cornelissen, G. The potential of biochar in improving drainage, aeration and maize yields in heavy clay soils. *PLoS ONE* **2018**, *13*, e0196794. [CrossRef] [PubMed]

43. Wong, J.T.F.; Chen, Z.; Wong, A.Y.Y.; Ng, C.W.W.; Wong, M.H. Effects of biochar on hydraulic conductivity of compacted kaolin clay. *Environ. Pollut.* **2018**, *234*, 468–472. [CrossRef] [PubMed]
44. de Jesus Duarte, S.; Glaser, B.; Pellegrino Cerri, C. Effect of biochar particle size on physical, hydrological and chemical properties of loamy and sandy tropical soils. *Agronomy* **2019**, *9*, 165. [CrossRef]
45. Jin, Z.; Chen, C.; Chen, X.; Hopkins, I.; Zhang, X.; Han, Z.; Jiang, F.; Billy, G. The crucial factors of soil fertility and rapeseed yield—A five year field trial with biochar addition in upland red soil, China. *Sci. Total Environ.* **2019**, *649*, 1467–1480. [CrossRef]
46. Karer, J.; Wimmer, B.; Zehetner, F.; Kloss, S.; Soja, G. Biochar application to temperate soils: Effects on nutrient uptake and crop yield under field conditions. *Agric. Food Sci.* **2013**, *22*, 390–403. [CrossRef]
47. Koide, R.T.; Nguyen, B.T.; Skinner, R.H.; Dell, C.J.; Peoples, M.S.; Adler, P.R.; Drohan, P.J. Biochar amendment of soil improves resilience to climate change. *Glob. Chang. Biol. Bioenergy* **2014**, *7*, 1084–1091. [CrossRef]
48. Lei, O.; Zhang, R. Effects of biochars derived from different feedstocks and pyrolysis temperatures on soil physical and hydraulic properties. *J. Soils Sediments* **2013**, *13*, 1561–1572. [CrossRef]
49. Laird, D.; Fleming, P.; Wang, B.; Horton, R.; Karlen, D. Biochar Impact on Nutrient Leaching from a Midwestern Agricultural Soil. *Geoderma* **2010**, *158*, 436–442. [CrossRef]
50. Eibisch, N.; Durner, W.; Bechtold, M.; Fuß, R.; Mikutta, R.; Woche, S.K.; Helfrich, M. Does water repellency of pyrochars and hydrochars counter their positive effects on soil hydraulic properties? *Geoderma* **2015**, *245–246*, 31–39. [CrossRef]
51. Wiersma, W.; van der Ploeg, M.J.; Sauren, I.J.M.H.; Stoof, C.R. No effect of pyrolysis temperature and feedstock type on hydraulic properties of biochar and amended sandy soil. *Geoderma* **2020**, *364*, 114209. [CrossRef]
52. Hussain, R.; Kumar Ghosh, K.; Ravi, K. Impact of biochar produced from hardwood of mesquite on the hydraulic and physical properties of compacted soils for potential application in engineered structures. *Geoderma* **2021**, *385*, 114836. [CrossRef]
53. Speratti, A.; Johnson, M.; Martins Sousa, H.; Nunes Torres, G.; Guimarães Couto, E. Impact of different agricultural waste biochars on maize biomass and soil water content in a brazilian cerrado arenosol. *Agronomy* **2017**, *7*, 49. [CrossRef]
54. Uzoma, K.C.; Inoue, M.; Andry, H.; Fujimaki, H.; Zahoor, A.; Nishihara, E. Effect of cow manure biochar on maize productivity under sandy soil condition. *Soil Use Manag.* **2011**, *27*, 205–212. [CrossRef]
55. Brockhoff, S.R.; Christians, N.E.; Killorn, R.J.; Horton, R.; Davis, D.D. Physical and mineral-nutrition properties of sand-based turfgrass root zones amended with biochar. *Agron. J.* **2010**, *102*, 1627–1631. [CrossRef]
56. Githinji, L. Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. *Arch. Agron. Soil Sci.* **2013**, *60*, 457–470. [CrossRef]
57. Barnes, R.T.; Gallagher, M.E.; Masiello, C.A.; Liu, Z.; Dugan, B. Biochar-induced changes in soil hydraulic conductivity and dissolved nutrient fluxes constrained by laboratory experiments. *PLoS ONE* **2014**, *9*, e108340. [CrossRef]
58. Liu, Z.; Dugan, B.; Masiello, C.A.; Barnes, R.T.; Gallagher, M.E.; Gonnermann, H. Impacts of biochar concentration and particle size on hydraulic conductivity and doc leaching of biochar–sand mixtures. *J. Hydrol.* **2016**, *533*, 461–472. [CrossRef]
59. Sorrenti, G.; Masiello, C.A.; Dugan, B.; Toselli, M. Biochar physico-chemical properties as affected by environmental exposure. *Sci. Total Environ.* **2016**, *563–564*, 237–246. [CrossRef]
60. Hussain, R.; Ghosh, K.K.; Ravi, K. Influence of biochar particle size on the hydraulic conductivity of two different compacted engineered soils. *Biomass Convers. Biorefin.* **2021**, *13*, 801–811. [CrossRef]
61. Ajayi, A.E.; Horn, R. Modification of chemical and hydrophysical properties of two texturally differentiated soils due to varying magnitudes of added biochar. *Soil Tillage Res.* **2016**, *164*, 34–44. [CrossRef]
62. Jačka, L.; Trakal, L.; Ouředníček, P.; Pohořelý, M.; Šípek, V. Biochar presence in soil significantly decreased saturated hydraulic conductivity due to swelling. *Soil Tillage Res.* **2018**, *184*, 181–185. [CrossRef]
63. Hussain, R.; Ravi, K. Investigating biochar-amended soil as a potential lightweight material for embankments. *Ecol. Eng.* **2022**, *180*, 106645. [CrossRef]
64. Lim, T.J.; Spokas, K.A.; Feyereisen, G.; Novak, J.M. Predicting the impact of biochar additions on soil hydraulic properties. *Chemosphere* **2016**, *142*, 136–144. [CrossRef]
65. Bayabil, H.K.; Stoof, C.R.; Lehmann, J.C.; Yitaferu, B.; Steenhuis, T.S. Assessing the potential of biochar and charcoal to improve soil hydraulic properties in the humid ethiopian highlands: The anjeni watershed. *Geoderma* **2015**, *243–244*, 115–123. [CrossRef]
66. Fu, G.; Qiu, X.; Xu, X.; Zhang, W.; Zang, F.; Zhao, C. The role of biochar particle size and application rate in promoting the hydraulic and physical properties of sandy desert soil. *Catena* **2021**, *207*, 105607. [CrossRef]
67. Obia, A.; Børresen, T.; Martinsen, V.; Cornelissen, G.; Mulder, J. Effect of biochar on crust formation, penetration resistance and hydraulic properties of two coarse-textured tropical soils. *Soil Tillage Res.* **2017**, *170*, 114–121. [CrossRef]
68. Zhang, J.; Chen, Q.; You, C. Biochar effect on water evaporation and hydraulic conductivity in sandy soil. *Pedosphere* **2016**, *26*, 265–272. [CrossRef]
69. Ojeda, G.; Mattana, S.; Àvila, A.; Alcañiz, J.M.; Volkmann, M.; Bachmann, J. Are soil–water functions affected by biochar application? *Geoderma* **2015**, *249–250*, 1–11. [CrossRef]
70. Mao, J.; Zhang, K.; Chen, B. Linking hydrophobicity of biochar to the water repellency and water holding capacity of biochar-amended soil. *Environ. Pollut.* **2019**, *253*, 779–789. [CrossRef]
71. Wang, H.; Shao, D.; Ji, B.; Gu, W.; Yao, M. Biochar effects on soil properties, water movement and irrigation water use efficiency of cultivated land in Qinghai-Tibet plateau. *Sci. Total Environ.* **2022**, *829*, 154520. [CrossRef] [PubMed]

72. Sun, C.; Zhou, R.; Zhao, Z.; Bai, B. Unveiling the hydroxyl-dependent viscosity of water in graphene oxide nanochannels via molecular dynamics simulations. *Chem. Phys. Lett.* **2021**, *778*, 138808. [CrossRef]
73. Abel, S.; Peters, A.; Trinks, S.; Schonsky, H.; Facklam, M.; Wessolek, G. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma* **2013**, *202–203*, 183–191. [CrossRef]
74. Basso, A.S.; Miguez, F.E.; Laird, D.A.; Horton, R.; Westgate, M. Assessing potential of biochar for increasing water-holding capacity of sandy soils. *Glob. Chang. Biol. Bioenergy* **2012**, *5*, 132–143. [CrossRef]
75. Amoakwah, E.; Frimpong, K.A.; Arthur, E. Corn cob biochar improves aggregate characteristics of a tropical sandy loam. *Soil Sci. Soc. Am. J.* **2017**, *81*, 1054–1063. [CrossRef]
76. Devereux, R.C.; Sturrock, C.J.; Mooney, S.J. The effects of biochar on soil physical properties and winter wheat growth. *Earth Environ. Sci. Trans. R. Soc. Edinb.* **2012**, *103*, 13–18. [CrossRef]
77. Li, S.; Zhang, Y.; Yan, W.; Shangguan, Z. Effect of biochar application method on nitrogen leaching and hydraulic conductivity in a silty clay soil. *Soil Tillage Res.* **2018**, *183*, 100–108. [CrossRef]
78. Ouyang, L.; Wang, F.; Tang, J.; Yu, L.; Zhang, R. Effects of biochar amendment on soil aggregates and hydraulic properties. *J. Soil Sci. Plant Nutr.* **2013**, *13*, 991–1002. [CrossRef]
79. Zhang, Y.; Yang, J.; Yao, R.; Wang, X.; Xie, W. Short-term effects of biochar and gypsum on soil hydraulic properties and sodicity in a saline-alkali soil. *Pedosphere* **2020**, *30*, 694–702. [CrossRef]
80. Celebi, A.T.; Barisik, M.; Beskok, A. Surface charge-dependent transport of water in graphene nano-channels. *Microfluid. Nanofluid.* **2017**, *22*, 7. [CrossRef]
81. Ni, J.J.; Bordoloi, S.; Shao, W.; Garg, A.; Xu, G.; Sarmah, A.K. Two-year evaluation of hydraulic properties of biochar-amended vegetated soil for application in landfill cover system. *Sci. Total Environ.* **2020**, *712*, 136486. [CrossRef] [PubMed]
82. Zhang, W.; Niu, J.; Morales, V.L.; Chen, X.; Hay, A.G.; Lehmann, J.; Steenhuis, T.S. Transport and retention of biochar particles in porous media: Effect of pH, ionic strength, and particle size. *Ecohydrology* **2010**, *3*, 497–508. [CrossRef]
83. Castan, S.; Sigmund, G.; Hüffer, T.; Hofmann, T. Biochar particle aggregation in soil pore water: The influence of ionic strength and interactions with pyrene. *Environ. Sci. Process. Impacts* **2019**, *21*, 1722–1728. [CrossRef] [PubMed]
84. Yang, W.; Wang, Y.; Sharma, P.; Li, B.; Liu, K.; Liu, J.; Flury, M.; Shang, J. Effect of naphthalene on transport and retention of biochar colloids through saturated porous media. *Colloids Surf. A Physicochem. Eng. Asp.* **2017**, *530*, 146–154. [CrossRef]
85. Meng, Q.; Jin, L.; Cheng, L.; Fang, J.; Lin, D. Release and sedimentation behaviors of biochar colloids in soil solutions. *J. Environ. Sci.* **2021**, *100*, 269–278. [CrossRef]
86. Wang, D.; Zhang, W.; Hao, X.; Zhou, D. Transport of biochar particles in saturated granular media: Effects of pyrolysis temperature and particle size. *Environ. Sci. Technol.* **2013**, *47*, 821–828. [CrossRef]
87. Ramezanzadeh, H.; Reyhanitabar, A.; Oustan, S.; Mohammadi, M.H.; van der Zee, S.E.A.T.M. Enhanced sorption of cadmium by using biochar nanoparticles from ball milling in a sandy soil. *Eurasian Soil Sci.* **2021**, *54*, 201–211. [CrossRef]
88. Ibrahim, A.; Usman, A.R.A.; Al-Wabel, M.I.; Nadeem, M.; Ok, Y.S.; Al-Omran, A. Effects of conocarpus biochar on hydraulic properties of calcareous sandy soil: Influence of particle size and application depth. *Arch. Agron. Soil Sci.* **2016**, *63*, 185–197. [CrossRef]
89. Zou, Y.; Zhang, S.; Shi, Z.; Zhou, H.; Zheng, H.; Hu, J.; Mei, J.; Bai, L.; Jia, J. Effects of mixed-based biochar on water infiltration and evaporation in aeolian sand soil. *J. Arid. Land* **2022**, *14*, 374–389. [CrossRef]
90. Zhan, S.; Song, M.; Li, Z.; Ma, H. Effects of different straw biochars on soil water infiltration and evaporation. *J. Soil Water Conserv.* **2021**, *35*, 294–300.
91. Xu, Q.; Liu, H.; Li, M.; Li, P. The presence of the biochar interlayer effectively inhibits soil water evaporation and salt migration to the soil surface. *Agriculture* **2023**, *13*, 638. [CrossRef]
92. Verheijen, F.G.A.; Jeffery, S.; van der Velde, M.; Penížek, V.; Beland, M.; Bastos, A.C.; Keizer, J.J. Reductions in soil surface albedo as a function of biochar application rate: Implications for global radiative forcing. *Environ. Res. Lett.* **2013**, *8*, 044008. [CrossRef]
93. Xiong, J.; Yu, R.; Islam, E.; Zhu, F.; Zha, J.; Sohail, M.I. Effect of biochar on soil temperature under high soil surface temperature in coal mined arid and semiarid regions. *Sustainability* **2020**, *12*, 8238. [CrossRef]
94. Yang, B.B.; Li, D.; Yuan, S.C.; Jin, L.C. Role of biochar from corn straw in influencing crack propagation and evaporation in sodic soils. *Catena* **2021**, *204*, 105457. [CrossRef]
95. Zhao, W.; Liu, Y.; Li, Z.; Bao, Z. Effects of biochar on infiltration and evaporation of soil water with sand Mulching. *J. Biobased Mater. Bioenergy* **2021**, *15*, 369–373. [CrossRef]
96. Novak, J.; Sigua, G.; Watts, D.; Cantrell, K.; Shumaker, P.; Szogi, A.; Johnson, M.G.; Spokas, K. Biochars impact on water infiltration and water quality through a compacted subsoil layer. *Chemosphere* **2015**, *142*, 160–167. [CrossRef]
97. Hussain, R.; Bordoloi, S.; Gupta, P.; Garg, A.; Ravi, K.; Sreedeep, S.; Sahoo, L. Effect of biochar type on infiltration, water retention and desiccation crack potential of a silty sand. *Biochar* **2020**, *2*, 465–478. [CrossRef]
98. Chen, Z.; Kamchoom, V.; Apriyono, A.; Chen, R.; Chen, C. Laboratory study of water infiltration and evaporation in biochar-amended landfill covers under extreme climate. *Waste Manag.* **2022**, *153*, 323–334. [CrossRef]
99. Wang, T.; Stewart, C.E.; Ma, J.; Zheng, J.; Zhang, X. Applicability of five models to simulate water infiltration into soil with added biochar. *J. Arid. Land* **2017**, *9*, 701–711. [CrossRef]
100. Gopal, P.; Bordoloi, S.; Ratnam, R.; Lin, P.; Cai, W.; Buragohain, P.; Garg, A.; Sreedeep, S. Investigation of infiltration rate for soil-biochar composites of water hyacinth. *Acta Geophys.* **2019**, *67*, 231–246. [CrossRef]

101. Abrol, V.; Ben-Hur, M.; Verheijen, F.G.A.; Keizer, J.J.; Martins, M.A.S.; Tenaw, H.; Tchehansky, L.; Graber, E.R. Biochar effects on soil water infiltration and erosion under seal formation conditions: Rainfall simulation experiment. *J. Soils Sediments* **2016**, *16*, 2709–2719. [CrossRef]
102. Wei, C.; Gao, W.; Whalley, W.R.; Li, B. Shrinkage characteristics of lime concretion black soil as affected by biochar amendment. *Pedosphere* **2018**, *28*, 713–725. [CrossRef]
103. Lu, Y.; Gu, K.; Shen, Z.; Wang, X.; Zhang, Y.; Tang, C.S.; Shi, B. Effects of biochar particle size and dosage on the desiccation cracking behavior of a silty clay. *Sci. Total Environ.* **2022**, *837*, 155788. [CrossRef] [PubMed]
104. Baronti, S.; Magno, R.; Maienza, A.; Montagnoli, A.; Ungaro, F.; Vaccari, F.P. Long term effect of biochar on soil plant water relation and fine roots: Results after 10 years of vineyard experiment. *Sci. Total Environ.* **2022**, *851*, 158225. [CrossRef]
105. Xu, K.; Yang, B.; Wang, J.; Wu, M. Improvement of mechanical properties of clay in landfill lines with biochar additive. *Arab. J. Geosci.* **2020**, *13*, 584. [CrossRef]
106. Pan, Z.; Garg, A.; Huang, S.; Mei, G. Swelling suppression mechanism of compacted expansive soil amended with animal and plant based biochar. *Waste Biomass Valorization* **2020**, *12*, 2653–2664. [CrossRef]
107. Zhang, Y.; Gu, K.; Tang, C.; Shen, Z.; Narala, G.R.; Shi, B. Effects of biochar on the compression and swelling characteristics of clayey soils. *Int. J. Geosynth. Ground Eng.* **2020**, *6*, 22. [CrossRef]
108. Kumar, H.; Cai, W.; Lai, J.; Chen, P.; Ganesan, S.P.; Bordoloi, S.; Liu, X.; Wen, Y.; Garg, A.; Mei, G. Influence of in-house produced biochars on cracks and retained water during drying-wetting cycles: Comparison between conventional plant, animal, and nano-biochars. *J. Soils Sediments* **2020**, *20*, 1983–1996. [CrossRef]
109. Lu, Y.; Gu, K.; Zhang, Y.; Tang, C.; Shen, Z.; Shi, B. Impact of biochar on the desiccation cracking behavior of silty clay and its mechanisms. *Sci. Total Environ.* **2021**, *794*, 148608. [CrossRef]
110. Hussain, R.; Ghosh, K.K.; Garg, A.; Ravi, K. Effect of biochar produced from mesquite on the compaction characteristics and shear strength of a clayey sand. *Geotech. Geol. Eng.* **2020**, *39*, 1117–1131. [CrossRef]
111. Kumar, H.; Huang, S.; Mei, G.; Garg, A. Influence of feedstock type and particle size on efficiency of biochar in improving tensile crack resistance and shear strength in lean clayey soil. *Int. J. Damage Mech.* **2021**, *30*, 646–661. [CrossRef]
112. Khitab, A.; Ahmad, S.; Khan, R.A.; Arshad, M.T.; Anwar, W.; Tariq, J.; Khan, A.S.R.; Khan, R.B.N.; Jalil, A.; Tariq, Z. production of biochar and its potential application in cementitious composites. *Crystals* **2021**, *11*, 527. [CrossRef]
113. Zong, Y.; Chen, D.; Lu, S. Impact of biochars on swell–shrinkage behavior, mechanical strength, and surface cracking of clayey soil. *J. Soil Sci. Plant Nutr.* **2014**, *177*, 920–926. [CrossRef]
114. Ajayi, A.E.; Horn, R. Biochar-induced changes in soil resilience: Effects of soil texture and biochar dosage. *Pedosphere* **2017**, *27*, 236–247. [CrossRef]
115. Chen, C.; Zhu, H.; Lv, Q.; Tang, Q. Impact of biochar on red paddy soil physical and hydraulic properties and rice yield over 3 years. *J. Soils Sediments* **2021**, *22*, 607–616. [CrossRef]
116. Teng, Y.; Zhang, Y.; Heng, L.; Meng, X.; Yang, Q.; Jiang, L. conductive polymer porous film with tunable wettability and adhesion. *Materials* **2015**, *8*, 1817–1830. [CrossRef]
117. Liu, Z.; Chen, X.; Jing, Y.; Li, Q.; Zhang, J.; Huang, Q. Effects of biochar amendment on rapeseed and sweet potato yields and water stable aggregate in upland red soil. *Catena* **2014**, *123*, 45–51. [CrossRef]
118. Li, Y.; Feng, G.; Tewolde, H.; Yang, M.; Zhang, F. Soil, biochar, and nitrogen loss to runoff from loess soil amended with biochar under simulated rainfall. *J. Hydrol.* **2020**, *591*, 125318. [CrossRef]
119. Zheng, H.; Wang, X.; Luo, X.; Wang, Z.; Xing, B. Biochar-induced negative carbon mineralization priming effects in a coastal wetland soil: Roles of soil aggregation and microbial modulation. *Sci. Total Environ.* **2018**, *610–611*, 951–960. [CrossRef]
120. Zhao, D.; Xu, M.; Liu, G.; Yao, X.; Tuo, D.; Zhang, R.; Xiao, T.; Peng, G. Quantification of soil aggregate microstructure on abandoned cropland during vegetative succession using synchrotron radiation-based micro-computed tomography. *Soil Tillage Res.* **2017**, *165*, 239–246. [CrossRef]
121. Zhang, J.; Wei, Y.; Liu, J.; Yuan, J.; Liang, Y.; Ren, J.; Cai, H. Effects of maize straw and its biochar application on organic and humic carbon in water-stable aggregates of a mollisol in northeast China: A five-year field experiment. *Soil Tillage Res.* **2019**, *190*, 1–9. [CrossRef]
122. Zhang, Q.; Song, Y.; Wu, Z.; Yan, X.; Gunina, A.; Kuzyakov, Y.; Xiong, Z. Effects of six-year biochar amendment on soil aggregation, crop growth, and nitrogen and phosphorus use efficiencies in a rice-wheat rotation. *J. Clean. Prod.* **2020**, *242*, 118435. [CrossRef]
123. Wang, D.; 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] [PubMed]
124. Muhammad, N.; Dai, Z.; Xiao, K.; Meng, J.; Brookes, P.C.; Liu, X.; Wang, H.; Wu, J.; Xu, J. Changes in microbial community structure due to biochars generated from different feedstocks and their relationships with soil chemical properties. *Geoderma* **2014**, *226–227*, 270–278. [CrossRef]
125. Zhao, Y.; Wang, X.; Yao, G.; Lin, Z.; Xu, L.; Jiang, Y.; Jin, Z.; Shan, S.; Ping, L. Advances in the effects of biochar on microbial ecological function in soil and crop quality. *Sustainability* **2022**, *14*, 10411. [CrossRef]
126. Zhang, M.; He, L.; Zhang, X.; Wang, S.; Zhang, B.; Hsieh, L.; Yang, K.; Tong, M. Improved removal performance of gram-negative and gram-positive bacteria in sand filtration system with arginine modified biochar amendment. *Water Res.* **2022**, *211*, 118006. [CrossRef]

127. Bossuyt, H.; Denef, K.; Six, J.; Frey, S.D.; Merckx, R.; Paustian, K. Influence of microbial populations and residue quality on aggregate stability. *Appl. Soil Ecol.* **2001**, *16*, 195–208. [CrossRef]
128. Liu, G.; Zheng, H.; Jiang, Z.; Wang, Z. Effects of biochar input on the properties of soil nanoparticles and dispersion/sedimentation of natural mineral nanoparticles in aqueous phase. *Sci. Total Environ.* **2018**, *634*, 595–605. [CrossRef]
129. Sun, J.; Lu, X.; Chen, G.; Luo, N.; Zhang, Q.; Li, X. Biochar promotes soil aggregate stability and associated organic carbon sequestration, and regulates microbial community structures in mollisols from northeast China. *EGUsphere* **2022**, 1–39. [CrossRef]
130. Bailey, V.L.; McCue, L.A.; Fansler, S.J.; Boyanov, M.I.; DeCarlo, F.; Kemner, K.M.; Konopka, A. Micrometer-scale physical structure and microbial composition of soil macroaggregates. *Soil Biol. Biochem.* **2013**, *65*, 60–68. [CrossRef]
131. Guhra, T.; Stolze, K.; Totsche, K.U. Pathways of biogenically excreted organic matter into soil aggregates. *Soil Biol. Biochem.* **2022**, *164*, 108483. [CrossRef]
132. Xin, Y.; Fan, Y.; Babalola, O.O.; Zhang, X.; Yang, W. Legacy effects of biochar and compost addition on arbuscular mycorrhizal fungal community and co-occurrence network in black soil. *Microorganisms* **2022**, *10*, 2137. [CrossRef] [PubMed]
133. Wang, C.; Chen, D.; Shen, J.; Yuan, Q.; Fan, F.; Wei, W.; Li, Y.; Wu, J. Biochar alters soil microbial communities and potential functions 3–4 years after amendment in a double rice cropping system. *Agric. Ecosyst. Environ.* **2021**, *311*, 107291. [CrossRef]
134. Fungo, B.; Lehmann, J.; Kalbitz, K.; Thionġo, M.; Okeyo, I.; Tenywa, M.; Neufeldt, H. Aggregate size distribution in a biochar-amended tropical ultisol under conventional hand-hoe tillage. *Soil Tillage Res.* **2017**, *165*, 190–197. [CrossRef]
135. Chen, L.; Li, X.; Peng, Y.; Xiang, P.; Zhou, Y.; Yao, B.; Zhou, Y.; Sun, C. Co-application of biochar and organic fertilizer promotes the yield and quality of red pitaya (Hylocereus polyrhizus) by improving soil properties. *Chemosphere* **2022**, *294*, 133619. [CrossRef]
136. Chaganti, V.N.; Crohn, D.M. Evaluating the relative contribution of physiochemical and biological factors in ameliorating a saline–sodic soil amended with composts and biochar and leached with reclaimed water. *Geoderma* **2015**, *259–260*, 45–55. [CrossRef]
137. Wang, C.; Shen, J.; Liu, J.; Qin, H.; Yuan, Q.; Fan, F.; Hu, Y.; Wang, J.; Wei, W.; Li, Y.; et al. Microbial mechanisms in the reduction of CH_4 emission from double rice cropping system amended by biochar: A four-year study. *Soil Biol. Biochem.* **2019**, *135*, 251–263. [CrossRef]
138. Sarker, T.C.; Incerti, G.; Spaccini, R.; Piccolo, A.; Mazzoleni, S.; Bonanomi, G. Linking organic matter chemistry with soil aggregate stability: Insight from 13C NMR spectroscopy. *Soil Biol. Biochem.* **2018**, *117*, 175–184. [CrossRef]
139. Hu, F.; Xu, C.; Ma, R.; Tu, K.; Yang, J.; Zhao, S.; Yang, M.; Zhang, F. Biochar application driven change in soil internal forces improves aggregate stability: Based on a two-year field study. *Geoderma* **2021**, *403*, 115276. [CrossRef]
140. Zhao, J.; Liu, F.; Wang, Z.; Cao, X.; Xing, B. Heteroaggregation of graphene oxide with minerals in aqueous phase. *Environ. Sci. Technol.* **2015**, *49*, 2849–2857. [CrossRef]
141. Abbas, Q.; Yousaf, B.; Amina; Ali, M.U.; Munir, M.A.M.; El-Naggar, A.; Rinklebe, J.; Naushad, M. Transformation pathways and fate of engineered nanoparticles (enps) in distinct interactive environmental compartments: A review. *Environ. Int.* **2020**, *138*, 105646. [CrossRef] [PubMed]
142. Mai, N.T.; Nguyen, A.M.; Pham, N.T.T.; Nguyen, A.T.Q.; Nguyen, T.T.; Do, C.L.; Nguyen, N.H.; Dultz, S.; Nguyen, M.N. Colloidal interactions of micro-sized biochar and a kaolinitic soil clay. *Sci. Total Environ.* **2020**, *738*, 139844. [CrossRef] [PubMed]
143. Jing, F.; Sun, Y.; Liu, Y.; Wan, Z.; Chen, J.; Tsang, D.C.W. Interactions between biochar and clay minerals in changing biochar carbon stability. *Sci. Total Environ.* **2022**, *809*, 151124. [CrossRef]
144. Jin, R.; Liu, Y.; Liu, G.; Liu, L.; Zhou, J. Influence of chromate adsorption and reduction on transport and retention of biochar colloids in saturated porous media. *Colloids Surf. A Physicochem. Eng. Asp.* **2020**, *597*, 124791. [CrossRef]
145. Hou, J.; Yu, J.; Li, W.; He, X.; Li, X. The effects of chemical oxidation and high-temperature reduction on surface functional groups and the adsorption performance of biochar for sulfamethoxazole adsorption. *Agronomy* **2022**, *12*, 510. [CrossRef]
146. Yang, W.; Feng, T.; Flury, M.; Li, B.; Shang, J. Effect of sulfamethazine on surface characteristics of biochar colloids and its implications for transport in porous media. *Environ. Pollut.* **2020**, *256*, 113482. [CrossRef] [PubMed]
147. Teutscherova, N.; Lojka, B.; Benito, M.; Masaguer, A.; Vázquez, E. Biochar reduces the stability of soil aggregates during intensive leaching experiment. *Agronomy* **2020**, *10*, 1910. [CrossRef]
148. Duan, M.; Liu, G.; Zhou, B.; Chen, X.; Wang, Q.; Zhu, H.; Li, Z. Effects of modified biochar on water and salt distribution and water-stable macro-aggregates in saline-alkaline soil. *J. Soils Sediments* **2021**, *21*, 2192–2202. [CrossRef]
149. Yuan, J.H.; Xu, R.K.; Zhang, H. The forms of alkalis in the biochar produced from crop residues at different temperatures. *Bioresour. Technol.* **2011**, *102*, 3488–3497. [CrossRef]