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S. I. BIOCHAR

Biochar as a potential soil additive for improving soil physical properties—a review

Abdulaziz G. Alghamdi[1]

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Abstract

Biochar, a solid product produced from biomass pyrolysis under low oxygen conditions, has gained wide acknowledgment in its usage as a means for carbon sequestration as well as improving the soil chemical and physical properties of the soil. Although the effects of biochar application on chemical characteristics and fertility of soils have been intensively investigated, there is little information on its role in improving soil physical characteristics. Therefore, this review aimed to (i) summarize the impact of biochar application on soil physical properties, (ii) discuss the factors and mechanisms influencing biochar performance on soil physical properties, and (iii) identify future research priorities. This review concluded that the improved impact of biochar application on soil physical characteristics is dependent upon feedstock and pyrolyetic conditions of biochars, application rate of biochar, biochar particle size, and soil type and texture. Pyrolysis temperature is the main factor controlling biochar properties such as porosity and surface area, which reflect their effects on soil physical characteristics. For the same feedstock, the temperature will control the properties of resulting biochars. But, the biochar properties greatly depend on the properties of feedstock. For example, manure-derived biochars contain a large amount of ash, but biochars from cellulose-lignin biomass mainly consist of the carbon fraction. Despite the profound effect of biochar in improving the physical properties of soil, the economic impact of its implementation in large-scale farming has not been established. Therefore, there is need for its economic evaluation.

Keywords Carbonaceous recalcitrant product · Hydraulic properties · Particle size · Soil additives · Soil physical properties

Introduction

Biochar is produced from the pyrolysis of biomass under low oxygen conditions. Biochar is a carbonaceous, recalcitrant material and has been used for several thousand years. It is called charcoal, when the feedstock is woody biomass. It is heated under conditions of limited or no air (Lehmann and Joseph 2009).

Recently, biochar has been considered as an agricultural amendment (Biederman and Harpole 2013; Spokas et al. 2012) to enhance agricultural productivity and sustainability. Biochar is not only rich in carbon but also plant nutrients (Ippolito et al. 2012), which are used to supply nutrient-deficient plants and to reclaim degraded soil (Novak et al. 2009; Woolf et al. 2010). Biochar amendments have been reported to influence physical, chemical, and biological properties of soil (Mukherjee and Lal 2013; Herath et al. 2013; Lehmann et al. 2011). Biochar has an ability to alter the biological, chemical, and physical properties of soil due to its physicochemical properties such as surface area, porosity, nutrient retention ability, available nutrient contents, and aromaticity especially when used with sandy soil (Igalavithana et al. 2017; El-Naggar et al. 2018). The biochar also ameliorates the negative effects of drought and salt stress in arid environment while mitigating acidity in Ultisols (Ali et al. 2017; Malik et al. 2018). In addition, the biochar can be used for the remediation of both organic and inorganic contaminants in soil and water (Abbas et al. 2018). Furthermore, biochar amendments have the potential to sequester atmospheric carbon dioxide (CO_2) into more stable soil C pools (Lehmann et al. 2009; Liang et al. 2010; Zimmerman 2010), which, in turn, reduce greenhouse gas emissions from soil (Augustenborg et al. 2012). Biochar has also been utilized to remediate environmental pollutants,

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✉ Abdulaziz G. Alghamdi
agghamdi@ksu.edu.sa

[1] Soil Science Department, College of Food and Agricultural Sciences, King Saud University, P.O. Box 2460, Riyadh 11451, Saudi Arabia

in waste management, and for renewable energy generation (Barrow 2012).

The utilization of biochar for amelioration of soil physical properties, especially the capacity of soil to hold water, has been attributed to the characteristics of biochar in terms of its high porosity (Atkinson et al. 2010; Hina et al. 2010; Liang et al. 2006a, b) and large inner surface area (Kishimoto and Sugiura 1985; Van Zwieten et al. 2009). The porosity of biochar depends upon pyrolysis. Schimmelpfennig and Glaser (2011) reported that an increase in pyrolysis temperature (up to ~ 750 °C) increases biochar porosity. Also, the type of feedstock used for biochar production affects its porosity (Hina et al. 2010). Biochar pore sizes range from < 2 to > 50 nm, and small diameter pore fractions increase with an increasing pyrolysis temperature (Downie et al. 2009).

Biochar has effects on soil physical and hydrological properties, such as soil bulk density, porosity, structure, aggregate stability, hydraulic conductivity, available water, and infiltration. These effects, in turn, could affect the growth and development of crops through water uptake and root respiration processes. In order to achieve sustainable agriculture with the use of biochar as a soil amendment, there is need to understand fully its interaction with soil particles as it affects the soil physical properties. However, there are few review articles on this topic, and thus, it necessitates more review for a comprehensive understanding. This review (i) summarizes the impact of biochar on soil physical characteristics, (ii) discusses the factors and mechanisms influencing biochar performance on soil physical characteristics, and (iii) identifies future research priorities in this field.

Biochar characteristics in relation to feedstock and pyrolysis temperature

Surface area

The surface area of biochar is dependent upon the temperature at which the biochar was produced and the type of feedstock used for biochar production. Table 1 describes the surface area of biochars produced from different feedstocks under varying temperatures, as reported from different studies. The data reported were collected from 15 different authors from different parts of the world. Biochar surface area ranges from 1.4 to 500 $m^2\ g^{-1}$. The lower boundary of 1.4 $m^2\ g^{-1}$ was reported by Li et al. (2018), who subjected pine sawdust to a pyrolysis temperature of 300 °C. Park et al. (2013) also reported the same result for biochar produced from *Pinus taeda* under a pyrolysis temperature of 300 °C. The upper boundary of 500 $m^2\ g^{-1}$ was reported by Suliman et al. (2016) when Douglas fir wood biochar was produced under a pyrolysis temperature of 600 °C. From the table, it could be deduced that surface area largely depends on pyrolysis temperature and type of feedstock. From all the studies reported in this review, surface area increased with increasing pyrolysis temperature with the exception of the report from Yue et al. (2017) and Angın (2013), who reported that surface area increased at lower temperatures and declined as the temperature increased. In the study by Yue et al. (2017), surface area increased up to a pyrolysis temperature of 400 °C and decreased after this temperature. While in the study by Angın (2013), surface area increased up to 500 °C pyrolysis temperature and decreased above this temperature. The increase in surface area at low temperature and its decrease at high temperature are a result of volatile organic matter loss at low pyrolysis temperature, and, at high temperature, the porous structure of biochar is destroyed (Tsai et al. 2012). At high temperature, melting occurs which might block some of the pores, destroying the porous structure of biochar under production and, hence, could result in a low surface area (Liu et al. 2010).

Another factor affecting surface area of biochar is the feedstock used for its production. The dependence of surface area on the type of feedstock employed is also affirmed by Zhao et al. (2013) who studied 12 different feedstocks at the same pyrolysis temperature of 500 °C. The feedstocks, in decreasing order of the surface area of their respective biochar, were sawdust > waste paper > bone dregs > wastewater sludge > pig manure > peanut shell > wheat straw > ow manure > shrimp hull > waterweeds > grass > *Chlorella*. Sawdust had the highest surface area of 203 $m^2\ g^{-1}$, which could be the result of its high lignin content.

Pore characteristics

The porous nature of biochar contributes to its high value, when used in agriculture. Its micropores could enhance soil fertility by adsorbing plant nutrients (Liang et al. 2006a, b), which then could be released into the soil solution for plant uptake. Macropores could aid water infiltration and aeration of the soil (Lehmann et al. 2006) and create a favorable environment for the survival of microorganisms (Steinbeiss et al. 2009). The porous nature of biochar could also aid soil water retention (Liu et al. 2016) and provide shelter for fungi and bacteria preventing them from predation by microanthropods and protists (Dempster et al. 2012). Colonies of fungal hyphae and bacteria within biochar have been observed (Luo et al. 2013; Jaafar et al. 2014; Hammer et al. 2014). Pore characteristics of biochars produced from different feedstocks under varying temperatures are also described in Table 1. Porosity greatly depends on pyrolysis temperature and feedstock types. In this review, it was observed that pore size has a mixed result in relation to pyrolysis temperature. In some studies, it was observed to increase with increasing temperature (Li et al. 2018), and above a pyrolysis temperature of 500 °C, it decreased (Tsai et al. 2012; Meng et al. 2013). Also, the pore volume generally increases with increasing pyrolysis

Table 1 Surface area and pore characteristics of different biochars

Feed stock	Pyrolysis temperature (°C)	Surface area (m^2 g^{-1})	Pore size (nm)	Specific pore volume (cm^3 g^{-1})	References
Swine manure	400	5.7	11	0.015	Tsai et al. (2012)
	500	3.9	21	0.020	
	600	3.4	19	0.016	
	700	59	3.6	0.053	
	800	63	4.0	0.063	
Swine manure	400	3.68	9.3	0.00851	Meng et al. (2013)
	700	98.06	2.5	0.06054	
Cow manure	300	5.02	–	0.82	Yue et al. (2017)
	400	10.22	–	0.79	
	500	2.38	–	0.85	
	700	2.39	–	0.66	
Sewage sludge	500	7.1	20.0	0.061	Huang et al. (2017)
Sewage sludge + rice straw		6.6	17.8	0.054	
Sewage sludge + saw dust		3.9	14.1	0.032	
Douglas fir wood	350	145	–	0.06	Suliman et al. (2016)
	600	500	–	0.2	
Hybrid poplar wood	350	208	–	0.08	
	600	416	–	0.17	
Douglas fir bark	350	171	–	0.07	
	600	423	–	0.17	
Safflower seed cake	400	2.67	–	0.0050	Angın (2013)
	450	3.33	–	0.0063	
	500	4.23	–	0.0080	
	550	3.78	–	0.0071	
	600	3.41	–	0.0064	
Pig manure	300	2.17	–	0.00879	Ren et al. (2018)
	700	32.2	–	0.0383	
Tea waste	700	421.3	1.9	0.0576	Rajapaksha et al. (2014) and Vithanage et al. (2015).
Burcucumber[?] [check]	700	2.3	0.7	0.0084	
Oak wood	400	270.7	1.1	0.1200	
Bamboo	400	475.6	1.1	0.2090	
Pine sawdust	300	1.388	9.940	0.0034	Li et al. (2018)
	600	371.237	1.636	0.1518	
Maize straw	300	3.785	13.250	0.0125	
	600	353.552	1.876	0.1659	
Chicken manure	300	4.005	20.583	0.0206	
	600	86.670	4.346	0.0942	
Sewage sludge	400	33.44	9.46	0.783	Mendez et al. (2013)
	600	37.18	8.37	0.935	
Pinus taeda	300	1.41	–	0.009	Park et al. (2013)
	350	7.37	–	0.028	
	500	239	–	0.075	
	700	321	–	0.045	
Radix isatidis	300	4.45	36.70	0.0075	Yuan et al. (2014)
	500	8.50	36.21	0.0125	
	700	11.80	37.23	0.0178	
Sewage sludge	300	14.37	–	0.108	Yuan et al. (2015)
	400	22.68	–	0.132	
	500	24.53	–	0.139	
	600	26.66	–	0.144	
	700	26.70	–	0.159	

Table 1 (continued)

Feed stock	Pyrolysis temperature (°C)	Surface area (m^2 g^{-1})	Pore size (nm)	Specific pore volume (cm^3 g^{-1})	References
Cow manure	500	21.9	5.04	0.028	Zhao et al. (2016)
Pig manure		47.4	6.35	0.075	
Shrimp hull		13.3	11.6	0.039	
Bone dregs		113	9.86	0.278	
Wastewater sludge		71.6	3.37	0.060	
Waste paper		133	2.51	0.084	
Sawdust		203	2.23	0.125	
Grass		3.33	11.9	0.010	
Wheat straw		33.3	6.10	0.051	
Peanut shell		43.5	3.72	0.040	
Chlorella		2.78	15.0	0.010	
Waterweeds		3.78	9.52	0.009	

temperature, although, in a few studies, the opposite is found. These results are similar to those of surface area. Partial carbonization occurs at low temperature and this could permit most of the amorphous carbon to remain, and, thus, an open structure might be blocked by the aliphatic and volatile constitutes (Keiluweit et al. 2010; Zhang et al. 2013). At high temperature, there is high carbonization whereby amorphous carbons are transformed into more dense aromatic carbons, and aliphatic volatile constitutes are removed leading to the formation of more pores (Keiluweit et al. 2010; Zhang et al. 2013). Similar to the surface area of biochar (see above section), pore characteristics of biochar are affected by the type of feedstock used in its production.

Effects of biochar on soil physical and hydrological properties

Soil bulk density

Bulk density is an indicator of soil compaction and soil health. It affects rooting depth and its restriction, soil aeration, infiltration, available water, plant nutrient availability, and activity of soil microorganism, which influence key soil processes and productivity. Many studies have revealed that biochar application has a significant effect ($P < 0.05$) on soil bulk density. Table 2 shows the effect of biochar on soil bulk density of different kinds of soil in terms of soil textural classes (ranging from sand to clay) and soil order (seven different soil orders), as reported in past studies. The highest effect of biochar on soil bulk density was reported by Głąb et al. (2016), who found that it decreased 35% after the addition of 4% biochar. From a total of 25 treatments with biochar, previous studies have shown that the percentage decrease in soil bulk density ranges from 2 to 35% with a mean value of 13%. All treatments differed significantly from a control. A few treatments showed no significant difference from their respective controls.

The variation in changes in bulk density following the same biochar application rate could be attributed to different kinds of soil (Herath et al. 2013). Herath et al. (2013) studied two contrasting soils, an Alfisol and an Andisol with the same soil textural class (silt loam). Following the same biochar application rate of 7.18 t C ha^{-1}, bulk density of the Alfisol decreased significantly by 7 and 11%, when using 350 °C and 550 °C pyrolysis temperatures, respectively, while there was no significant difference in the Andisol. This could be due to the lower bulk density of the Andisol (0.75 g cm^{-3}), which was not much different from the mean bulk density of the biochar (~ 0.6 g cm^{-3}). The Alfisol had a higher bulk density of 1.13 g cm^{-3}. This could be due to the type of clay, and the Andisol was characterized as having a shrinking and swelling clay.

Studies also have indicated that soil textural classes play a role in the changes in soil bulk density after the addition of biochar as an amendment. Coarse-textured soils have exhibited a higher decrease in bulk density compared to fine-textured soils. The highest change (decrease) in bulk density was found in a coarse-textured soil (loamy sand) with a decrease of 35% (Głąb et al. 2016). A few treatments that have been non-significant were found in medium- to fine-textured soils (Castellinia et al. 2015). This could be due to the fact that a coarse-textured soil (sand) has a higher bulk density of ~ 1.6 g cm^{-3} with a big difference from the bulk density of biochar, ~ 0.6 g cm^{-3}; a fine-textured soil (clay) with a bulk density of ~ 1.1 g cm^{-3} has a bulk density closer to that of biochar. The big difference between the bulk density of sand and biochar could allow interaction between the biochar particles and soil particles resulting in a decrease in the final soil bulk density. Also, biochar is highly porous (Hina et al. 2010;

Table 2 Effects of biochar on soil bulk density and porosity

Soil textural class	Soil order	Study type	Study duration	Biochar feedstock	Biochar pyrolysis temperature (°C)	Biochar rate	Bulk density (g cm^{-3})	Rate of changes in bulk density (%)	Rate of change in porosity (%)	References
Silt loam	Alfisol	Incubator	295 days	Corn stover	control	7.18 t C ha^{-1}	1.01			Herath et al. (2013)
					350		0.94	−7	10	
					550		0.91	−11	19	
	Andisol				control		< 0.8			
					350		< 0.8	Ns	Ns	
					550		< 0.8	Ns	ns	
Loamy sand		Pots	3 months	*Miscanthus* × *giganteus* and winter wheat straw	300	0	1.800a			Głąb et al. (2016)
						0.5%	1.599b	−13	23	
						1%	1.547c	−16	29	
						2%	1.466d	−23	37	
						4%	1.330e	−35	52	
Fine loamy	Ultisol	Incubator	128 days	Pine chips and poultry litter (50:50)	500	0	1.565a			Novak et al. (2016)
						2%	1.472bc	−6		
				Pine chips and poultry litter (80:20)		2%	1.438bc	−8		
				100% poultry litter		2%	1.508bd	−4		
				100% pine chips		2%	1.515bd	−3		
Sandy loam		Greenhouse	Not available	Using corn stover, switchgrass, soybean, and hardwood	550–650	0	1.56a			Aller et al. (2017)
						1% Fresh Biochar	1.53b	−2		
						1% Aged Biochar	1.56a	Ns		
Silt loam						0	1.53a			
						1% Fresh Biochar	1.48b	−3		
						1% Aged Biochar	1.47b	−4		
Clay loam						0	1.66a			
						1% Fresh Biochar	1.63b	−2		
						1% Aged Biochar	1.61b	−3		
Clay loam	Mollisol	Field	1 year	Wood residue	850	10 Mg ha^{-1}		11% reduced		Sandhu et al. (2017)
Silt loam soil	Alfisol	Field	4 months	Oak wood	650	Control	1.7a			Mukherjee et al. (2014)
						0.5%	1.3b	31		
Sandy soil	Entisol	Laboratory				Control	1.49			Suliman et al. (2017)
				Pine wood	350	2%	1.27	−17		
					600		1.26	−18		
				Pine bark	350		1.28	−16		
					600		1.29	−16		
				Hybrid poplar wood	350		1.28	−16		
					600		1.27	−17		
Clay soil	Vertisol	column		Fruit trees	500	0%				Castellinia et al. (2015)
						1%		Ns	13	
						3%		Ns	37	
Silty clay	Ultisol	Incubation	105 days	*Leucaena Leucocephala*	700	0%	1.42a			Jien and Wang (2013)
						2.5%	1.15b	−23	24	
						5%	1.08b	−31	27	
Sandy loam	Kurosol	Field	30 months	Acacia green waste	550	47 Mg ha^{-1}	reduced		ns	Hardie et al. (2014)
Loamy	Entisol	Field	30 months	*Miscanthus sp.*	450 °C	0, 3.5 and 10 Mg ha^{-1}	Ns		Ns	Moragues-Saitua et al. (2017)
Sandy loam soil	Inceptisol		15 months			0, 10 and 20 Mg ha^{-1}	Ns		Ns	

Ns not significant

Means with different letters were significantly different while means with the same letters are not

Liang et al. 2006a, b), while sand has a low porosity; their interaction could lead to an increase in porosity of a sandy soil as well as a decrease in bulk density. Also, the feedstock used for the production of biochar and the pyrolysis temperature plays a role in the variation in changes in bulk density, as reported by Suliman et al. (2017), who found that bulk density decreased with increasing pyrolysis temperature. Biochar application rate is another factor that contributes to the variation in the changes in soil bulk density. In general, an increase in biochar application rate leads to a decrease in soil bulk density (Table 1).

Soil porosity

Similar to the impact of biochar on soil bulk density, although in a reverse manner, biochar has a profound effect on soil porosity as illustrated in Table 2. According to the studies reported in Table 1, soil porosity was found to increase following the application of biochar as a soil amendment. A few treatments were found not to be significantly different from the control, but most treatments had significantly increased soil porosity. The percentage increment in soil porosity ranged from 13 to 52%. The highest increment (35%) was reported by Głąb et al. (2016) following application of 4% biochar to a loamy sand soil. This same treatment had the highest percentage decrease in soil bulk density, as mentioned in the previous section (2.1).

There is wide variation on the effect of biochar on soil porosity even when the same rate is applied. This variation could be related to soil textural class and soil type in terms of soil order. Generally, it has been noted that coarse-textured soils exhibit a great increase in soil porosity compared to fine-textured soil. This could be due to the fact that coarse-textured soil has low porosity compared to fine soil with higher porosity. Biochar is characterized with a high porosity of 70 to 90%. The profound effect of biochar in sandy soil suggests that the mechanical interaction of soil particles and biochar adds to the pores of the sandy soil. The biochar particles can settle between the soil particle matrix without blocking the existing pores, thereby creating new pores to increase the macroporosity (Steiner et al. 2011). Also, the dilution effect of the amendment with low bulk density can contribute to the overall increase in porosity (Bhogal et al. 2009; Hati et al. 2007; Soane 1990). Hardie et al. (2014) proposed the following three mechanisms that could lead to an increase in soil porosity by the addition of biochar: (i) pore contribution from the high-porosity biochar material, (ii) modification of the pore system by creating packing or pores, and (iii) aggregate stability improvement. However, differences in soil–climate–management combinations might result in different outcomes through these mechanisms (Verheijen et al. 2010).

Soil order is a factor related to changes in soil porosity following biochar application, as reported by Herath et al. (2013), who found that an Alfisol had a significant effect on porosity while an Andisol exhibited no significant effect, even though each soil was treated with the same amount of biochar. This could be the result of different soil minerals in these two contrasting soils.

An increase in biochar application rate has led to a corresponding increase in soil porosity. The increase in soil porosity is of high benefit to the productivity of the soil, because it affects the hydraulic properties of soil. Saturated hydraulic conductivity is sensitive to a change in soil porosity (Ball and Smith 1991; Schjønning et al. 2013). A good porous soil creates a suitable environment for root growth and microbial activities, which, in turn, result in high productivity of the soil.

Soil aggregate stability

Soil aggregate stability is a key factor enabling a soil to resist mechanical stresses such as the effects of rainfall, surface runoff, and water erosion (Canasveras et al. 2010). The breakdown of soil aggregates results in fine particles, which are prone to wind and water erosion, and which, upon resedimentation, are capable of forming a soil crust by clogging the soil pores (Yan et al., 2008). Aggregate stability is one of the soil physical properties that can serve as an indicator of soil quality (Arshad and Coen 1992); it is included in the international standardization of soil quality measurements by Hortensius and Welling (1996). Aggregates house and protect organic matter, and they improve soil structure, soil aeration, root growth and penetration, biota movement within soil, available water, and drought resistance. The effect of soil aggregate stability is shown in Table 3. From the data collected in past experiments as shown in the table, biochar has increased significantly soil aggregate stability while some studies show no significant effect. The increase in soil aggregate stability ranges from 6 to 217%. Biochar application rate does not determine the extent of increase in soil aggregate stability. From the studies reported in this review, a biochar application rate of 1% had the highest percentage increase (217%) in soil aggregate stability (Wang et al. 2017), while a higher biochar application rate of 5% was able to increase the aggregate stability by just 10% (Jien and Wang 2013). The increase in soil aggregate stability following biochar application could be due to the high carbon associated with biochar. The carbon molecules form bonds with the oxides, and the organic matter serves as food for soil microorganism making the environment favorable for them. The substrates supplied to the microorganisms by the labile organic matter on the surfaces of biochar enhance the excretion of mucilage by microorganism, which, in turn, builds stable soil aggregates (Liang et al. 2010).

Table 3 Impacts of biochar on soil aggregate stability from the reports of different studies

Soil textural class	Soil order	Study type	Study duration	Biochar feedstock	Biochar pyrolysis temperature (°C)	Biochar rate	% Improvement in aggregate stability	References
Silt loam	Alfisol	Incubator	295 days	Corn stover	control	Control		Herath et al. (2013)
					350	7.18 t C ha^{-1}	> 17	
					550			
	Andisol				Control	Control		
					350	7.18 t C ha^{-1}	7–15	
					550			
Silt loam	Entisol	Incubator	60 weeks	Walnut shell	900	0, 0.5, 1%	217	Wang et al. 2017
				Softwood	600–700	0, 0.5, 1%	126	
Fine sandy loam	Mollisol			Walnut shell	900	0, 0.5, 1%	Ns	
				Softwood	600–700	0, 0.5, 1%	Ns	
Sandy loam	Mollisol	Field	1 year	Corn stover	850	10 Mg ha^{-1}	reduced	Sandhu et al. (2017)
Silt loam soil	Alfisol	field	4 months	Oak wood	650	0, 0.5%	Ns	Mukherjee et al. (2014)
Clay loam	Ultisol	Pot	11 days	Rice straw	250–450	0 and 1%	Ns	Peng et al. (2011)
Silty clay	Ultisol	Incubation	105 days	*Leucaena leucocephala*	700	0%		Jien and Wang (2013)
						2.5%	6	
						5%	10	
Sandy loam	Kurosol	Field	30 months	Acacia green waste	550	47 Mg ha^{-1}	Ns	Hardie et al. (2014)
Sandy Loam	Entisol	Column	5 weeks	Conocarpus wastes	400	0, 0.5, 1, 1.5, and 2.0%	Increased	Al-Wabel et al. (2013)

Ns not significant

The mixed effects of biochar on soil aggregate stability (significant and not significant), irrespective of the rate of biochar application rate, indicate that there are some other factors playing a role in these changes. For example, salt content in a soil affects soil aggregate stability (Bearden and Petersen 2000). Also, the process of aggregation may increase over time, with time soil-biochar interactions creating a stable soil aggregate through the complexation of soil and biochar mineral phases. Labile (aliphatic-C) and refractory (aromatic-C) parts of biochar may go through two phases of aggregate formation (fast and slow) following biochar application (Mukherjee and Lal 2014). The second phase involves the formation of specific chemical bonding resulting in soil stable aggregates, and it is proposed to be slow (Mukherjee and Lal 2014). Other factors affecting aggregate stability could include the climatic conditions, the type and amount of clay, and the soil texture.

Water repellency

Soil water repellency (also known as "hydrophobicity" or "soil non-wetting") has been a subject of discussion due to its effect on soil physical properties. It reduces the affinity of soils to take up water, such that wetting is resisted for periods ranging from a few seconds to days or even weeks (King 1981; Doerr and Thomas 2000). It incurs a high cost in terms of plant growth (House 1991; York 1993) and negatively affects the hydrological and geomorphological functions of the soil. These include a reduction in soil infiltration and an enhancement of surface runoff, thus accelerating soil erosion, uneven wetting patterns, development of preferential flow, and leaching of agrichemicals (Imeson et al. 1992; Shakesby et al. 1993; Ritsema et al. 1993, 1997; Briggs et al. 2012). As a result of a higher volume of entrapped air, which leads to decrease in the fraction of saturated soil pores, soil available water content and hydraulic conductivity are reduced. Water repellency and delayed wetting commonly contribute to these phenomena (Kinney et al. 2012; Eibisch et al. 2015). Nonetheless, soil aggregation could be improved with a moderate hydrophobicity. Application of biochar to soil has been shown to either increase water repellency or to have no effect (Table 4). A slight increase in water repellency (ranging from 1.02 to 1.79 s) has been noted following biochar application. According to the degree of classification of water repellency, this range can be classified as wettable because it is less than 5 s. The following classification has been used to characterize repellency: wettable, water drop penetration test (WDPT) < 5 s; slightly repellent, WDPT = 5–60 s; strongly repellent, WDPT = 60–600 s; severely repellent, WDPT = 600–3600 s; and extremely repellent, WDPT > 3600 s (Dekker and Jungerius 1990). Hence, these soils with biochar are more or less free from the

Table 4 Changes in soil water repellency as affected by biochar application from different studies

Soil textural class	Soil order	Study type	Study duration	Biochar feedstock	Biochar pyrolysis temperature (°C)	Biochar rate	water repellency	References
Silt loam	Alfisol	Incubator	295 days	Corn stover	350	7.18 t C ha^{-1}	Ns	Herath et al. (2013)
					550		Ns	
	Andisol				350		Slightly increased	
					550		Ns	
Fine sand		Laboratory	300 days	Hardwood	500–600	0%	1.05	Ajayi and Horn (2016)
						2%	1.41 ns	
						5%	1.79**	
						10%	1.70**	
Sandy loamy Silt	Gleysol					0, 2, 5 and 10%	No effect	
Sandy clay loam		Plots	2 years	Orchard pruning	500	22 and 44 Mg ha^{-1}	No effect	Baronti et al. (2014)
Loam sand		Green house	3 months	*Miscanthus* × *giganteus* and winter wheat straw	300	0.5%	1.02 s	Głąb et al. (2016)
						1%	1.03 s	
						2%	1.15 s	
						4%	1.62 s	

Ns not significant

detriments caused by water repellency and thus could aid soil aggregation.

Biochar pyrolysis temperature has been found to affect the soil repellency when biochar is added, as reported by Herath et al. (2013). They found that pyrolysis of corn stover (feedstock) at a temperature of 350 °C significantly increased water repellency and a temperature of 550 °C had no effect. Kinney et al. (2012) reported similar trends from biochars produced from three different feedstocks: pyrolysis at 300 °C resulted in a very hydrophobic biochar, while increased temperature decreased hydrophobicity. Hallin et al. (2015) gave an explanation for this phenomenon. They said that, on one hand, the organic functional groups of the feedstock are retained when the pyrolysis temperature is lower, less than 500 °C, making the biochar produced water repellent. On the other hand, the organic group is volatilized at higher temperatures, above 500 °C, making the biochar water loving. Novak et al. (2012) also suggested that changes in the proportions of hydrophobic and hydrophilic functional groups result in the reduction of biochar repellency when subjected to higher temperature. It is thought that the biomass feedstock used and pyrolysis conditions largely determine the hydraulic properties of biochar. Moreover, it is also stated that biochar hydrophobicity changes over time. A wooden biochar that is freshly produced has higher repellency compared to an older carbon with a lower repellency (Briggs et al. 2012).

Soil hydraulic conductivity

Biochar application to soils can increase, decrease, or have no effect on soil hydraulic conductivity, as indicated in Table 5. From reported findings, applying biochar has enhanced soil hydraulic conductivity 28–176% compared to non-treated soil. The highest increase of 176% was found in a clay soil treated with biochar at application rate of 16 Mg ha^{-1} (Asai et al. 2009), with a mean increase of 73%. A decrease in soil hydraulic conductivity in the range of 1–270% was also reported by Lim et al. (2016). The highest decrease (− 270%) was found in coarse sand soil treated with 5% biochar. In a study conducted by Al-Wabel et al. (2013), to investigate the impact of conocarpus biochar application on hydraulic properties of sandy loam soil, biochar application reduced the soil saturated hydraulic conductivity. Similarly, Igalavithana et al. (2017) found that applying biochar produced from corn residue at 500 °C resulted in a highly significant decrease in saturated hydraulic conductivity, especially with increasing application rates of biochar. Their result indicated that saturated hydraulic conductivity decreased by 46.6%, 63.4%, 76.7%, and 83.5% following application of corn residue biochar at 2.5%, 5%, 7.5%, and 10%, respectively. However, some biochars had no significant effect on soil hydraulic conductivity, even if they were applied at a high rate of 4% (Głąb et al. 2016). The effect of biochar on hydraulic conductivity can be summarized as follows, based on the above studies: (i) increase in soil hydraulic conductivity was more profound in fine-textured soil (clay), (ii) decrease in soil hydraulic conductivity was pronounced for coarse-textured soil (sand), and (iii) little or no effect in medium-textured soil.

The first trend could be due to the rearrangement of soil particles and the formation of macroporosity (Abel et al. 2013; Liu et al. 2012) and improving soil aggregation that aids soil drainage. Biochar application to a fine texture soil improves soil hydraulic conductivity due to the level of pore organization and the rearrangement of particles (Sun and Lu 2013), and these effects do not exclude those due to expansive clay (Lu et al. 2014). Mubarak et al. (2009) also mentioned that there could be a slight increase in the flow of water following the addition of high application rates of biochar due to restructuring of the fragile structural porosity created by preparation of the sample.

The second trend of decreasing soil hydraulic conductivity in a coarse texture soil following biochar application as a soil amendment could be due to clogging or filling of the macropores by biochar particles. Most of the biochars used have a very small particle size of < 2 mm in diameter. Because coarse-textured soil is associated with macropores, this makes it possible for the biochar to fill some of the soil pores, reducing the porosity, and this decrease in porosity results in a decrease in water flow. Increasing the rate of biochar application to soil increases the proportion of small and medium pores (micro- and mesopores, respectively) due to the filling of pores by biochar particles (Hartge and Horn 2014); thus, the saturated hydraulic conductivity decreases.

The third trend, that of biochar having little or no effect on medium-textured soil, could be the result of a balance in the proportion of micro- and macropores of this soil class. As biochar particles fill the large pores, reducing the macroporosity; simultaneously, there is rearrangement of particles leading to formation of new macropores and, thereby, a stable water flow results.

Generally, as biochar application rate increases, there is an increase in soil hydraulic conductivity of a fine-textured soil and a corresponding decrease in a coarse-textured soil. However, there is still need for more studies in this area of research to have a solid explanation behind the impact of biochar on soil hydraulic conductivity.

Water infiltration

The downward flow of water into the soil is known as infiltration. Water infiltration is an important hydrological process that affects runoff and soil loss. The water in soil is replenished by infiltration. Poor management can restrict infiltration rate leading to runoff or ponding on the surface of the soil, where it evaporates. Thus, water stored in the soil for plant growth is depleted causing a decrease in plant

Table 5 Effects of biochar on soil hydraulic conductivity of different soils

Soil textural class	Soil order	Study type	Study duration	Biochar feedstock	Biochar pyrolysis temperature (°C)	Biochar rate	Soil hydraulic conductivity (cm h^{-1})	Change %	References
Silty clay	Ultisol	Incubation	105 days	*Leucaena leucocephala*	700	0%	16.7a		Jien and Wang (2013)
						2.5%	30.0b	80	
						5%	33.1c	98	
Clay loam		Field	1 year	Wood	Not stated	0	0.59b		Asai et al. (2009)
						4 Mg ha^{-1}	0.89b	51	
						8 Mg ha^{-1}	0.77b	31	
						16 Mg ha^{-1}	1.63a	176	
Sandy loam	Kurosol	Field	30 months	Acacia green waste	550	47 Mg ha^{-1}	Increased		Hardie et al. (2014)
Sandy Loam	Entisol	Column	5 weeks	Conocarpus wastes	400 °C	0%	4.85a		Al-Wabel et al. (2013)
						0.50%	4.80a	Ns	
						1.0%	4.47b	− 9	
						1.5%	4.31c	− 13	
						2.0%	4.12d	− 18	
Loamy	Entisol	Field	30 months	*Miscanthus sp.*	450 °C	0, 3.5 and 10 Mg ha^{-1}	Ns		Moragues-Saitua et al. (2017)
Sandy loam soil	Inceptisol		15 months			0, 10 and 20 Mg ha^{-1}	Ns		

Ns not significant

Means with different letters were significantly different while means with the same letters were not production, thereby resulting in less biomass that contributes to soil organic matter. In addition, soil structure is negatively affected. Table 6 shows the effect of biochar on water infiltration rate into the soil. There are few data on this aspect of the impact of biochar on soil physical properties. Biochar had mixed effects on water infiltration. Studies show that infiltration rate has increased following application of biochar (Novak et al. 2016; Prober et al. 2014), decreased (Al-Wabel et al. 2013; Githinji 2014), or had no significant effect (Busscher et al. 2010). These effects are similar to those of soil hydraulic conductivity.

The decrease in water infiltration rate following biochar application could be the result of biochar's pores essentially filling with water (Aharoni 1997) or their physical disintegration (Verheijen et al. 2010). In addition, Verheijen et al. (2010) suggested that soil compaction is possibly aided by the structural degradation of biochar resulting from water flushing, heavy traffic during application, and the effect of soil tillage after application. Dislodged fragments are presumed to clog soil pores. As reported by Spokas et al. (2014), biochars produced from pelletized lignocellulosic and manure broke down physically into flake-like fragments when shaken in water. The size of the fragments ranged from micrometer to nanometer, with some having jagged edges (see SEM images presented in Spokas et al. 2014). This leads to the hypothesis that biochars are possibly suspended in percolating water and, thus, they move down the soil profile. The jagged-edge morphology of these biochar particles and the size of the primary biochar particles could make it possible for clogging of soil micropores, thereby causing a reduction in water infiltration. This hypothesis has merit, considering that Joseph et al. (2013) reported formation of nano-scale fragments from pyrolyzed black carbon material.

Prober et al. (2014) reported an increase in water infiltration after a 2-year experiment in which biochar was applied at a rate of 20 Mg ha^{-1} to a clay loam soil, and this result could be due to the creation of more pores in the soil matrix. The interaction of clay soil and biochar could result in the creation of more pores, because biochar is highly porous (Hina et al. 2010; Liang et al. 2006a, b), and clay soil has an abundance of micropores and not macropores that allow settling in of biochar particles. However, there is need for more studies to understand fully the interaction between biochar and soil as it affects water infiltration.

Plant-available water

In a climate where rainfall is not stable, as in arid regions, plant growth and development are favored by an increase in plant available water (Uzoma et al. 2011; Van Zwieten et al. 2010; Yamato et al. 2006). In this review, biochar

Table 6 Impacts of biochar on water infiltration from the reports of different studies

Soil textural class	Soil order	Study type	Study duration	Biochar feedstock	Biochar pyrolysis temperature (°C)	Biochar rate	Water infiltration (mL min^{-1})	Rate of change (%)	References
Sandy loamy	Ultisol	Incubator	128 days	Pine chips and poultry litter (50:50)	500	0	0.086b		Novak et al. (2016)
						2%	0.168a	95.3	
				Pine chips and poultry litter (80:20)		2%	0.110b	ns	
				100% poultry litter		2%	0.047b	ns	
				100% pine chips		2%	0.119b	ns	
Sandy loam	Entisol	Pots	5 weeks	Wood	400	0%	0.763a		Al-Wabel et al. (2013)
						0.5%	0.761a	ns	
						1.0%	0.548c	−28	
						1.5%	0.564b	−26	
						2.0%	0.534d	−30	
Clay loam		Pots	2 years	Tree residues	600	0 and 20 Mg ha^{-1}	Increased		Prober et al. (2014)
Loamy sand		Incubation	96 days	Pecan	700	0, 11, 22, and 44 Mg ha^{-1}	ns		Busscher et al. (2010)
Sandy loam		Greenhouse	<2 months	Peanut hulls	500	0, 25, 50, 75, and 100% by volume	decreased		Githinji (2014)

application as a soil amendment has been found to increase plant-available water, although in some cases, it had no significant effect (Table 7). From the 13 different experiments reported in this review regarding the effect of biochar on plant-available water, eight of the studies had a significant increase while the other five had no significant effect. The percentage increase in plant-available water was up to 130% (Esmaeelnejad et al. 2016), which was recorded following a biochar application rate of 2% to a sandy loam soil.

By incorporating biochar into the soil, especially on light soils, the chemical and physical properties of biochar are expected to increase the storage capacity of water, thereby achieving a long-term improvement in soil productivity. The positive effect of biochar is more profound in a coarse-textured soil than in a fine-textured soil. Seventy percent of the coarse-textured soils had a significant increase in plant-available water. Some factors, such as soil texture, aggregation, and soil organic matter, have been linked to the changes in soil water content (Verheijen et al. 2010). Mukherjee and Lal (2013) considered soil texture to be the most important factor. In another report, the specific surface area and intra-particle porosity were the most essential factors that caused a rise in the soil available water content (Crabbe 2009; Uzoma et al. 2011). The high porosity of biochar could have a positive impact in soil water retention (Ogawa et al. 2006) and, thus, increase the plant-available water. A sandy soil has a specific surface area less than 10 $m^2 g^{-1}$ (Herbrich et al. 2015) while that of biochar can be as high as 500 $m^2 g^{-1}$ (Graber et al. 2012). This property of biochar makes it an important factor that increases the water-holding capacity of soil when mixed with biochar.

However, there are some other properties that influence plant-available water following biochar application. They include the type of soil in terms of soil order, as shown by Herath et al. (2013) who used two contrasting soils, an Alfisol and an Aandisol with the same textural class (silty loam) for their experiment. The result showed that the Alfisol had a significant increase in plant-available water, while there was no effect in the Andisol. This could be due to the difference in mineral composition of the two soils and in some other soil properties. Also, the biochar application rate has an influence on plant-available water, as reported by Głąb et al. (2016) who found that plant-available water increased with increasing biochar rate. A percentage increase of 25 and 75%, with reference to the control, was recorded following biochar application rates of 2 and 4%, respectively. Also, the feedstock used for producing biochar is another factor.

The general increase in plant-available water following biochar application is advantageous in reducing the frequency of irrigation, especially where plants fully depend on irrigation. This might in a long run reduce the cost of production.

Factors and mechanisms affecting biochar impacts on soil physical properties

Biochars differ in their physical and chemical properties, and soil properties also differ widely (Brady and Weil 1984). Therefore, the degree of changes in soil physical properties following biochar application is dependent upon the following factors: (i) feedstock and pyrolyetic conditions of biochars, (ii) application rate of biochar, (iv) biochar particle size, and (v) soil type and texture.

The amount of biochar applied has been reported to influence the response of soil to biochar as an amendment. An increase in biochar application rate leads to a decrease in soil bulk density. Increasing the amount of biochar applied leads to an increase in soil porosity (Table 1). Different feedstocks have different properties, which, in turn, yield biochars of varying characteristics. Wang et al. (2017) studied two different feedstocks, walnut shell and softwood. Biochar produced from walnut shell led to a higher increase in aggregate stability compared to the other feedstock. Also, wheat straw reduced bulk density and increased available water more than wood feedstocks (Burrell et al. 2016). The age of biochar is another factor influencing biochar impacts on soil physical properties. Aller et al. (2017) reported a decrease in soil bulk density when a fresh biochar was applied to a sandy loam soil while an aged biochar had no effect on the same soil.

Al-Wabel et al. (2013) reported an increase in ash content, pH, electrical conductivity, basic functional groups, carbon stability, and total content of C, N, P, K, Ca, and Mg as pyrolysis temperature increased, while biochar yield, total content of O, H, S, unstable forms of organic C, and acidic functional groups decreased. These changes will consequently affect the performance of biochar. In general, a biochar from a high pyrolysis temperature (≥ 500 °C) could possess lower water repellency with higher water retention than that from a low pyrolysis temperature (Kinney et al. 2012; Gray et al. 2014). Kinney et al. (2012) reported that water repellency of biochar produced at 500 °C decreased 13-fold compared with same one produced at a pyrolysis temperature of 300 °C. Another factor influencing biochar performance is its particle size. This can directly affect the interaction of biochar and the soil matrix, thereby influencing the impact of biochar on soil physical properties. Herath et al. (2013) proposed that biochar with small particles could enhance aggregate formation, because it could easily interact or mix with soil particles compared to biochar with large particles. Specific surface area is a function of particle size. As the particle size increases, the specific surface area decreases. This is an important factor affecting soil water-holding capacity (Crabbe 2009; Uzoma et al. 2011). The combination of biochar with other soil amendments, such as manure and inorganic fertilizers, could enhance the positive effect of biochar on soil physical properties (Lentz et al. 2014). Also, soil order has been shown to

Table 7 Changes in plant available water as affected by biochar application from different studies

Soil textural class	Soil order	Study type	Study duration	Biochar feedstock	Biochar pyrolysis temperature (°C)	Biochar rate	Plant-available water (cm^3 cm^{-3})	Change (%)	References
Silt loam	Alfisol	Incubator	295 days	corn stover	control	Control	0.03a		Herath et al. (2013)
					350	7.18 t C ha^{-1}	0.06b	100	
					550		0.05ab	Ns	
	Andisol				Control	Control	0.06a		
					350	7.18 t C ha^{-1}	0.06a	Ns	
					550		0.07a	Ns	
loamy sand		pots	3 months	*Miscanthus* × *giganteus* and winter wheat straw	300 °C	0.5%	0.04c		Głąb et al. (2016)
						1%	0.04c	Ns	
						2%	0.05b	25	
						4%	0.07a	75	
silt loam soil	Alfisol	field	4 months	oak wood	650	0 and 0.5%	No effect		Mukherjee et al. (2014)
Sandy loam		Field	3 years	Wood	~450	0, 8, 16, and 32 Mg ha^{-1}	Increased		de Melo Carvalho et al. (2014)
Sandy loam		Incubation	180 days	Rice husk and wood	350–550	0 and 2%	Increased	≤ 130	Esmaeelnejad et al. (2016)
Sandy soil	Entisol	Laboratory		Wood	350–600	0 and 2%	Increased		Suliman et al. (2017)
Sandy loam		Laboratory		Control	400–800	0 and 4%	0.18 b		Mollinedo et al. (2015)
				Corn stover			0.23 a	27	
				Switchgrass			0.23 a	27	
Clay loam				Control			0.19 b		
				Corn stover			0.25 a	31	
				Switchgrass			0.23 a	21	
Loam		Field	4 years	Peanut shells	350–500	0	0.21b		Du et al. (2016)
						28 Mg ha^{-1}	0.24a	14	
Loam		Field	1 year	Crop straw	450	0 to 16 Mg ha^{-1}	No effect		Liu et al. (2016)
Clay soil	Vertisol	column	2.5 years	Fruit trees	500	0, 1 and 3%	No effect		Castellinia et al. (2015)
sandy loam	Kurosol	Field	30 months	Acacia green waste	550	0 and 47 Mg ha^{-1}	No effect		Hardie et al. (2014)
Clayey		Field and lab	30 days	Corn stover and wood	450	0.5%	No effect		Bayabil et al. (2015)
Clay		Incubation	180 days	Sugarcane	400–800	0	0.04c		Kameyama et al. (2016)
						1%	0.01bc	Ns	
						3%	0.06b	50	
						5%	0.06ab	50	
						10%	0.09a	125	

affect the performance of biochar. Herath et al. (2013) employed two contrasting soil orders, an Alfisol and an Andisol with the same soil textural class (silt loam). Bulk density of the Alfisol decreased significantly while there was no significant effect in the Andisol. The results could be due to the different mineral compositions of the two soils and some other characteristics.

Future research priorities

i. There is little or no research concerning the effects of biochar on a degraded soil, especially its soil physical properties. There is need for research on this topic to know the ability of biochar for use in reclamation of degraded land.
ii. Most of the studies with biochar have been laboratory or greenhouse studies, and only a few have been field experiments. There is need for more field experimentation because laboratory or greenhouse conditions might be different from those of the field.
iii. Researchers should investigate the combination of biochar and other soil amendments such as inorganic fertilizers. This is because the amount of biochar required for a good impact on soil physical properties, such as a biochar application rate of 5%, might not be realistic for large-scale farming. This amount of biochar might not be possible, considering the processes and technology involved in the production of biochar.
iv. There is need to research on the best application methods: tilling into the soil, broadcasting, or placement, in order to recommend a method that could be most effective in the changes of soil physical properties.
v. The long time, residual effect of biochar in soil should also be considered in order to avoid possible permanent damage to the soil.

Conclusion

This review has used available data concerning the impacts of biochar on soil physical properties in order to explain the interactive effect of biochar and soil particles. An understanding of this interaction will increase soil productivity. Biochar has a promising role in improving most of the soil physical properties at an application rate of 1 to 4%. However, there is need to consider the suitable pyrolysis temperature, because it affects the properties of biochar and, thus, influences its performance. The higher the biochar pyrolysis temperature, the lower the hydrophobic nature of biochar, and this results in increasing water retention and water-holding capacity. The porosity of biochar also increases with increasing pyrolysis temperature, which, in turn, influences biochar performance.

Despite the profound effect of biochar in improving the physical properties of soil, a high rate of about 2 to 4%, which is generally the most effective rate, might not be economically realistic in large-scale crop production. More research is needed concerning the economic viability of biochar, when used as a soil amendment to sustain crop production. Also, more studies are needed to determine the effectiveness of integration of biochar with other soil amendments, such as inorganic fertilizer.

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