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Biochar and Soil Physical Health

Kayode S. Are

Abstract

The use of organic materials for reclamation of soil physical health indicators of degraded soil is germane for sustainable agriculture. Despite the soil conservation effectiveness of organic fertilizer, its adoption remains low among smallholder farmers in most parts of sub-Saharan Africa because of its offensive odor and bulkiness. Farmers desire materials that are not bulky, handled with ease, ensure maximum nutrient retention, improve soil structural quality, reduce soil compaction, and increase water retention, which will also increase soil productivity and crop yield. These are the greatest attractions for the introduction of biochar for improvement of soil physical health. The pyrolytic processes of various organic materials to biochar have suppressed the effects of distractive odor of fresh and composted organic materials while reducing the bulkiness experienced during application. The potentials of biochar in improving nutrient retention and release have been published by various authors, but little information is available for soil physical health indicators. Therefore, the potentials of biochar in restoring physical health indicators such as particle size distribution, bulk density, pore size distribution, soil water retention and distribution, compaction and aggregate size distribution and stability of degraded soil shall be discussed in this chapter.

Keywords: degraded soil, biochar, physical health indicator, soil productivity, sustainable agriculture

1. Introduction

Soil physical health is the ability of a given soil to meet plant and ecosystem requirements for water, aeration, and strength over time and to resist and recover from processes that might diminish that ability [1]. Application of organic materials for soil amendment, especially the composted manures, plays important roles in reclaiming and improving the physical health of degraded soils [2]. They have profound influence on almost all soil properties—such as structure (and hence on water infiltration and storage, susceptibility to surface runoff and erosion), cation exchange capacity, nutrient availability, buffering (pH, nutrient availability), color, and plant pest pressure. In spite of these potentials, their adoption as soil amendment remains low among smallholder farmers in most parts of sub-Saharan Africa because of their offensive odor and bulkiness. However, one of the greatest attractions for the use of biochar is the suppression of the effects of distractive odor of fresh and composted organic materials through pyrolytic processes, while the bulkiness experienced during application of composted manure is reduced.

Biochar is a carbon-rich organic matter, which is generally derived from the incomplete combustion of waste biomass, and it is produced by the slow thermochemical pyrolysis of biomass materials. Organic wastes, such as livestock manures,

sewage sludge, crop residues, and composts are converted to biochars and then applied to soils as an amendment. Biochar application as soil amendment improves crop productivity, enhances soil properties, and increases carbon storage in the soil due to its highly recalcitrant carbon content [3]. This practice has, however, received a growing interest as a sustainable process to improve the properties of highly degraded tropical soils [4, 5]. Biochars are characteristically very light materials with a high porosity and surface area, which alter some soil physical properties such as the bulk density (BD), water-holding capacity (WHC), surface area, and penetration resistance (PR) [6]. In Nigeria, when comparing the potential of poultry biochar with composted and noncomposted poultry litter, Are et al. [2] recorded an increase in soil water retention of between 3.3 and 31.3% following application of poultry litter biochar than uncharred poultry manures at lower water suction. Elsewhere, Major et al. [7] reported that the surface soils of oxisols amended with char at 20 Mg ha⁻¹ contained more water by volume, and the water was held more tightly than unamended soils. In China, Chen [8] reported a decrease in bulk density by 4.5 and 6% with addition of 2.25 and 4.50 Mg ha⁻¹, respectively, while an increase in water holding capacity from 25 to 36% was recorded by Kinney [9] with 7% biochar by weight addition.

In spite of the benefits of biochar on soil physical properties reported by different authors [2, 6–9], most positive effects of biochar are seen with coarse- or medium-textured soils, suggesting improvement of water holding capacity (WHC) by biochar addition [10] but not with fine-textured soils. Research has shown that unfavorable soil physical changes sometimes occur when biochar is added as soil amendment. Soil aggregation, for instance, may not be immediately enhanced by biochar addition [6]. The application of oak-650 biochar (0.5%, w/w) by Mukherjee and Lal [11] on a degraded silty clay loam soil reduced aggregation by 10% relative to the control. Mukherjee [11] suggested that (i) there may be a threshold application rate below which no aggregate stability is achieved, and/or (ii) a higher interaction time is required. On the other hand, Tryon [12] reported that application of pine (*Pinus* spp.) and oak (*Quercus* spp.) biochars increased available water content (AWC) in a sandy soil, while having no effect in a loamy soil, and it decreased moisture content in a clayey soil, indicating that the effect of biochar on AWC can be strongly influenced by the soil textural classes. Similarly, Masiello et al. [13] reported that a high rate (up to 11.3 Mg ha⁻¹) of maize stover biochar pyrolyzed at 350 and 550°C did not improve AWC in amended silt loam soils after incubation for 295 days, which was attributed to clogging of micropores by ash over time. The contrasting behaviors of biochars have been attributed by various researchers to biochar's particle size, shape, and internal structure, which alter pore characteristics and consequently influence soil water storage. With these contrasting trends (both positive and negative) of future biochar, future studies, especially at field scale with similar soil types with different biochar combinations over time, may shed light on this aspect. This chapter will discuss the practical use of biochar as it relates to the overall soil physical health.

2. Physical properties of biochar

Biochar is difficult to classify based on its properties, both chemical and physical, because of the variability imparted to it by the production conditions (time, temperature) and feedstock. Biochars (**Figure 1**) are of different particle sizes and do not have the same properties since their characteristics are controlled by many factors. Operating factors during the pyrolysis process that influence the resultant physical properties of biochar of any given biomass feedstock include heating rate, highest treatment temperature, pressure, reaction residence time, reaction vessel (orientation,



Figure 1.
 Biochars from feedstocks with different particle sizes.

dimensions, stirring regime, catalysts, etc.), pretreatment (drying, comminution, chemical activation, etc.), the flow rate of ancillary inputs (e.g., nitrogen, carbon dioxide, air, steam, etc.), and posttreatment (crushing, sieving, activation, etc.).

Although all of these parameters contribute to the final biochar structure, the pyrolysis highest treatment temperature has been identified by Downie et al. [14] as the most important of the factors since the fundamental physical changes (i.e., the release of volatiles, the formation of intermediate melts, and the volatilization of the intermediate melts) are all temperature dependent. The temperature ranges, however, under which these stages occur, vary with feedstock. Heating rates and pressures are expected to have the second greatest influence since they affect the physical mass transfer of volatiles evolving at the given temperature from the reacting particles [15, 16].

An additional mechanism producing the structural complexity of biochars is the occurrence of cracking. Biochar is typically laced with macrocracks, which can be related to both feedstock properties and the rate at which carbonization is carried out [17]. Wood biochar is generally broken and cracked due to shrinkage stresses developed because the surface of the material decomposes faster than its interior. Brown et al. [18] concluded that high-temperature (1000°C) surface area is controlled primarily by low-temperature (<450°C) cracking and high-temperature microstructural rearrangement.

The physical characteristics can be both directly and indirectly related to the way in which they affect soil systems. The physical characteristics of biochar depend not only upon the starting organic material (biomass), but also upon the carbonization

or pyrolysis system by which they are made (including the pre- and posthandling of the biomass and biochar) [14].

The fundamental molecular structure of biochar creates both its surface area and porosity. However, pyrolysis processing of biomass enlarges the crystallites and makes them more ordered. This effect increases with highest treatment temperature. Lua et al. [15] demonstrated that increasing the pyrolysis temperature from 250 to 500°C increases the Brunauer, Emmett, and Teller equation (BET) surface area due to the increasing evolution of volatiles from pistachio-nut shells, resulting in enhanced pore development in biochars. For turbostratic arrangements, the successive layer planes are disposed approximately parallel and equidistant, but rotated more or less randomly with respect to each other (**Figure 2**). The spacing between the planes of turbostratic regions of biochar is larger than that observed in graphite [19].

In relating biochars with soil physical properties, biochar's particle size, shape, and internal structure play important roles in controlling soil water storage because they alter pore characteristics. For instance, biochar has pores inside particles (intrapores), which may provide additional space for water storage beyond the pore space between particles (interpores) [20]. Particle size may influence both intrapores and interpores through different processes because the size and connectivity of these particles likely differ. In addition, when applied in the field, biochar particles may have different sizes and shapes compared to soil particles. This addition of biochar grains with different shapes and sizes will change interpore characteristics (size, shape, connectivity, and volume) of soil and thus will affect water storage and mobility. For instance, fine biochar particles can fill pores between coarse soil particles, decreasing pore size and changing interpore shape.

An important physical property of biochar is its stability in the environment. However, degradation of at least some components (such as volatile matter or labile OM) of biochar may occur [21, 22]. On the other hand, subsoils are characteristically different due to variations in microbial activity and oxygen content, which affect biochar oxidation and aging.

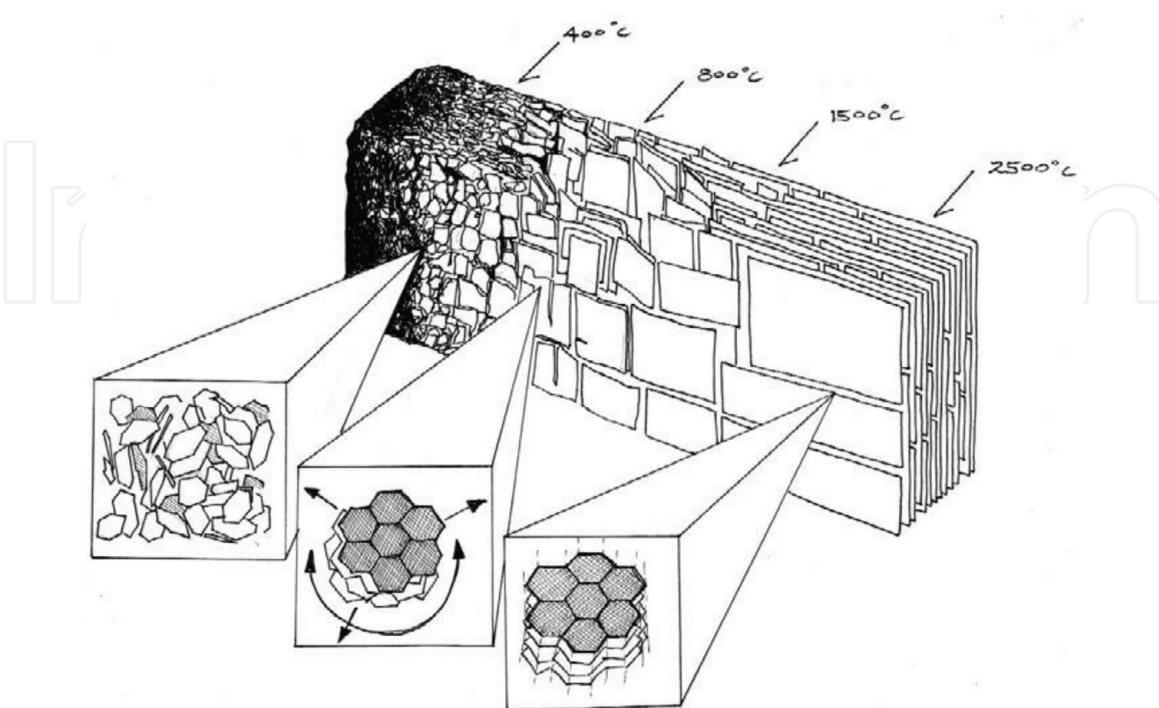


Figure 2.

Ideal biochar structure development with highest treatment temperature (HTT): (a) increased proportion of aromatic C, highly disordered in amorphous mass; (b) growing sheets of conjugated aromatic carbon, turbostratically arranged; and (c) structure becomes graphitic with order in the third dimension (source: [14]).

3. Soil physical health and biochars

3.1 What is soil physical health?

Soil health synonymous to soil quality is usually considered to have three main aspects: physical, chemical, and biological. It is considered to be important for the assessment of the extent of land degradation or amelioration, and for identifying management practices for sustainable land use. However, the knowledge of the physical properties of soil is essential for improving soil health to achieve optimal productivity for each soil type in a given climatic condition. According to Dexter [23], soil physical health manifested in various ways. For instance, soils poor physical health are those that exhibit one or more of the following symptoms: poor water infiltration, run-off of water from the surface, hard-setting, poor aeration, poor rootability, and poor workability. On the other hand, good soil physical health occurs when soils exhibit the opposite or the absence of the conditions listed above. However, there has been no single measure of soil physical health [24] but an integration of a range of some physical properties to obtain an overall assessment.

3.2 Soil physical health indicators as affected by biochar amendment

As mentioned earlier in this chapter, the effects of biochar on soil physical health indicators depend on several factors, such as biomass or feedstock type, pyrolytic condition, application rate, and environmental condition. The effects of biochar-amended soil in relation to some physical properties are discussed here.

3.2.1 Soil surface area

Surface area is an important soil physical health indicator that influences essential functions of soil fertility, including water, nutrient retention, aeration, and microbial activity [14]. For instance, the limited capacity of sandy soil to store water and plant nutrients is partly related to the relatively small surface area of its soil particles [25]. Coarse sands have a very low specific surface area of about $0.01 \text{ m}^2 \text{ g}^{-1}$, compared to fine sands of $0.1 \text{ m}^2 \text{ g}^{-1}$ and clays' large specific surface area ranging from $5 \text{ m}^2 \text{ g}^{-1}$ for kaolinite to about $750 \text{ m}^2 \text{ g}^{-1}$ for Na-exchanged montmorillonite [25]. Therefore, soils containing a large fraction of clay may have high total water-holding capacities but inadequate aeration. Meanwhile, Troeh and Thompson [25] reported that high organic matter contents have the potentials to overcome the problem of too much water held in a clay soil, while increasing the water contents in a sandy soil. However, studies have shown that biochar will similarly change the physical nature of soil, having much of the same benefit of other organic amendments in this regard [2, 26]. Biochar-specific surfaces, being generally higher than sand and comparable to or higher than clay, will therefore cause a net increase in the total soil-specific surface when added as an amendment [14]. The high surface area of biochar provides space for formation of bonds and complexes with cations and anions with metals and elements of soil on its surface, which may improve the water and nutrient retention capacity of soil. A long-term soil column incubation study by Laird et al. [27] indicated increases in specific surface area of an amended clayey soil from 130 to $153 \text{ m}^2 \text{ g}^{-1}$ as the biochar concentration increased from 0 to 20 g kg^{-1} .

3.2.2 Bulk density and pore-size distribution

Many studies have observed decreases in bulk density and increases in porosity as a result of biochar application [2, 6, 7, 26, 28]. Roughly, 2% (by weight) of biochar in

soil is an enough addition to show a significant decrease in bulk density in amended soils [6, 7]. The rate of biochar application as well as the density and porosity of the original soil are critical in predicting the effects of biochar addition to any soil. Using peanut hulls, Githinji [28] recorded reductions in bulk density with increased rate of biochar amendment, and he [28] recorded the highest bulk density of 1.33 g cm^{-3} for the soil without biochar amendment, decreasing to 1.09 g cm^{-3} for 25% rate, 0.89 g cm^{-3} for 50% rate, 0.61 g cm^{-3} for 75% rate, and 0.36 g cm^{-3} for 100% rate of biochar application. Since bulk density is a measure of the relative mass of a solid relative to the bulk volume the solid occupies, including the void spaces, it follows that the greater is the portion occupied by the pores, the lower is the bulk density of a solid. The upper limit of the bulk density would be a situation where there are no pores, and this limit will approach that of particle density of a solid.

The relationship between total surface area and pore-size distribution is logical. It is logical that this physical feature of biochars will also be of importance to their behavior in soil processes. As shown in **Figure 2**, the increase in HTT results in more structured regular spacing between the planes. Interplanar distances also decrease with the increased ordering and organization of molecules, all of which result in larger surface areas per volume. Githinji [28] reported that for the nonamended soil, porosity was $0.50 \text{ cm}^3 \text{ cm}^{-3}$, increasing to 0.55, 0.61, 0.69, and $0.78 \text{ cm}^3 \text{ cm}^{-3}$, respectively, for 25, 50, 75, and 100% rates of biochar application. In another trial comparing poultry litter biochar-amended soil and uncharred poultry manure, Are et al. [2] recorded a significance increase in storage pores ($0.5\text{--}50 \text{ }\mu\text{m}$ equivalent cylindrical radius) of a biochar-amended soil than uncharred poultry manure. However, this was not the case of transmission pores, where the soil amended with poultry biochar had lower transmission pores than uncharred poultry materials [2]. Mesoporosity may also increase significantly at the expense of macropores in waste-derived biochar-amended soil compared to control, with the higher rate of biochar application having a greater effect [29].

3.2.3 Soil water retention

The quantification of the amount of water held at field capacity (θ_{fc}) and at permanent wilting point (θ_{pwp}), and the amount of plant available water (θ_{paw}) of soil with biochar amendment is an efficient way to quantify how biochar affects soil water conditions and plant growth. Previous studies have shown that biochar increased water retention of soil [7, 30]. Gaskin et al. [31] reported a doubling in the mean volumetric water content of a loamy sandy soil at 2 kPa following the application of peanut hull biochar at a rate of 88 t/ha. Whereas Are et al. [2] also reported as high as 33% change in moisture content with application of poultry litter biochar to a sandy loam soil. However, the mechanisms controlling these observations should be understood. Sandy soils, which have larger pore space, are particularly appealing target for biochar amendment because studies on sand and sandy loam often show an increase in plant available water after biochar amendment [32, 33]. However, few studies focused on the mechanism of how biochar increase the available water. Without understanding the mechanisms that control biochar-driven changes of water retention of soil, it is difficult to predict when and by how much biochar will improve soil water retention.

Biochar's particle size, shape, and internal structure may play important roles in controlling soil water storage because they alter pore characteristics. For instance, biochar has pores inside particles (intrapores), which may provide additional space for water storage beyond the pore space between particles (interpores) [20]. Particle size may influence both intrapores and interpores through different processes because the size and connectivity of these particles likely differ. Intraporosity increases plant available water, suggesting that biochar with high intraporosity

will be most useful. Feedstock type, pyrolysis temperature, and charring residence time influence biochar's intraporosity [34]. Biochars with low intraporosity such as wastewater sludge biochar and poultry litter biochar are less favorable for soil water storage at low water potentials (< -16.5 kPa) because their internal porosity is very low [35]. In addition, the efficiency of biochar for improving soil water retention will be reduced if biochars are hydrophobic, but hydrophobicity can likely be managed by pretreatment [21]. Hydrophobic biochar has positive water entry pressure, meaning that an applied force is required for water to enter intrapores. Biochar hydrophobicity can prevent water from penetrating into biochar intrapores, prohibiting an improvement of soil water retention [10]. This indicates that biochars with low hydrophobicity will enhance soil water retention than those with high hydrophobic. Jeffery et al. [10] reported that grass species biochar did not improve soil water retention; this is probably due to its high hydrophobicity, although it is notable that grass biochar has lower hydrophobicity compared to leaf or wood biochars [9]. Biochar's hydrophobicity varies with production temperature and feedstock [36], but it is usually eliminated by brief environmental exposure. Pretreating biochar either by initially wetting it, or by composting is likely to significantly reduce problems associated with hydrophobicity [35].

3.2.4 Hydraulic conductivity

Hydraulic conductivity (K) measures the ease with which water can move through a soil, subject to a hydraulic gradient and is essential in infiltration-related applications such as irrigation and drainage management [37]. Saturated hydraulic conductivity (K_{sat}) is the conductivity measured, while the soil is saturated. In a trial in Ibadan, Nigeria, Are et al. [2] recorded a significant reduction in K_{sat} (9.2 mm h^{-1}) than other amendments ($16.5\text{--}18.2 \text{ mm h}^{-1}$) in their poultry biochar trial. The reduction in the k_{sat} of poultry's biochar treatment soils was linked to the ash deposited by the biochar, which perhaps reduced the larger soil pores and thus led to the reduction in pore space and volumes. Several studies [2, 28, 38–40] have linked the reduction in soil hydraulic conductivity, especially sandy soil, to a reduction in porosity imposed by the fine-grained particles of biochar. Devaraux et al. [38] was of the opinion that the decrease was due to biochar's large surface area and the high number of pores, which had to be filled up before water drained under the force of gravity, meaning that more biochar in the soil might lead to the retention of more water in the storage pores. Barnes et al. [39], on the other hand, related shifts in K_{sat} to the physical mechanisms of the biochar, such as swelling and grain segregation, leading to the clogging of pores, decrease in pore radii, and possibly a variation in the bulk density and sample heterogeneity in the course of their experiment.

Contrasting results have been reported on the K_{sat} of a clay loam soil in Laos, following the application of biochar [40]. Asai et al. [40] reported a significant increase in K_{sat} on a clay loam soil with biochar amendment, whereas Major et al. [41] reported no significant effect in a clay soil following the addition of 20 t ha^{-1} biochar produced from wood. In a study by Barnes et al. [39], K_{sat} significantly increased in clay soil, decreased in sandy soil, and had no significant effect for sandy loam rich in organic matter following incorporation of biochar. The mixed results demonstrate that the interactions between applied biochar and soil amended with biochar, and the resulting effects on hydraulic conductivity are dependent on soil texture.

3.2.5 Soil aggregate stability and penetration resistance

Few data are available on aggregate stability and penetration resistance (PR) of biochar-amended soil. However, available information that exists is conflicting.

Examples of the few studies, which investigated soil aggregation with biochar amendment, are shown in **Table 1**. In a study by George et al. [42], the low-temperature (220°C) hydrochar made from spent brewer's grains, a residue from beer brewing, responded positively on aggregation of Albic Luvisol when (i) incubated for 5 months at 20°C in dark and (ii) used in a pot study with same hydrochar/soil combination (**Table 1**). These incubation and greenhouse studies involving plant indicate that hydrochar significantly increased water stable aggregates (WSA) compared to control, but the extent of WSA differed because the greenhouse study had 2–5 times higher rate of WSA formation compared to laboratory incubation. These data suggest that plant roots and mycorrhizal fungi, which were absent in the incubation study, had an important role in soil aggregation. In a field experiment, Are et al. [2] found that the poultry biochar amendment increased the WSA of a sandy loam soil from 41.6 to 59.1% of a four-season trial. In contrast, with and without mixing Bt and E horizons with pecan shell (*Carya illinoensis*), biochar amendment decreased aggregation (**Table 1**) compared to control [43]. Mixing of biochar from pecan with switchgrass increased aggregation; however, the effect was significantly lower when soil was treated only with biochar and without mixing with switchgrass [44]. This trend indicates that a positive effect on soil aggregate stability requires presence of a substrate (i.e., switchgrass) along with biochar as an amendment. However, the application of biochar at the rate of 1% to an ultisol had no effect on aggregate stability [45]. Clearly, there exists limited information

Soil type	Biochar type	Study type (scale)	Rate of biochar application % (g g ⁻¹)	Aggregation (%)		Penetration resistance (MPa)		Source
Norfolk loamy sand: E	Pecan shells, 700°C	Laboratory	0	14.3		1.19 ^a	0.80 ^b	[43]
			2.1	12.9		1.27 ^a	0.88 ^b	
			0	27.3		0.71 ^a	0.76 ^b	
			2.1	20.9		0.88 ^a	0.94 ^b	
Norfolk loamy sand: E and Bt	Pecan shells, 700°C	Laboratory	0	9.95	13.0 [*]	1.04 ^a	1.10 ^b	[44]
			0.5	9.53	12.7 [*]	0.96 ^a	1.15 ^b	
			1.0	10.7	12.3 [*]	1.03 ^a	1.02 ^b	
			2.0	9.23	11.8 [*]	0.82 ^a	0.87 ^b	
Albic Luvisol	Hydrochar, 220°C	Laboratory	0	49.8	—	—	—	[42]
			5	69.0	—	—	—	
			10	65.1	—	—	—	
		Greenhouse	0	10.3	—	—	—	
			5	20.8	—	—	—	
			10	33.8	—	—	—	
Alfisol		Field	0	41.6	—	—	—	[2]
			0.25	59.1	—	—	—	

^aMeasured after 44 days.
^bMeasured after 96 days.
^{*}With switchgrass addition.

Table 1.
Impact of biochar on aggregation and penetration resistance.

about how biochar affects aggregation and whether another substrate, plant roots, mycorrhizal fungi, or active-C source might be needed to increase WSA in biochar-amended soils. Nevertheless, the highest concentration of black-C was observed in the finest size fraction ($<0.53\ \mu\text{m}$) of soil aggregates [46] suggesting preferential embedding of black-C particles compared to other organic compounds within aggregates. However, it was suggested by Jeffery et al. [10] that the hydrophobicity of biochar [10] may have increased the resistance of aggregates to slaking in water, which ultimately increased the aggregate stability.

The resistance of the soil to root penetration as determined by cone penetration resistance (PR) may not be alleviated by biochar addition over short time period but may be altered in the long run as aging of biochar changes its properties [47]. Along with time, soil type is also an important factor because another study reported reduction in PR with application of the same biochar on a different soil type (Norfolk loamy sand Ap) [44]. Nevertheless, the effect of biochar amendment on soil aggregation and PR requires additional research by including variations in biochar and soil type.

4. Conclusions

This review synthesizes available data on soil physical health indicators as influenced by application of biochars. The physical properties of biochar products affect many of the functional roles that they may play in improving soil physical health and environmental management. The large variation of physical characteristics observed in different biochar products means that some will be more effective than others in certain applications. It is important that the physical characterization of biochars is undertaken before they are experimentally applied to environmental systems, and variations in outcomes may be correlated with these features. The pyrolysis temperature, charring time of biochar and most importantly, the particle size of biochar play important factors in order to implement any biochar amendment project. The higher the biochar pyrolysis temperature, the finer the particle size, and the higher are the bulk density and water retention. The relationship may be inverse in relation to soil hydraulic conductivity and pore size distribution. This, however, depends on the soil type. Evidence has shown that biochar with finer particles when applied to sandy soil will reduce the macropores and hydraulic conductivity, whereas, in a clayey soil, biochar with finer particles will increase the interpores and soil hydraulic conductivity. Application rates of 0.25–2% (g g^{-1}) biochar can significantly improve soil physical health in terms of water-stable aggregates and water retention.

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Conflict of interest

The author declares that there is no conflict of interest.

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