sustainability

MDPI

Review

Application of Biochar for Improving Physical, Chemical, and Hydrological Soil Properties: A Systematic Review

Shakeel Ahmad Bhat [1], Alban Kuriqi [2,3], Mehraj U. Din Dar [4,5], Owais Bhat [1], Saad Sh. Sammen [6,*], Abu Reza Md. Towfiqul Islam [7], Ahmed Elbeltagi [8], Owais Shah [1], Nadhir AI-Ansari [9,*], Rawshan Ali [10] and Salim Heddam [11]

[1] College of Agricultural Engineering and Technology, Sher E Kashmir University of Agricultural Sciences and Technology-Kashmir, Srinagar 190025, India
[2] CERIS, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal
[3] Civil Engineering Department, University for Business and Technology, 10000 Pristina, Kosovo
[4] Department of Agriculture, Mata Gujri College, Fatehgarh Sahib 140406, India
[5] Department of Soil and Water Engineering, Punjab Agricultural University, Ludhiana 141004, India
[6] Department of Civil Engineering, College of Engineering, Diyala University, Baqubah 32001, Iraq
[7] Department of Disaster Management, Begum Rokeya University, Rangpur 5400, Bangladesh
[8] Agricultural Engineering Department, Faculty of Agriculture, Mansoura University, Mansoura 35516, Egypt
[9] Civil, Environmental and Natural Resources Engineering, Lulea University of Technology, 97187 Lulea, Sweden
[10] Department of Petroleum, Koya Technical Institute, Erbil Polytechnic University, Erbil 44001, Iraq
[11] Agronomy Department, Faculty of Science, Hydraulics Division University, 20 Août 1955, Route El Hadaik, BP 26, Skikda 21024, Algeria
* Correspondence: saad123engineer@yahoo.com (S.S.S.); nadhir.alansari@ltu.se (N.A.-A.)

Citation: Ahmad Bhat, S.; Kuriqi, A.; Dar, M.U.D.; Bhat, O.; Sammen, S.S.; Towfiqul Islam, A.R.M.; Elbeltagi, A.; Shah, O.; AI-Ansari, N.; Ali, R.; et al. Application of Biochar for Improving Physical, Chemical, and Hydrological Soil Properties: A Systematic Review. *Sustainability* **2022**, *14*, 11104. https://doi.org/10.3390/su141711104

Academic Editors: Teodor Rusu and Waqas Ahmed

Received: 16 May 2022
Accepted: 19 August 2022
Published: 5 September 2022

Abstract: Biochar is a carbon-based substance made by the pyrolysis of organic waste. The amount of biochar produced is determined by the type of feedstock and pyrolysis conditions. Biochar is frequently added to the soil for various reasons, including carbon sequestration, greenhouse gas mitigation, improved crop production by boosting soil fertility, removing harmful contaminants, and drought mitigation. Biochar may also be used for waste management and wastewater treatment. Biochar's various advantages make it a potentially appealing instrument material for current science and technology. Although biochar's impacts on soil chemical qualities and fertility have been extensively researched, little is known about its impact on enhancing soil physical qualities. This review is intended to describe biochar's influence on some crucial soil physical and hydrological properties, including bulk density of soil, water holding capacity, soil porosity, soil hydraulic conductivity, soil water retention, water repellence–available plant water, water infiltration, soil temperature, soil color, and surface albedo. Therefore, we propose that the application of biochar in soils has considerable advantages, and this is especially true for arable soils with low fertility.

Keywords: biochar; carbon sequestration; hydraulic conductivity; retention curve; albedo; temperature

1. Introduction

Biochar is a carbonaceous porous substance derived from biomass. The carbon component's abundance and chemical composition vary depending on the source material. Biochar has been made from various feedstocks, including agricultural residues, wood waste, livestock wastes, and sewage sludge [1–4]. Biochar can be generated using various thermochemical processes, including gasification, pyrolysis, and hydrothermal carbonization [5]. Because of its broad surface area, high porosity, and abundance of functional groups, biochar is an appealing choice for environmental remediation. It can be used as an adsorbent and catalyst material to remove various harmful pollutants in water and wastewater [4,6]. Biochar's use as an adsorbent and a nitrogen source in enhancing soil fertility has long been known [7,8]. However, the capacity for Biochar to be used as a support material and catalyst in advanced oxidation processes has only recently been realized [9].

"Black gold" is a term given to biochar. Biochar is made by high aromatization of organic waste, including agricultural straw, chicken manure, and urban sludge, at high temperatures and anaerobic conditions, reducing pollution and maximizing resource use [10]. Biochar has wide surface areas [7], large charge densities [11], low bulk densities [12,13], high porous structures, and high organic carbon (OC) contents [14–16], according to numerous reports [17]. Biochar has been shown to improve soil biological and chemical properties, such as pH, EC, zeta potential, and cation exchange capacity (CEC) [18,19].

Adding biochar to soil has been shown in several studies to reduce bulk density [14,20]. The biophysical requirement for root and microbial respiration is mediated by increased soil porosity and aeration, resulting in a decreased soil bulk density (SBD). A 10 t ha^{-1} biochar amendment decreased SBD in an Alfisol low in OC but not in an Andisol high in organic OC [14]. Organic amendments have been described as a critical alternative for encouraging the production and stabilization of soil aggregates and microbial activity [21]. Since mean weight diameter (MWD) is a critical soil quality indicator, it can affect infiltration and soil erosion. Biochar improves soil structure by enhancing aggregate stability and encouraging the production of macro aggregates [14,22].

Porosity has long been recognized as a significant soil property that influences the processes in the root zone, including plant respiration and root water uptake [23]. Biochar soil amendment improved soil porosity [1] and structure [24]. However, the degree to which these enhanced properties differed depended on the soil conditions and biochar feedstocks used. For instance, in sandy clay loam soil SBD, porosity, and water content were substantially improved. Additionally, following biochar amendment, SBD, soil structure (SS), and porosity in clay soils improved significantly [24]. Biochar's highly porous structure aided in soil water preservation [25], but it did not inherently increase usable water capacity [14] (Figure 1).

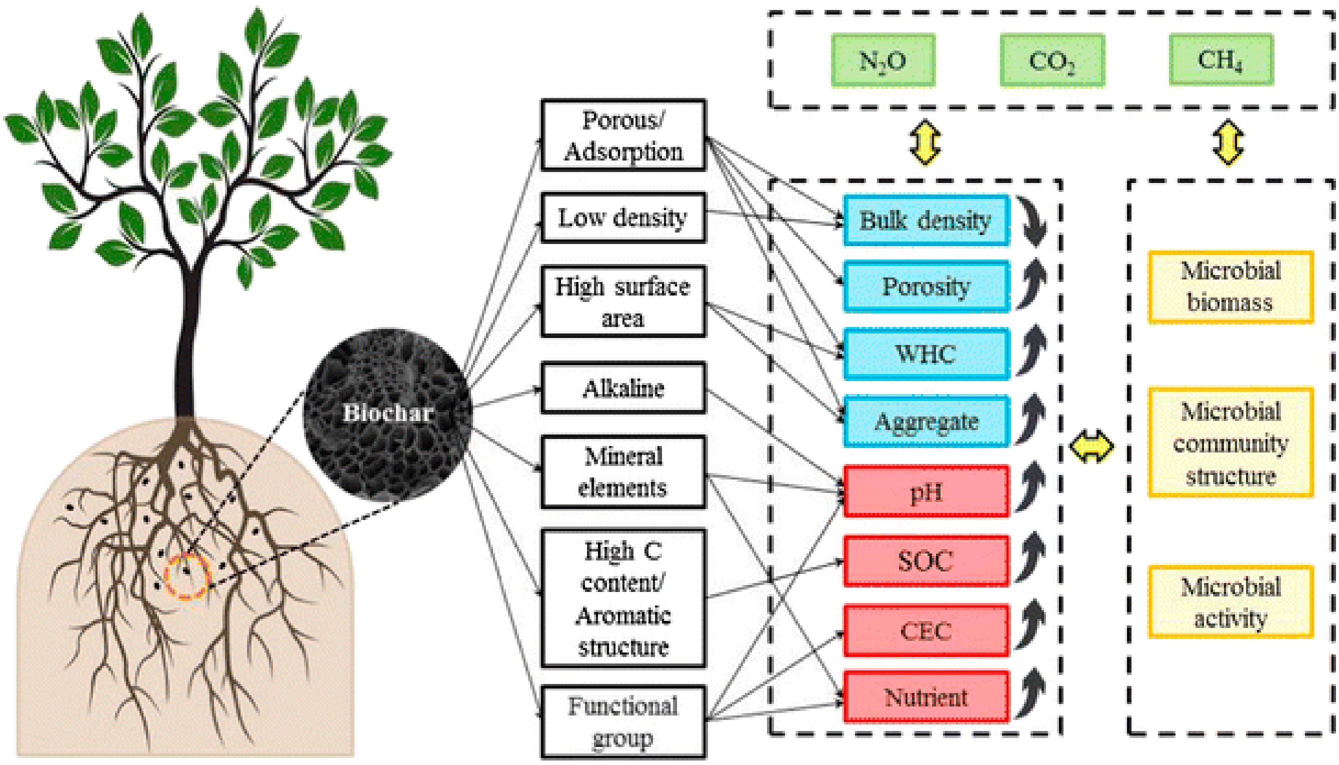

Figure 1. Effect of biochar on soil physical, chemical, and hydraulic properties (reprinted and adapted from [26]).

Furthermore, adding biochar increased the quantity of available water in the soil at any matric potential [25]. Biochar substantially improved the available water capacity (AWC) in coarse-textured soils; depending on the pyrolysis temperature of the biochar employed, the extent varies [27]. This influence, however, varied depending on the soil texture [28]. Soil hydraulic conductivity (K) was previously thought to be a significant soil property that governs infiltration and movement of water within the soil profile, affecting the probability of soil runoff following heavy rainfall. Applying biochar can cause the soil's saturated hydraulic conductivity (K_{sat}) to increase [14,25]. On the other side, such shifts were not found in the United States's traditional Midwestern agricultural soils. Although much attention has been paid to improvements in plant growth and productivity [29] and soil organic carbon (SOC) mineralization [30], studies on biochar's impact on soil hydrological and physical properties have been few [25]. Furthermore, in the limited research, the effects of biochar on soil physical qualities were inconsistent or contradictory, which varied with a wide range of soil and biochar circumstances. Unfortunately, there has been no quantitative evaluation of biochar's effects on soil physical properties, particularly soil hydrological parameters.

2. Biochar Properties

The chemical and physical characteristics of biochar vary depending on the nature of feedstock, the pyrolysis temperature, and the pyrolysis procedure [31,32]. Soil physical properties (e.g., soil particle distribution), soil porosity and surface area (SA), and chemical characteristics (such as pH, EC, zeta potential, OC, polycyclic aromatic hydrocarbons, element composition, and nutrient content) are modified by biochar application [33,34] (Figure 2).

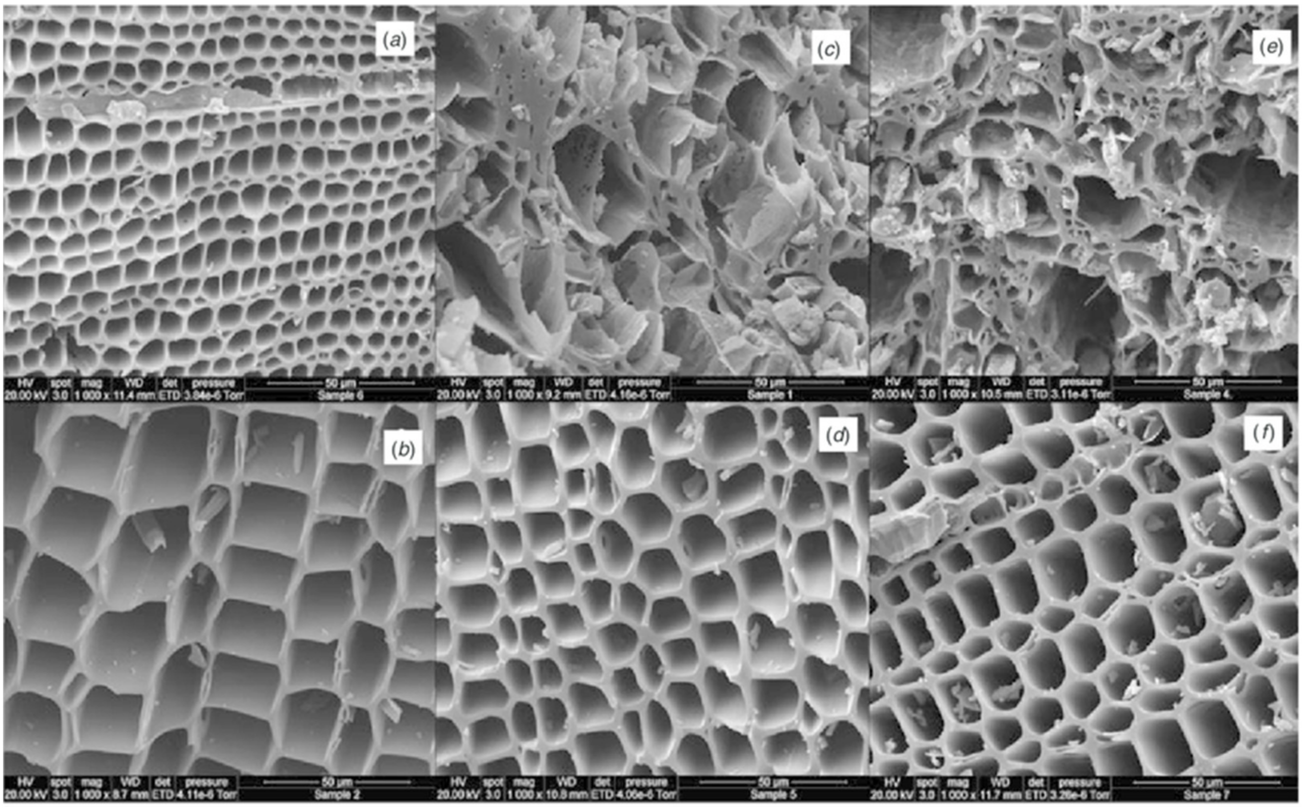

Figure 2. SEM images of various biochars (**a**) Ctr-EU, (**b**) Ctr-PI, (**c**) L-EU, (**d**), L-PI, (**e**) S-EU, (**f**) S-PI. (reprinted and adapted from [35]).

Compared to other plant-based feedstocks, hardwood biomass pyrolysis produces a higher OC [32,34]. After pyrolysis, the abundance of lignocellulose in hardwood biomass results in a greater C content. On the other hand, biochar made from animal manure has been shown to have higher nutrient content (N, P, K) and higher CEC than biochar made from plant-based feedstock [16,36]. Increased pyrolysis temperature of biochar raises nutrient concentration, soil porosity, SSA and C content, lowering O and H concentrations, improving pH, and lowering volatile matter concentrations [7,34,37]. The creation of micropores (intra-particle pores) is due to the splitting of aliphatic alkyl and ester groups, resulting in the loss of volatile compounds (i.e., cellulose and hemicelluloses) and, hence, the rise of SSA with pyrolysis temperatures [38]. Because no lignocellulosic component is present in biochar generated from animal manure and solid waste, the SSA is less affected by the pyrolysis temperature. It has a lower SSA than plant-based biochar pyrolyzed at the same high temperature [7]. The release of nutrients during the heating process could cause the pH to rise as the pyrolysis temperature rises [39].

CEC is a measure of biochar's negative surface charge, which may rise or fall with pyrolysis temperature depending on the functional groups in the biochar that have a net negative charge. Furthermore, the physicochemical characteristics of biochar, which are affected by the type of feedstock and pyrolysis conditions, determine its flexibility and stability. Because of the development of intra-particle pores and a high SSA caused by higher volatile matter degradation at high temperatures (>400 °C), biochar pyrolyzed at high temperatures is viable for the sorption of organic pollutants and heavy metals, improved soil characteristics and carbon sequestration [7,39]. Furthermore, the electrostatic attraction between the charged biochar surface and the ionic contaminant varies with pyrolysis temperature. This is attributed to changes in the biochar functional groups that control charge action. Because of the decreased oxidation of volatile materials, biochar pyrolyzed at low temperatures is also suitable for growing plants. As a result, characterizing the feedstock and pyrolysis temperature before using it for a specific application is essential.

3. The Impact of Biochar Application on the Physical and Hydrological Properties of Soil

3.1. Soil Bulk Density

Soil bulk density is a crucial measure of soil physical properties. It is closely linked to how soil particles are packed or arranged. Low SBD improves soil composition, facilitates nutrient release and preservation, and reduces soil compaction efficiently. Biochar has a porous structure and a density of 0.05–0.57 kg m^{-3}, smaller than mineral soil. Biochar applications significantly decreased SBD relative to the control group, according to Laird et al. [20]. Applying 25 g kg^{-1} biochar in silty soil reduced the SBD from 1.52 g cm^{-3} to 1.33 g cm^{-3} [40]. The soil stimulates soil fungal growth and microbial activity after biochar incorporation, as well as soil agglomeration; the formation of roots and hyphae affects SBD [41]. It has been shown that applying biochar to the soil reduces SBD and increases overall porosity [42,43]. Biochar composition, type of soil, biochar particle size, and biochar addition rate all affected SBD reduction (Table 1).

3.2. Soil Porosity

Soil pores provide oxygen for plants and animals and influence water transformation, preservation, and consumption. Biochar's pore distribution, connectedness, and particle size substantially impact the soil pore structure. The surface area of biochar is determined by the pores, which are loose and porous. The volatile matter reduces as the pyrolysis temperature rises, pore space and porosity rise, and SA rises [44]. A broad surface area encourages microbial activity and plants root development in soil pores by increasing soil microorganisms. Crop roots, on the other hand, relax the soil and alter the porosity indirectly. Wide pores and a low water-retaining capability characterize sandy soil.

Table 1. The effects of biochar on the soil bulk density, porosity, and soil organic carbon.

Biochars	Temp. (°C)	Rates (t ha^{-1})	BD (g cm^{-3})	Porosity (cm^3 cm^{-3})	SOC (g kg^{-1})	References
Corn	Control	0	1.66	0.37	3	
	350	4	1.3	0.51	30.5	[45]
	650	4	1.32	0.50	7.5	
Corn cob	Control	0	1.52	0.43	1.03	
	500–550	10	1.49	0.44	1.39	[46]
	500–550	20	1.45	0.45	1.71	
Birch	Control	0	1.30	50.9	1.81	[47]
	400	9	1.25	52.8	1.81	
Straw	Control		1.43	-	-	[48]
	525		1.17	84.3	-	
Eucalyptus trees	Control	0	1.58	-	4.1	
	350	1	1.55	-	10.3	[49]
	350	2	1.50	-	18.1	
	350	4	1.34	-	25.4	

Soil porosity, permeability, and saturated hydraulic conductivity increase dramatically after adding biochar [42]. According to Jeffery et al. [50], crop productivity improved by 10% and 13% after applying biochar to coarse and medium textured soils. Biochar allows the soil pore distribution (PD) of soil to shift to a narrower pore size distribution, which benefits crop development [51]. The improvement in soil porosity after applying biochar was observed in the 5–10 µm and 25 µm ranges [52]. Biochar increases overall porosity and the content of pores greater than 0.25 mm in diameter in frozen soil, resulting in the highest structural stability index [53]. According to studies, straw biochar raises macropores and mesopores in clay soils, and soil particles can be mixed with biochar to create stable big agglomerates [54]. The incorporation of biochar increases the porosity of the soil. It allows the reorganization of soil pores, which changes the distribution of soil pores. In brief, biochar can decrease soil compaction, help in water conservation and productivity by changing soil porosity and particle density (SPD), improve soil pore connectivity, and increase water and air circulation.

3.3. Water-Holding Capacity of Soil (SWHC)

Moisture is an essential component in the soil condition and its composition is determined by soil texture and precipitation levels [55]. The hydraulic properties are the foundation for understanding soil water flow and solute transfer in soil [56]. Biochar's high porosity and specific SA lower soil water permeability resistance, raise water-holding capacity, and alter water residence time and flow direction in soil [57,58]. The microporous composition of biochar influences SWHC. Biochar has been shown in studies to raise the SWHC in the region. Since sandy soil has lower water retaining potential than clay soil, applying biochar to sandy soil has a greater advantage [59]. According to Verheijen et al. [60], soil bulk density decreased after applying biochar to the soil.

In contrast, the soil water-holding capacity rose to its maximum. The reduction effect was more noticeable in sandy soil than in loam. Adding 25% and 5% biochar to sandy soil preserved 260 percent and 370 percent more water than in controlled trials [61]. The change in soil water content (SWC) may cause an increased output yield [62]. Field tests revealed no substantial changes in crop yield after adding biochar (@20 t ha^{-1}). A higher SWC was observed after three consecutive years, and corn yields rose by 28%, 30%, and

140%, respectively, compared to the regulation [63]. However, it is unclear if the WHC rises as the volume of biochar added rises. As a result, by varying the soil–biochar ratios, biochar is an ecologically friendly and long-lasting material.

3.4. Soil Water Retention Curve or Soil Water Characteristic Curve (SWCC)

The curve representing the graphical relationship between soil water suction (or matric suction) and soil water content (or soil moisture) is one of the most significant hydraulic characteristics in soil [64]. The SWCC is mainly influenced by the shape and composition of the soil [56]. Since the SWCC represents the relationship between soil pore condition and water content, it is influenced by factors that impact soil pore condition and water characteristics. Biochar amendment will change the size of soil pores, PD, porosity, and connectivity of soil pores, impacting water retention and soil mechanical ability. Water preservation was higher in biochar with a lower pore volume and average pore diameter. As a result, biochar will increase the hydraulic conductivity in soil water, particularly when used as a sandy soil amendment. Including biochar can change the soil's SWRC (Table 2) [16,28].

Table 2. Influence of biochar in soil's water retention (SWR).

Soil Texture	Pyrolysis Temp °C	Biochar Feedstock	Soil Water Retention (SWRC)	References
Sand	350,600	Pinewood, Pine bark	Increased	[65]
Silty sand	500	Peanut-shell	Increased	[66]
Sandy Clay	300−350	Water hyacinth	Increased	[67]
Kaolin clay	500	Peanut-shell	Increased	[68]
Sandy clay loam, Loam	450	*Miscanthus* sp.	Increased	[69]
Sand	400	*Mesquite*	Increased	[28]

3.5. Soil Hydraulic Conductivity (K)

Biochar application to soils will increase, reduce or have no effect on soil hydraulic conductivity, as shown in Table 3. According to the results, biochar application increased soil hydraulic conductivity by 28–176% compared to non-treated soil [70]. Applying biochar to clay soil at a rate of 16 Mg ha^{-1} [71] had the largest increase of 176%, with a mean increase of 73%, recording a 1–270% decline in K [70].

Table 3. Biochar and hydraulic conductivity.

Soil Textural	Type of Study	Duration of Study	Type of Feedstock	Biochar Application Rate	K (cm h^{-1})	References
Silty clay soil	I	105 days	*Leucaena leuco cephala*	0%	16.7 ^{a}	[24]
				2.5%	30.0 ^{b}	
				5%	33.1 ^{c}	
				0	0.59 ^{b}	[71]
				4 Mg ha^{-1}	0.89 ^{b}	
Clay loam soil	F	1 year	Wood	8 Mg ha^{-1}	0.77 ^{b}	[72]
				16 Mg ha^{-1}	1.63 ^{a}	
Sandy loam soil	F	30 months	Acacia green waste	0%	4.85 ^{a}	[73]
				0.50%	4.80 ^{a}	
Sandy loam	C	5 weeks	Conocarpus wastes	1%	4.47 ^{b}	
				1.5%	4.31 ^{c}	
				2%	4.12 ^{d}	
Loamy soil	F	30 months	*Miscanthus* sp.	0, 3.5, and 10 Mg ha^{-1}	Ns	[69]
Sandy loam soil.		15 months		0, 10, and 20 Mg ha^{-1}	Ns	

Note: F is for Field, I is for Incubation. C is for Column, NS is Non-Significant, and the letters a, b, c, and d represent the significant difference between various K values, and the increase was significant.

The most important reduction (270%) was observed in coarse sandy soil treated with 5% biochar. Biochar application decreased the soil saturated hydraulic conductivity in a study performed by Al-Wabel et al. [72] to examine the effect of cono carpus biochar addition on K of sandy loam soil. Similarly, Igalavithana et al. [74] discovered that applying biochar made from corn residue at 500 °C reduced Ksat, particularly as biochar application rates increased. Following the application of corn residue biochar at 2.5%, 5%, 7.5% and 10%, K_{sat} reduced by 46.6%, 63.4%, 76.7% and 83.5%, respectively. However, even when introduced at a high rate of 4%, certain biochars had no noticeable impact on K [75]. Based on the tests above, the impact of biochar on K can be described as follows: (i) fine-textured soil (clay) had a greater increase in K, (ii) coarse-textured soil (sand) had a greater reduction in K, and (iii) medium-textured soil (sand) had little to no effect.

The first pattern may be attributed to soil particle rearrangement, microporosity formation [27], and improved soil accumulation that aids soil drainage. The degree of pore organization and particle rearrangement improved by biochar application to fine-textured soil increases K [54]. These results do not preclude those caused by expansive clay [76]. According to Mubarak et al. [77], due to the restructuring of the delicate structural porosity produced by sample preparation, there may be a slight rise in water flow following high biochar application rates. The second pattern of decreased K in coarse texture soil after applying biochar as a soil amendment may be due to biochar particles clogging macropores. Most biochars used to have a particle size smaller than 2 mm. Biochar can clog parts of the soil pores and reduce porosity and water flow because coarse-textured soil is linked with macropores. Increased biochar application to soil raises the fraction of small and medium pores, reducing K due to the filling of pores by biochar particles [71].

The third pattern, in which biochar has little to no impact on medium-textured soil, might be due to a balance in the proportion of micro- and macropores in this soil type. If biochar particles occupy vast pores, diminishing microporosity, particle rearrangement occurs, resulting in the creation of new macropores and, as a result, a steady water flow. Generally, as the quantity of biochar added is raised, the K of fine-textured soil increases. In contrast, the hydraulic conductivity of coarse-textured soil decreases. However, further study in this field is needed to provide a solid understanding of biochar's effect on K.

3.6. Plant-Available Water (PAW)

Biochar enhanced plant-available water (PAW) in 21 of the 29 soils, according to Table 4, concluding that biochar increases available water in 72% of cases. There was a 4 to 130% rise in plant-available water with biochar. Biochar particles with higher specific surface area (SSA) and porosity may have contributed to the increased available water. Biochar has an SSA of up to 3000 $m^2\ g^{-1}$, sandy loam has an SSA of 10 to 40 $m^2\ g^{-1}$, silt loam has an SSA of 5 to 150 $m^2\ g^{-1,}$ and clayey soils have an SSA of 150 to 250 $m^2\ g^{-1}$. Biochar is a porous material with a high SSA that can retain water within the pores and particles. In comparison to macropores and mesopores, micropores depend on capillary and adhesive forces to keep water in place. As a result, applying biochar to soil alters the overall porosity, PD, water movement, and water-retention (WR) properties.

Since biochar increases the amount of water available to plants, using it on cropland may reduce irrigation frequency. This is particularly significant in water-scarce or semi-arid areas. Since sandy soils have less microporosity and a smaller SSA than clayey soils, biochar's beneficial effect on rising water retention may be more significant in sandy soils. Table 4 shows no evident tendency for a bigger increase in WR in sandy soils than in clayey soils. This is due to a scarcity of matched research comparing various textural groups using the same quantity of biochar. The tests used various amounts of biochar and were conducted in various soil texture classes. Comparisons were difficult because the temperature of the pyrolysis reaction, experiment duration, and the feedstock used in each sample differed. When used in small amounts, biochar does not affect the water available. According to several studies, biochar addition at 10 Mg ha^{-1} did not affect AW [75,78,79]; however, greater application rates resulted in a considerable rise in AW.

In many cases, observations were taken shortly after biochar was combined with soil. The majority of tests were conducted in the lab. Long-term field studies will better illustrate how soil–biochar interactions evolve. Biochar has a mixed impact on available water, as shown in Table 4. Biochar tends to affect the amount of water available. Burrell et al. [49] found that while straw biochar increased AW, woodchip biochar did not affect the same concentration. Second, the seven studies that found no impact of biochar indicate that biochar may not always increase available water depending on the soil type. The amount of biochar used indicates that biochar's benefits are site-specific (Table 4).

Thirdly, according to this literature review, biochar may either increase [79], decrease [80], or have no impact [81] on AW in clayey soils. Biochar seems to work better in soils with a coarse texture. It is also worth noting that while biochar can help with water retention in some situations, it does not necessarily mean more water for the plants. The hydrophobicity of biochar may be a factor in cases where it does not improve water retention. Due to the existence of OM on the surface of biochar particles, fresh biochar formed at low temperatures may have water-repellent properties, as previously mentioned. Biochar will improve the water available to plants in the long run.

Table 4. For various soil and management circumstances, the impact of biochar application on PAW.

Location	Soil	Study Type	Study Duration	Biochar Feedstock	Biochar Rate	PAW (%)	References
Malaysia	Sand	P	170 days	Rice husk	0 20g kg^{-1} 50g kg^{-1}	0.047 ^{b} 0.062 ^{a,b} 0.082 ^{a}	[82]
Iran	Sandy loam	I	180 days	Rice husk and wood	0, 20 g kg^{-1}	Increased	[83]
China	Sand	I	180 days	Straw, woodchips, and wastewater sludge	20, 40, 60 g kg^{-1}	No effect	[84]
USA	Silty clay loam	L	2 weeks	Wood	0 and 1%	Increased	[85]
Zambia	Sandy loam	F	1 year	Corn cob, rice husk	0–40 g kg^{-1}	Increased	[86]
China	loam	F	1 year	Crop straw	0–16 Mg ha^{-1}	No effect	[87]
Brazil	Sandy loam	F	3 years	Wood	0, 8, 16, 32Mg ha^{-1}	Increased	[88]

Note: P is for Pot, F is for Field, and L is for the lab. and I am Incubation, and a, b indicates significant differences between the treatments.

3.7. Infiltration

Infiltration is the downward flow of water through the surface. Water infiltration is a crucial hydrological process influencing surface runoff and soil erosion. Infiltration replenishes the water in the soil. Poor management may reduce the infiltration rate, resulting in runoff or ponding on the soil surface, where it evaporates. As a result, water retained in the soil for the growth of plants is exhausted, resulting in lower plant production and less biomass, which contributes to SOM. In addition, the composition of the soil is harmed. The effect of biochar on the infiltration rate into the soil is shown in Table 5. There are data on the impact of biochar on soil's physical or hydrological properties in this region. Infiltration was affected differently by biochar. Biochar application increased infiltration rate [89,90], decreased infiltration rate [73,91] or had no impact [73,91,92]. These results are comparable to those of K in soil.

Table 5. Biochar's effects on water infiltration as reported in many studies.

Soil Texture	Type of Study	Duration of Study	Type of Feedstock	Biochar Application Rate	Water Infiltration (mL min^{-1})	References
Clay loam	P	Two years	Plant residues	0 and 20 Mg ha^{-1}	Increased	[90]
Sandy loamy	I	128 days	Pine chips and poultry litter (50:50) and (80:20) 100% poultry litter 100% pine chips	0% 2% 2% 2% 2%	0.086 [b] 0.0168 [a] 0.110 [b] 0.047 [b] 0.119 [b]	[89]
Loamy sand	I	96 days	Pecan	0, 11, 22, and 44 Mg ha^{-1}	Not significant	[92]
Sandy loamy	P	5 weeks	Wood	0% 0.5% 1% 1.5% 2%	0.763 [a] 0.761 [a] 0.548 [c] 0.564 [b] 0.534 [d]	[73]
Sandy loamy	G	<2 months	Peanut hulls	0, 25, 50, 75, and 100% by volume	Decreased	[91]

Note: a, b, c, d mean that the treatments differ significantly.

The decline in infiltration rate after biochar application may be due to the pores in biochar filling with water [93] or their physical disintegration [93]. Furthermore, Verheijen et al. [94] indicated that structural deterioration of biochar caused by water flushing, heavy traffic during the application, and soil tillage's impact after application might all contribute to soil compaction. It is thought that dislodged particles clog soil pores. When biochar made from pelletized lignocellulosic and manure was shaken in the water, it broke down physically into flake-like fragments, according to Spokas et al. [94]. The fragments were micrometer to a nanometer in size, with some having jagged edges [95]. As a result, biochar may be suspended in percolating water and migrate along with the soil profile. The biochar particles' jagged-edge shape and size can block soil micropores, decreasing water penetration. Joseph et al. [96] confirmed the creation of nano-scale fragments from pyrolyzed black carbon content, and this hypothesis has validity. After a two-year experiment in which biochar was put into clay loam soil at a rate of 20 Mg ha^{-1}, Prober et al. [90] observed an increase in water penetration, which they believe was due to the formation of more pores in the soil matrix. Since biochar is highly porous [35] and micropores dominate clay soils, the interaction of biochar with clay soils may result in more pores. However, more research is required to fully comprehend the relationship between biochar and soil and how it affects infiltration.

3.8. Water Repellency

Runoff, bypass flow, water infiltration, water retention, integrity, and other hydrological processes influence the water repellency in soil. Aggregation, microbial activity, organic matter (OM) breakdown, and water input and dispersion are all affected by biochar application. The above processes impact soil physical processes, while extreme soil water repellency (SWR) can reduce penetration and harm-related hydrological processes [97].

Fire-affected forest soils can be highly hydrophobic [98,99]. The question is whether biochar has an impact on soil water repellency. Biochar's microstructure is frequently hydrophobic, which means that when applied to soil, it repels water [100,101]. Based on the limited evidence available, biochar appears to have little or no effect on SWR (Table 6). In the three studies mentioned in Table 6, biochar did not affect water repellency. Biochar application at 1.5, 2.5, and 5.0% decreased SWR, with the 5.0% rate having the greatest effect, decreasing SWR five times relative to the control, according to Devereux et al. [25]. Biochar application at 1.5, 2.5, and 5.0% decreased water repellency the most, according to Głąb et al. [75], with the 5.0% rate having the greatest impact, reducing water repellency five-fold compared to the control. Biochar application at 4.0% improved SWR slightly compared to 0.5%, however biochar application at 1 and 2% had no impact, according to Głąb et al. [75]. Dekker and Jungerius [102] classified WDPT as wettable, moderately repellent, seriously repellent, and extremely repellent with WDPT, ranging from 5 s to 5 to 60 s, 60 to 600 s, 600 to 3600 s, and greater than 3600 s, respectively. Biochar reduced the soil's WDPT from 11 to 4 and 2 s, according to Devereux et al. [25], implying that biochar application decreased the soil's water repellency from moderately water repellent to non-water repellent.

According to Glab et al. [75], biochar raised the WDPT of the soil to 1.62 s, from 1.02 s, but the increase was minor. The water repellency of biochar may be affected by interactions between the temperature of biochar production, biochar placement technique, the soil texture, soil water quality, application time, and other parameters. New biochar repels water better than old biochar in general [98]. The hydrophobicity of biochar can be affected by the pyrolysis temperature. Low-temperature biochar has the potential to be more water-resistant than biochar generated at high temperatures. The biochar feedstock determines how much repellency increases as the pyrolysis temperature rises. According to Kinney et al. [100], the drop in SWR as the pyrolysis temperature increased was higher for maize stover and apple wood biochar than for magnolia leaf biochar. In both coarse and fine soils, Page-Dumroese et al. and Hussain et al. [103,104] observed that biochar mixed with the soil exhibited less SWR than the biochar applied at the surface, especially when the soil water content approached 25%. As biochar–soil interactions strengthen and repellent layers erode, the strength of water repellency will decrease. Finally, the study revealed that biochar had little to no influence on the SWR (Table 6).

Table 6. Biochar effects on SWR under various management scenarios.

Location	Soil	Type of Study	Duration of Study	Type of Feedstock	Biochar Rate	SWR (S = m/s)	References
Germany	Sandy	L and F	<6 months	Corn	1, 2.5, 5%	No effect	[27]
Italy	Sandy clay loam	P	Two years	Orchard pruning	22, 44 Mg ha^{-1}	No effect	[105]
New Zealand	Silt loam	G	295 days	Corn stover at	17.3, 11.3, 10.0 Mg ha^{-1}	No effect	[14]
UK	Sandy loam	G	<10 weeks	Wood	0% 1.5 2.5% 5%	11 ^{a} 4.1 ^{b} 2 ^{c}	[25]
Portland	Loamy sand	G	Three months	*Miscanthus* giganteus, winter wheat.	0.5% 1% 2% 3% 4%	1.02 1.03 1.15 1.62	[75]

Note: L means Lab, G means Greenhouse, P means Pots, and F means Field. and a, b, and c represent the significant differences between the treatments.

3.9. Soil Temperature

Biochar application can affect soil temperature due to its inherent electrical and thermal properties and changes in soil parameters. According to a few published studies, biochar treatment can impact soil temperature. Corncob biochar applied at 4.5, and 9.0 Mg ha^{-1} to winter wheat–corn crop in the North China Plain decreased daytime soil temperature fluctuations [106]. Biochar lowered soil surface temperature by 0.8 degrees in very hot soils. The same study raised soil temperature by 0.6 degrees in less-hot soils. On grassland and fallow fields in Poland, wood biochar decreased the amplitude of average soil temperature in grassland. It enhanced the amplitude in fallow soil, but the mean soil temperature observed at the 0–15 cm depth remained unchanged [107]. According to Ventura et al. [108], in Italy, biochar applied at 30 and 60 Mg ha^{-1} did not affect soil temperature at the 7.5 cm level. Although mean soil temperature does not appear to alter considerably, data show that biochar can decrease the daytime surface temperature in the soil while enhancing nocturnal soil temperature. These soil temperature fluctuations can have a significant effect on reducing extreme temperature swings in the soil.

3.10. Surface Albedo

Biochar's dark color darkens the soil and affects the soil surface's albedo. Surface albedo is the percentage of solar energy reflected in the atmosphere by the soil. Dark soils absorb light and reflect less light than grey soils. Biochar application from 4.5 to 30 Mg ha^{-1} was found to minimize albedo or soil reflectance in studies conducted in China [106] and Poland [107]. Soils containing biochar have a lower reflectance than soils containing biochar, decreasing evaporation and raising soil water content. Even at low application rates, Verheijen et al. [109] revealed that applying pine (*Pinus* spp.) biochar to the soil at rates of 1, 10, 100, and 200 t Mg ha^{-1} can reduce soil albedo. Variations in soil surface albedo are more evident in damaged soils with little to no plant cover than in soils with suitable vegetation, which reduces albedo changes [107,110].

3.11. Soil Color

Biochar is a black particulate matter that darkens the color of the soil and affects the reflectance and temperature of the soil surface, thereby affecting soil heat [111,112]. The soil color surrounding the charcoal kiln in Ghana was darker than in the rest of the nation. Surface reflectivity was reduced by 37% compared to other places, and the average surface temperature rose by 4 °C [42]. Briggs et al. [108] investigated how the soil color changed after biochar application and found that the Munsell color value changed as the biochar application rate increased. The Munsell color value was 5.5 when the adding rate was 10 g kg^{-1}. The value dropped to 3.6 when the application rate was raised to 50 g kg^{-1}. According to Oguntunde et al. [113], the Munsell color of the soil reduced to 2.5 from 3.1 after adding biochar.

4. Future Recommendations

Although most case studies have shown that biochar has favorable effects on soil parameters in agro settings, there may be some less well-known negative consequences of biochar on some soils. According to recent reports, additional substances, such as PAHs and VOCs, were created during the manufacture of biochar and persisted on the surface of the biochar particles. Such elements would be detrimental to the development of crops and the soil microbial community. Therefore, future research has to focus on the eco-toxicological impacts of applying biochar on developing soil microbes and crops in agronomic environments. In addition, most of the studies on biochar are confined to laboratory and greenhouse conditions. At the same time, little has been undertaken on a field scale, which needs introspection. The research conducted in the lab should be in sync with field studies. Differences in soil qualities, weather, and environmental variables may account for the discrepancy between field and laboratory investigations. As a result, large-scale field studies are required to learn more about the impacts of biochar on soil's physical and hydrological qualities under various environmental situations. Since biochar ages with time, drastically changing its properties and affecting soil water properties, a comprehensive strategy should be adopted to properly replace biochar with fresh material. Biochar research is limited to very short spans. As a result, it is critical to conduct long-term field research to evaluate the impact of biochar on soil water characteristics and the changes in biochar functioning that result over a while. Biochar surface functionality and hydrophobicity should be considered before its application on a large scale. These two qualities are crucial in determining biochar's capacity to improve soil water retention. It is critical to conduct further study in this area. Given the higher costs of biochar, this is likely to impact the return on investment. More studies into biochar modification (using pre- or post-pyrolysis treatments) are critical to maximizing the low-dosage–high-efficiency advantage.

5. Conclusions

Biochar's unique physical and chemical features offer much potential for improving the soil. Biochar can lower soil bulk density, enhance soil porosity, infiltration, and hydraulic characteristics, darken soil color and raise soil temperature by adding it to the soil. To understand the interacting effect of biochar and soil particles, this review analyzed existing data on the effects of biochar on soil physical parameters. Biochar enhances the physical environment of the soil in general. Biochar appears to benefit sandy soils more than clayey soils. Biochar application can boost water-retention capacity and plant-available water continuously. Biochar application improves soil's physical qualities, depending on the biochar (pyrolysis conditions and biomass type). This information is required to assess the technology's economic feasibility.

Author Contributions: Conceptualization: S.A.B. and M.U.D.D.; methodology: O.B. and O.S.; software and validation: R.A. and A.E.; writing—original draft preparation, S.A.B. and M.U.D.D.; writing—review and editing: A.K., S.S.S. and S.H.; visualization and supervision: A.K., S.S.S. and A.R.M.T.I.; funding acquisition: N.A.-A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Saxena, J.; Rawat, J.; Kumar, R. Conversion of biomass waste into Biochar and the effect on mung bean crop production. *CLEAN Soil Air Water* **2017**, *45*, 1501020. [CrossRef]
2. Stella Mary, G.; Sugumaran, P.; Niveditha, S.; Ramalakshmi, B.; Ravichandran, P.; Seshadri, S. Production, characterization and evaluation of Biochar from pod (*Pisum sativum*), leaf (*Brassica oleracea*) and peel (*Citrus sinensis*) wastes. *Int. J. Recycl. Org. Waste Agric.* **2016**, *5*, 43–53. [CrossRef]
3. Bera, T.; Purakayastha, T.J.; Patra, A.K.; Datta, S.C. Comparative analysis of physicochemical, nutrient, and spectral properties of agricultural residue biochars as influenced by pyrolysis temperatures. *J. Mater. Cycles Waste Manag.* **2018**, *20*, 1115–1127. [CrossRef]
4. Mohan, D.; Sarswat, A.; Ok, Y.S.; Pittman, C.U. Organic and inorganic contaminants removal from water with Biochar, a renewable, low cost and sustainable adsorbent—A critical review. *Bioresour. Technol.* **2014**, *160*, 191–202. [CrossRef]
5. Tripathi, M.; Sahu, J.N.; Ganesan, P. Effect of process parameters on production of Biochar from biomass waste through pyrolysis: A review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 467–481. [CrossRef]
6. Sharma, M.; Singh, J.; Baskar, C.; Kumar, A. A comprehensive review on biochar formation and its utilization for wastewater treatment. *Pollut. Res.* **2018**, *37*, S1–S18.
7. Ahmad, M.; Rajapaksha, A.U.; Lim, J.E.; Zhang, M.; Bolan, N.; Mohan, D.; Vithanage, M.; Lee, S.S.; Ok, Y.S. Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere* **2014**, *99*, 19–33. [CrossRef]
8. Vijayaraghavan, K. Recent advancements in biochar preparation, feedstocks, modification, characterization and future applications. *Environ. Technol. Rev.* **2019**, *8*, 47–64. [CrossRef]
9. Kumar, A.; Shalini.; Sharma, G.; Naushad, M.; Kumar, A.; Kalia, S.; Guo, C.; Mola, G.T. Facile hetero-assembly of superparamagnetic Fe3O4/BiVO4 stacked on Biochar for solar photo-degradation of methyl paraben and pesticide removal from soil. *J. Photochem. Photobiol. Chem.* **2017**, *337*, 118–131. [CrossRef]
10. Nguyen, V.T.; Nguyen, T.B.; Chen, C.W.; Hung, C.M.; Chang, J.H.; Dong, C.D. Influence of pyrolysis temperature on polycyclic aromatic hydrocarbons production and tetracycline adsorption behavior of Biochar derived from spent coffee ground. *Bioresour. Technol.* **2019**, *284*, 197–203. [CrossRef]
11. Rajapaksha, A.U.; Chen, S.S.; Tsang, D.C.W.; Zhang, M.; Vithanage, M.; Mandal, S.; Gao, B.; Bolan, N.S.; Ok, Y.S. Engineered/designer biochar for contaminant removal/ immobilization from soil and water: Potential and implication of biochar modification. *Chemosphere* **2016**, *148*, 276–291. [CrossRef] [PubMed]
12. Jain, S.; Singh, A.; Khare, P.; Chanda, D.; Mishra, D.; Shanker, K.; Karak, T. Toxicity assessment of *Bacopa monnieri* L. grown in Biochar amended extremely acidic coal mine spoils. *Ecol. Eng.* **2017**, *108*, 211–219. [CrossRef]
13. Liu, Y.; Zhu, J.; Ye, C.; Zhu, P.; Ba, Q.; Pang, J.; Shu, L. Effects of biochar application on the abundance and community composition of denitrifying bacteria in a reclaimed soil from coal mining subsidence area. *Sci. Total Environ.* **2018**, *625*, 1218–1224. [CrossRef]
14. Herath, H.M.S.K.; Camps-Arbestain, M.; Hedley, M. Effect of Biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol. *Geoderma* **2013**, *209*, 188–197. [CrossRef]

15. Herath Jones, B.E.H.; Haynes, R.J.; Phillips, I.R. Effect of amendment of bauxite processing sand with organic materials on its chemical, physical and microbial properties. *J. Environ. Manag.* **2010**, *91*, 2281–2288. [CrossRef]
16. Singh, B.; Singh, B.P.; Cowie, A.L. Characterisation and evaluation of biochars for their application as a soil amendment. *Soil Res.* **2010**, *48*, 516–525. [CrossRef]
17. Villagra-Mendoza, K.; Horn, R. Effect of biochar addition on hydraulic functions of two textural soils. *Geoderma* **2018**, *326*, 88–89. [CrossRef]
18. Abujabhah, I.S.; Bound, S.A.; Doyle, R.; Bowman, J.P. Effects of biochar and compost amendments on soil physico-chemical properties and the total community within a temperate agricultural soil. *Appl. Soil Ecol.* **2016**, *98*, 243–253. [CrossRef]
19. Lehmann, J.; Pereira da Silva, J.; Steiner, C.; Nehls, T.; Zech, W.; Glaser, B. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: Fertilizer, manure and charcoal amendments. *Plant Soil* **2003**, *249*, 343–357. [CrossRef]
20. Laird, D.A.; Fleming, P.; Davis, D.D.; Horton, R.; Wang, B.; Karlen, D.L. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma* **2010**, *158*, 443–449. [CrossRef]
21. Six, J.; Bossuyt, H.; Degryze, S.; Denef, K. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res.* **2004**, *79*, 7–31. [CrossRef]
22. Ouyang, L.; Wang, F.; Tang, J.; Yu, L.; Zhang, R. Effects of biochar amendment on soil aggregates and hydraulic properties. *J. Soil Sci. Plant Nutrit.* **2013**, *13*, 991–1002. [CrossRef]
23. Hillel, D.; Hatfield, J.L. (Eds.) *Encyclopedia of Soils in the Environment*; Elsevier: Amsterdam, The Netherlands, 2005; Volume 3.
24. Jien, S.H.; Wang, C.S. Effects of Biochar on soil properties and erosion potential in a highly weathered soil. *Catena* **2013**, *110*, 225–233. [CrossRef]
25. 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]
26. Li, Y.; Hu, S.; Chen, J.; Müller, K.; Li, Y.; Fu, W.; Lin, Z.; Wang, H. Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: A review. *J. Soils Sediments* **2018**, *18*, 546–563. [CrossRef]
27. Uzoma, K.C.; Inoue, M.; Andry, H.; Zahoor, A.; Nishihara, E. Influence of biochar application on sandy soil hydraulic properties and nutrient retention. *J. Food Agric. Environ.* **2011**, *9*, 1137–1143.
28. 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]
29. 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*, 0179079. [CrossRef]
30. Wang, J.; Chen, G.; Christie, P.; Zhang, M.; Luo, Y.; Teng, Y. Occurrence and risk assessment of phthalate esters (PAEs) in vegetables and soils of suburban plastic film greenhouses. *Sci. Total Environ.* **2015**, *523*, 129–137. [CrossRef]
31. Lehmann, J.; Joseph, S. *Biochar for Environmental Management: Science and Technology*; Earthscan: London, UK, 2009; pp. 1–12.
32. Tan, Z.; Zou, J.; Zhang, L.; Huang, Q. Morphology, pore size distribution, an nutrient characteristics in biochars under different pyrolysis temperatures and atmospheres. *J. Mater. Cycl. Waste* **2018**, *20*, 1036–1049. [CrossRef]
33. Tan, X.; Liu, Y.; Zeng, G.; Wang, X.; Hu, X.; Gu, Y.; Yang, Z. Application of Biochar for the removal of pollutants from aqueous solutions. *Chemosphere* **2015**, *125*, 70–85. [CrossRef]
34. Yargicoglu, E.N.; Sadasivam, B.Y.; Reddy, K.R.; Spokas, K. Physical and chemical characterization of waste wood derived biochars. *Waste Manag.* **2015**, *36*, 256–268. [CrossRef] [PubMed]
35. Hina, K.; Bishop, P.; Arbestain, M.C.; Calvelo-Pereira, R.; Macia-Agullo, J.A.; Hindmarsh, J.; Hanly, J.A.; Macias, F.; Hedley, M.J. Producing biochars with enhanced surface activity through alkaline pre-treatment of feedstocks. *Aust. J. Soil Res.* **2010**, *48*, 606–617. [CrossRef]
36. Jindo, K.; Mizumoto, H.; Sawada, Y.; Sanchez-Monedero, M.A.; Sonoki, T. Physical and chemical characterization of biochars derived from different agricultural residues. *Biogeosciences* **2014**, *11*, 6613–6621. [CrossRef]
37. Downie, A.; Crosky, A.; Munroe, P. Physical properties of Biochar. In *Biochar for Environmental Management: Science and Technology*; Routledge: London, UK, 2009; pp. 13–32.
38. Kim, W.K.; Shim, T.; Kim, Y.S.; Hyun, S.; Ryu, C.; Park, Y.K.; Jung, J. Characterization of cadmium removal from aqueous solution by Biochar produced from a giant Miscanthus at different pyrolytic temperatures. *Bioresour. Technol.* **2013**, *138*, 266–270. [CrossRef] [PubMed]
39. Qiao, J.T.; Li, X.M.; Li, F.B. Roles of different active metal-reducing bacteria in arsenic release from arsenic-contaminated paddy soil amended with Biochar. *J. Hazard. Mater.* **2018**, *344*, 958–967. [CrossRef]
40. Zhang, Y.; Wang, J.; and Feng, Y. The effects of biochar addition on soil physicochemical properties: A review. *Catena* **2021**, *202*, 105284. [CrossRef]
41. Steiner, C.; Teixeira, W.G.; Lehmann, J.; Nehls, T.; de Macêdo JL, V.; Blum, W.E.; Zech, W. Long-term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant Soil* **2007**, *291*, 275–290. [CrossRef]
42. Oguntunde, P.G.; Abiodun, B.J.; Ajayi, A.E.; van de Giesen, N. Effects of charcoal production on soil physical properties in Ghana. *J. Plant Nutrit. Soil Sci.* **2008**, *171*, 591–596. [CrossRef]

43. Qin, X.; Li, Y.; Wang, H.; Liu, C.; Li, J.; Wan, Y.; Gao, Q.; Fan, F.; Liao, Y. Long-term effect of biochar application on yield-scaled greenhouse gas emissions in a rice paddy cropping system: A four-year case study in south China. *Sci. Total Environ.* **2016**, *569*, 1390–1401. [CrossRef]
44. Chen, B.L.; Yuan, M.X. Enhanced sorption of polycyclic aromatic hydrocarbons by soil amended with Biochar. *J. Soils Sediments* **2011**, *11*, 62–71. [CrossRef]
45. Saffari, N.; Hajabbasi, M.A.; Shirani, H.; Mosaddeghi, M.R.; Owens, G. Influence of corn residue biochar on water retention and penetration resistance in a calcareous sandy loam soil. *Geoderma* **2021**, *38*, 114734. [CrossRef]
46. Amoakwah, E.; Frimpong, K.A.; Okae-Anti, D.; Arthur, E. Soil water retention, air flow and pore structure characteristics after corn cob biochar application to a tropical sandy loam. *Geofis. Int.* **2017**, *307*, 189–197. [CrossRef]
47. Karhu, K.; Mattila, T.; Bergstrom, I.; Regina, K. Biochar addition to agricultural soil increased CH4 uptake and water holding capacity—Results from a short-term pilot field study. *Agric. Ecosyst. Environ.* **2011**, *140*, 309–313. [CrossRef]
48. Burrell, L.D.; Zehetner, F.; Rampazzo, N.; Wimmer, B.; Soja, G. Long term effects of Biochar on soil physical properties. *Geoderma* **2016**, *282*, 96–102. [CrossRef]
49. Butnan, S.; Deenik, J.L.; Toomsan, B.; Vityakon, P. Biochar properties affecting carbon stability in soils contrasting in texture and mineralogy. *Agric. Nat. Resour.* **2018**, *51*, 492–498. [CrossRef]
50. Jeffery, S.; Verheijen, F.G.A.; van der Velde, M.; Bastos, A.C. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agric. Ecosyst. Environ.* **2011**, *144*, 175–187. [CrossRef]
51. 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]
52. Rasa, K.; Heikkinen, J.; Hannula, M.; Arstila, K.; Kulju, S.; Hyväluoma, J. How and why does willow biochar increase a clay soil water retention capacity? *Biomass Bioenergy* **2018**, *119*, 346–353. [CrossRef]
53. Wang, Y.Z.; Zhang, K. Heavy Metal Pollution in Soil and Agricultural Products on Roadside of Highway in Seasonally Frozen Soil Area. *Rev. Fac. Agron. Univ. Zulia* **2019**, *36*, 754–763.
54. Sun, F.F.; Lu, S.G. Biochars improve aggregate stability, water retention, and pore space properties of clayey soil. *J. Plant Nutr. Soil Sci.* **2014**, *177*, 26–33. [CrossRef]
55. Fu, Q.; Zhao, H.; Li, T.; Hou, R.; Liu, D.; Ji, Y.; Zhou, Z.; Yang, L. Effects of biochar addition on soil hydraulic properties before and after freezing-thawing. *Catena* **2019**, *176*, 112–124. [CrossRef]
56. Carrick, S.; Buchan, G.; Almond, P.; Smith, N. A typical early-time infiltration into a structured soil near field capacity: The dynamic interplay between sorptivity, hydrophobicity, and air encapsulation. *Geoderma* **2011**, *160*, 579–589. [CrossRef]
57. Major, J.; Rondon, M.; Molina, D.; Riha, S.J.; Lehmann, J. Nutrient Leaching in a Colombian Savanna Oxisol Amended with Biochar. *J. Environ. Qual.* **2012**, *41*, 1076–1086. [CrossRef]
58. 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]
59. Cheng, C.H.; Lehmann, J.; Thies, J.E.; Burton, S.D.; Engelhard, M.H. Oxidation of black carbon by biotic and abiotic processes. *Org. Geochem.* **2006**, *37*, 1477–1488. [CrossRef]
60. Verheijen, F.G.; 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]
61. 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]
62. Yang, Y.; Ma, S.; Zhao, Y.; Jing, M.; Xu, Y.; Chen, J. A Field Experiment on Enhancement of Crop Yield by Rice Straw and Corn Stalk-Derived Biochar in Northern China. *Sustainability* **2015**, *7*, 13713–13725. [CrossRef]
63. Vitkova, J.; Kondrlova, E.; Rodny, M.; Surda, P.; Horak, J. Analysis of soil water content and crop yield after biochar application in field conditions. *Plant Soil Environ.* **2017**, *63*, 569–573.
64. Bayat, H.; Mazaheri, B.; Mohanty, B.P. Estimating soil water characteristic curve using landscape features and soil thermal properties. *Soil Tillage Res.* **2019**, *189*, 1–14. [CrossRef]
65. Suliman, W.; Harsh, J.B.; Abu-Lail, N.I.; Fortuna, A.M.; Dallmeyer, I.; Garcia-Pérez, M. The role of biochar porosity and surface functionality in augmenting hydrologic properties of a sandy soil. *Sci. Total Environ.* **2017**, *574*, 139–147. [CrossRef] [PubMed]
66. Ni, J.; Chen, X.; Ng, C.; Guo, H. Effects of Biochar on water retention and matric suction of vegetated soil. *Géotech. Lett.* **2018**, *18*, 124–129. [CrossRef]
67. Bordoloi, S.; Garg, A.; Sreedeep, S.; Lin, P.; Mei, G. Investigation of cracking and water availability of soil-biochar composite synthesized from invasive weed water hyacinth. *Bioresour. Technol.* **2018**, *263*, 665–677. [CrossRef]
68. Wong, J.T.F.; Chen, Z.; Chen, X.; Ng, C.W.W.; Wong, M.H. Soil-water retention behavior of compacted biochar-amended clay: A novel landfill final cover material. *Int. J. Soil Sediments* **2017**, *17*, 590–598. [CrossRef]
69. Moragues-Saitua, L.; Arias-González, A.; Gartzia-Bengoetxea, N. Effects of biochar and wood ash on soil hydraulic properties: A field experiment involving contrasting temperate soils. *Geoderma* **2017**, *305*, 144–152. [CrossRef]
70. 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]

71. 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: 1. Soil physical properties, leaf SPAD and grain yield. *Field Crops Res.* **2009**, *111*, 81–84. [CrossRef]
72. Hardie, M.; Clothier, B.; Bound, S.; Oliver, G.; Close, D. Does Biochar influence soil physical properties and soil water availability? *Plant Soil* **2014**, *376*, 347–361. [CrossRef]
73. Al-Wabel, M.I.; Al-Omran, A.; El-Naggar, A.H.; Nadeem, M.; Usman, A.R.A. Pyrolysis temperature induced changes in characteristics and chemical composition of Biochar produced from conocarpus waste. *Bioresour. Technol.* **2013**, *131*, 374–379. [CrossRef]
74. Igalavithana, A.D.; Ok, Y.S.; Niazi, N.K.; Rizwan, M.; Al-Wabel, M.I.; Usman, A.R.A.; Moon, D.H.; Lee, S.S. Effect of corn residue Biochar on the hydraulic properties of sandy loam soil. *Sustainability* **2017**, *9*, 266–276. [CrossRef]
75. 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]
76. Lu, S.; Sun, F.; Zong, Y. Effect of rice husk biochar and coal fly ash on some physical properties of expansive clayey soil (vertisol). *Catena* **2014**, *114*, 37–44. [CrossRef]
77. Mubarak, I.; Mailhol, J.C.; Angulo-Jaramillo, R.; Ruelle, P.; Boivin, P.; Khaledian, M. Temporal variability in soil hydraulic properties under drip irrigation. *Geoderma* **2009**, *150*, 158–165. [CrossRef]
78. Xiao, Q.L.; Zhu, H.; Zhang, X.; Li, Y.; Shen, Y.F.; Li, S. Soil amendment with Biochar increases maize yields in a semi-arid region by improving soil quality and root growth. *Crop Pasture Sci.* **2016**, *67*, 495–507. [CrossRef]
79. Kameyama, K.; Miyamoto, T.; Shiono, T.; and Shinogi, Y. Influence of sugarcane bagasse-derived biochar application on nitrate leaching in calcaric dark red soil. *J. Environ. Qual.* **2012**, *41*, 1131–1137. [CrossRef] [PubMed]
80. Castellinia, M.; Giglio, L.; Niedda, M.; Palumbo, A.D.; Ventrella, D. Impact of biochar addition on the physical and hydraulic properties of a clay soil. *Soil Tillage Res.* **2015**, *154*, 1–13. [CrossRef]
81. 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]
82. Manickam, T.; Cornelissen, G.; Bachmann, R.T.; Ibrahim, I.Z.; Mulder, J.; Hale, S.E. Biochar application in Malaysian sandy and acid sulfate soils: Soil amelioration effects and improved crop production over two cropping seasons. *Sustainability* **2015**, *7*, 16756–16770. [CrossRef]
83. Esmaeelnejad, L.; Shorafa, M.; Gorji, M.; Hosseini, S.M. Enhancement of physical and hydrological properties of a sandy loam soil via application of different biochar particle sizes during incubation period. *Span. J. Agric. Res.* **2016**, *14*, 1103. [CrossRef]
84. Zong, Y.; Xiao, Q.; Lu, S. Acidity, water retention, and mechanical physical quality of a strongly acidic Ultisol amended with biochars derived from different feedstocks. *J. Soils Sediments* **2016**, *16*, 177–190. [CrossRef]
85. 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. *GCB Bioenergy* **2015**, *7*, 1084–1091. [CrossRef]
86. 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]
87. Liu, C.; Tang, H.L.X.; Guan, Z.; Reid, B.J.; Upamali, A.; Yong, R.; Ok, S.; Sun, H. Biochar increased water holding capacity but accelerated organic carbon leaching from a sloping farmland soil in China. Environ. *Sci. Pollut. Res.* **2016**, *23*, 995–1006. [CrossRef] [PubMed]
88. De Melo Carvalho, M.T.; de Holanda Nunes Maia, A.; Madari, B.E.; Bastiaans, L.; van Oort, P.A.J.; Heinemann, A.B.; da Silva, M.A.S.; Petter, F.A.; Marimon, B.H., Jr.; Meinke, H. Biochar increases plant available water in a sandy soil under an aerobic rice cropping system. *Solid Earth* **2014**, *6*, 887–917. [CrossRef]
89. 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* **2016**, *142*, 160–167. [CrossRef]
90. Prober, S.M.; Stol, J.; Piper, M.; Gupta, V.; Cunningham, S.A. Enhancing soil biophysical condition for climate-resilient restoration in Mesic woodlands. *Ecol. Eng.* **2014**, *71*, 246–255. [CrossRef]
91. Githinji, L. Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. *Arch. Agron. Soil Sci.* **2014**, *60*, 457–470. [CrossRef]
92. Busscher, W.J.; Novak, J.M.; Evans, D.E.; Watts, D.W.; Niandou, M.A.S.; Ahmedna, M. Influence of pecan biochar on physical properties of a Norfolk loamy sand. *Soil Sci.* **2010**, *175*, 10–14. [CrossRef]
93. Aharoni, C. The solid–liquid interface in capillary condensation. Sorption of water by active carbons. *Langmuir* **1997**, *13*, 1270–1273. [CrossRef]
94. Verheijen, F.G.; Jeffery, S.; Bastos, A.C.; van der Velde, M.; Diafas, I. *Biochar Application to Soils. EUR 24099 EN.*; Office for the Official Publications of the European Communities: Luxembourg, 2010. [CrossRef]
95. Spokas, K.A.; Novak, J.M.; Masiello, C.A.; Johnson, M.G.; Colosky, E.C.; Ippolito, J.A.; Trigo, C. Physical disintegration of Biochar: An overlooked process. *Environ. Sci. Technol. Lett.* **2014**, *1*, 326–333. [CrossRef]
96. Joseph, S.; Graber, E.R.; Chia, C.; Munroe, P.; Donne, S.; Thomas, T.; Nielsen, S.; Marjo, C.; Rutlidge, H.; Pan, G.X.; et al. Shifting paradigms: Development of high-efficiency biochar-based fertilizers based on nano-structures and soluble components. *Carbon Manag.* **2013**, *4*, 323–343. [CrossRef]
97. Omondi, M.O.; Xia, X.; Nahayo, A.; Liu, X.; Korai, P.K.; Pan, G. Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma* **2016**, *274*, 28–34. [CrossRef]

98. Briggs, C.; Breiner, J.M.; Graham, R.C. Physical and chemical properties of Pinus ponderosa charcoal: Implications for soil modification. *Soil Sci.* **2012**, *177*, 263–268. [CrossRef]
99. DeBano, L. The role of fire and soil heating on water repellency in wildland environments: A review. *J. Hydrol.* **2000**, *231–232*, 195–206. [CrossRef]
100. Kinney, T.J.; Masiello, C.A.; Dugan, B.; Hockaday, W.C.; Dean, M.R.; Zygourakis, K.; Barnes, R.T. Hydrologic properties of biochars produced at different temperatures. *Biomass Bioenergy* **2012**, *41*, 34–43. [CrossRef]
101. Gray, M.; Johnson, M.G.; Dragila, M.I.; Kleber, M. Water uptake in biochars: The roles of porosity and hydrophobicity. *Biomass Bioenergy* **2014**, *61*, 196–205. [CrossRef]
102. Dekker, L.W.; Jungerius, P.D. Water repellency in the dunes with special reference to the Netherlands. *Catena* **1990**, *18*, 173–183.
103. Page-Dumroese, D.; Robichaud, P.R.; Brown, R.E.; Tirocke, J.M. Water repellency of two forest soils after biochar addition. *Trans. ASABE* **2015**, *58*, 335–342.
104. Hussain, R.; Ravi, K.; Garg, A. Influence of Biochar on the soil water retention characteristics (SWRC): Potential application in geotechnical engineering structures. *Soil Tillage Res.* **2020**, *204*, 104713. [CrossRef]
105. Baronti, S.; Vaccari, F.P.; Miglietta, F.; Calzolari, C.; Lugato, E.; Orlandini, S.; Pini, R.; Zulian, C.; Genesio, L. Impact of biochar application on plant water relations in *Vitis vinifera* (L.). *Eur. J. Agron.* **2014**, *53*, 38–44. [CrossRef]
106. Zhang, Q.; Wang, Y.; Wu, Y.; Wang, X.; Du, Z.; Liu, X.; Song, J. Effects of biochar amendment on soil thermal conductivity, reflectance, and temperature. *Soil Sci. Soc. Am. J.* **2013**, *77*, 1478–1487. [CrossRef]
107. Usowicz, B.; Lipiec, J.; Lukowski, M.; Marczewski, W.; Usowicz, J. The effect of biochar application on thermal properties and albedo of loess soil under grassland and fallow. *Soil Tillage Res.* **2016**, *164*, 45–51. [CrossRef]
108. Ventura, F.; Salvatorelli, F.; Piana, S.; Pieri, L.; Pisa, P.R. The effects of Biochar on the physical properties of bare soil. *Earth Environ. Sci. Trans. R. Soc. Edinb.* **2012**, *103*, 5–11. [CrossRef]
109. Verheijen, F.G.; 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]
110. Gopinath, A.; Divyapriya, G.; Srivastava, V.; Laiju, A.R.; Nidheesh, P.V.; Kumar, M.S. Conversion of sewage sludge into biochar: A potential resource in water and wastewater treatment. *Environ. Res.* **2021**, *194*, 110656. [CrossRef]
111. Alghamdi, A.G. Biochar as a potential soil additive for improving soil physical properties—A review. *Arab. J. Geosci.* **2018**, *11*, 1–16. [CrossRef]
112. Blanco-Canqui, H. Biochar and soil physical properties. *Soil Sci. Soc. Am. J.* **2017**, *81*, 687–711. [CrossRef]
113. Oguntunde, P.G.; Fosu, M.; Ajayi, A.E.; van de Giesen, N. Effects of charcoal production on yield, chemical properties and texture of soil. *Biol. Fertil. Soils* **2004**, *39*, 295–299. [CrossRef]