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Biochar

REVIEW **Open Access**

Biochar impacts on soil water dynamics: knowns, unknowns, and research directions

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Abstract

Amidst intensifying global agricultural water demand, optimizing management practices and understanding the role of soil amendments, particularly biochar (BC), in modulating soil water dynamics are critical. Here, we review the potential impacts of BC on soil water dynamics, elucidate mechanistic underpinnings, and identify critical research gaps and prospective avenues. In general, BC modifies soil structure, hydraulic properties, surface albedo, and heat fluxes, which influence soil water storage, energy balance, and irrigation paradigms. Depending on soil texture and BC properties, BC demonstrates a greater reduction in bulk density and saturated hydraulic conductivity in coarse-textured soils compared to fine-textured soils. BC application generally increases water holding capacity (WHC) while exhibiting no consistent impact on soil water infiltration. Increased WHC of soils results from increased porosity, surface area, and soil aggregation. Increased porosity arises from a confluence of factors, encompassing new pores formation, reorganization of pores, increased soil aggregation, dilution effects of BC, reduced soil compaction, and biotic interactions, including increased population of burrowing invertebrates. BC tends to increase plant-available water in coarser soils, attributed to its hydrophilic nature, augmented specific surface area, and enhanced overall porosity. However, BC may induce soil water repellency, contingent upon variables such as feedstock composition, pyrolysis temperature, and specific soil attributes. While BC exhibits transformative potential in enhancing soil hydraulic properties, scalability concerns and economic viability pose challenges to its widespread agricultural application. Overall, BC offers promising avenues for sustainable water management. However, it is imperative to explore large-scale applications and conduct long-term field studies across different management, climate, and soil types to fully understand how different types of BC impact soil water dynamics.

Highlights

- Biochar generally improves soil water retention in coarse-textured soils.
- In coarse-textured soils, biochar increases porosity and PAW but decreases bulk density and K_{sat}.
- The effects of biochar on infiltration rates vary depending on soil types, as well as biochar particle size, production temperature, and depth of placement.
- Further studies on the mechanisms governing water retention in biochar-amended soils are warranted.
- Long-term studies encompassing various soil and biochar types are necessary.

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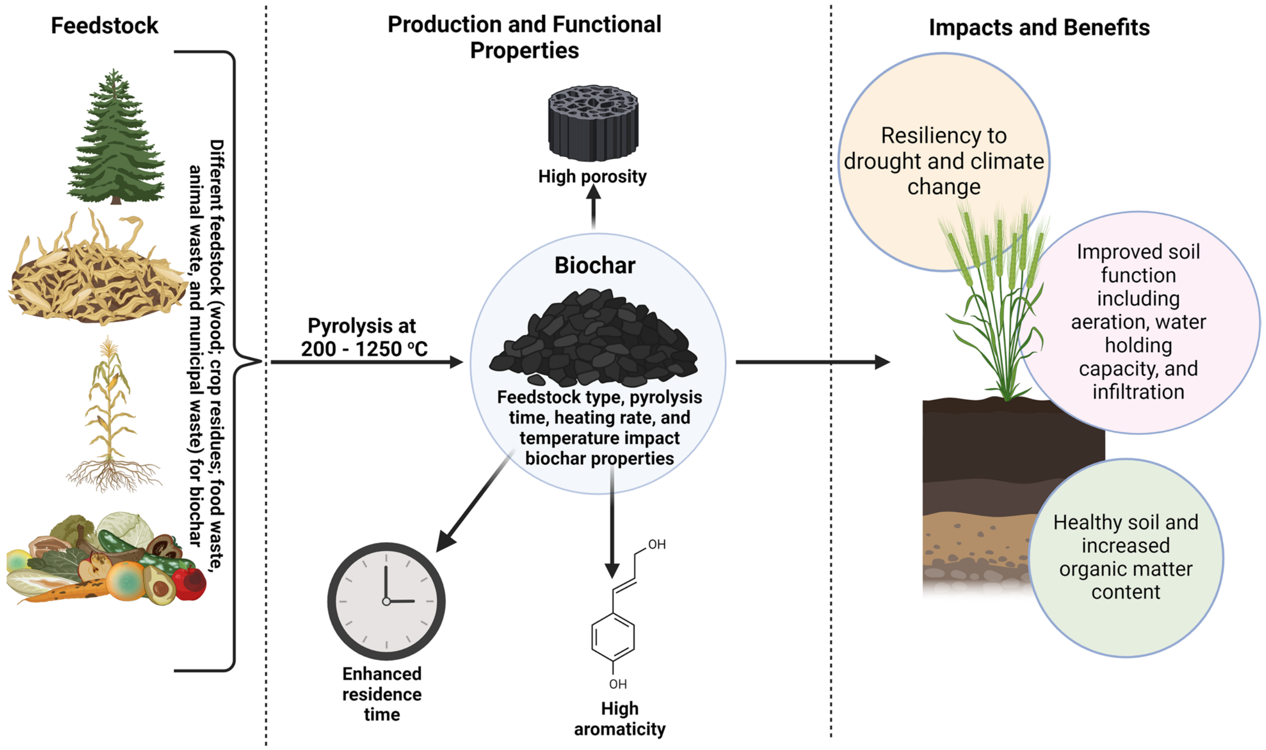
Graphical Abstract



1 Introduction

The rise in global population, shifts in land-use patterns, and climatic unpredictabilities have exerted profound pressures on agriculture and water systems (Doklega et al. 2023; FAO 2017; Mubarak et al. 2021; Vörösmarty et al. 2000). Consequently, the agricultural domain is progressively embracing diverse strategies, notably the integration of soil amendments (Lasheen et al. 2023; Saudy et al. 2021a), to augment irrigation water-use efficiency (El-Metwally et al. 2022; Makhlouf et al. 2022), soil water retention (Salem et al. 2021), and agricultural yield (Cho et al. 2023; Ramadan et al. 2023; Saudy et al. 2021a, 2021b). Recent research results emphasize biochar (BC) as a potent soil amendment, delineating its capacity for enhanced carbon (C) sequestration and amelioration of agricultural output by modulating soil physicochemical attributes (Agegnehu et al. 2017; Park et al. 2023a, b; Yun et al. 2022). Biochar is a carbon-enriched material produced through pyrolysis of biomass under anaerobic or oxygen-limited conditions (Jeong et al. 2016; Sohi et al. 2010). It predominantly comprises stable aromatic carbon, moderately labile aliphatic carbon, and mineral ash residues. Notably, BC's longevity in soil surpasses that of conventional organic matter forms, attributable to its recalcitrant nature (Jeong et al. 2016; Joseph et al. 2021; Weber and Quicker 2018).

Historically, BC research predominantly emphasized its role in carbon sequestration, climate change mitigation, and soil fertility enhancement (Saudy et al. 2021b). However, contemporary investigations increasingly pivot towards elucidating BC's influence on soil physical and hydrological properties (Blanco-Canqui 2017; Bohara et al. 2019; Cernansky 2015). Many studies have elucidated BC impacts on soil water dynamics, with outcomes contingent upon BC source materials, production conditions, and initial soil properties (Bohara et al. 2019; Yu et al. 2017). For instance, BCs from hemlock and switchblade grass increased water holding capacity (WHC) in loamy sands (Yu et al. 2017), while coffee husk BC increased the water use efficiency of corn in sandy soils (de Sousa Lima et al. 2017). In addition, corn cob BC increased saturated hydraulic conductivity (K_{sat}) and WHC in sandy loam soil (Zhou et al. 2018). Despite burgeoning recognition of BC's multifaceted impacts across global agroecological landscapes, comprehensive reviews delineating BC's efficacy in soil water management remain conspicuously scant. Existing syntheses primarily emphasize BC's chemical attributes, waste utilization, and broader environmental implications (Gul et al. 2015; Wang and Wang 2019; Xiao et al. 2017; Yang et al. 2020). Further, reviews in the soil water sector have predominantly focused on individual hydraulic parameters, such as Razzaghi et al.'s (2020) focus on soil water retention, indicating a notable knowledge gap in comprehensive assessments encompassing multiple hydraulic aspects. As such, there is a need for a comprehensive review of research reports with focus on BC management for modulating soil water availability and refining irrigation strategies within BC-applied fields. The review should not only emphasize current research gaps but also compellingly outline the path for future research directions. Indeed, enhancing water retention and optimizing agricultural water use are paramount for strengthening the resilience of agroecosystems, particularly in the face of the expanding global irrigated land and the challenges posed by declining water quality and availability (Nilahyane et al. 2023).

Therefore, this review aims to (i) critically evaluate extant literature concerning BC application and its ramifications on soil water dynamics, (ii) identify prevalent challenges and critical research gaps, and (iii) highlight needs and opportunities for future research. Over 150 scholarly articles published between 1990 and 2023 were reviewed and summarized.

2 Impact of feedstock and pyrolysis conditions on biochar characteristics and their ripple effect on soil water dynamics

Biochar is produced via the pyrolysis of various organic feedstocks including wood, manure, green waste, algae, and various crop residues and byproducts like straw, cobs, husks, and bagasse, employing either slow or fast heating regimes within a temperature spectrum of 200 to 1250 °C, under limited to no oxygen conditions (Fig. 1; Tripathi et al. 2016). This thermochemical process entails the degradation of biomass, encompassing dehydration, decarboxylation, and dehydrogenation reactions, the specifics of which are influenced by factors such as biomass type, pyrolysis temperature, heating rate, and vapor residence time (Laird et al. 2009; Tripathi et al. 2016). Depending on the production temperature and residence time, pyrolysis can be categorized into slow, intermediate, and fast pyrolysis. In slow pyrolysis, feedstocks are pyrolyzed at temperatures ranging from 400–500 °C, employing a heating rate of approximately 0.1 to 1 °C per second, for a duration ranging between 300 and 550 s (Tripathi et al. 2016). Fast pyrolysis involves heating biomass to a temperature range of 850–1250 °C, with a heating rate between 10 and 200 °C per second, for a brief duration ranging from 0.5 to 10 s. Intermediate pyrolysis occurs within the temperature range of 500 to 650 °C, employing a heating rate varying from 1 to 10 °C per second, and a residence time lasting between 0.5 and 20 s (Tripathi et al. 2016).

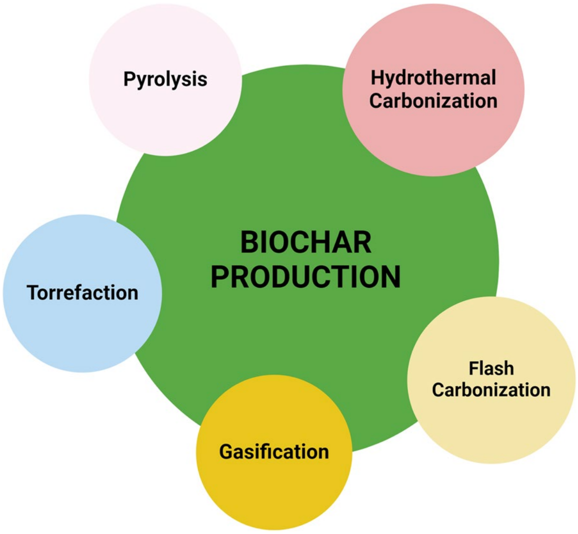


Fig. 1 Biochar production techniques

Yield, morphology, and structural properties of the resulting BCs are intricately influenced by multiple operational parameters. These include the residence time of feedstock, amount of vapor in the pyrolysis unit, heating rate, temperature, pyrolyzer bed height, pressure, carrier gas flow rate, catalyst, and feedstock types (Ahmad et al. 2014; Tripathi et al. 2016).

Important BC physical properties that influence soil moisture dynamics include surface area, pore space, pore size distribution, particle density, surface functional groups, hydrophilicity, thermal properties, and mechanical strength (Blanco-Canqui 2017). Notably, BC derived from fast pyrolysis exhibits greater particle density, more volatiles, and less fixed carbon relative to its counterparts from slow pyrolysis and gasification processes (Brewer et al. 2011). In general, higher pyrolysis temperatures tend to produce BCs with higher surface area and pore space. For example, in a recent study, BC produced at 450 to 550 °C temperatures increased soil structure due to higher specific surface area and cation exchange capacity (CEC). However, temperature exceeding 550 °C resulted in the loss of O content and therefore enhanced BC's hydrophobicity (Ghorbani et al. 2022). Similarly, surface area of BC, produced from sugarcane leaf biomass, increased from 8.1 $m^2 g^{-1}$ to 178.5 $m^2 g^{-1}$ as the pyrolysis temperature increased from 450 °C to 650 °C (Jeong et al. 2016). Surface area of 0.02 $m^2 g^{-1}$ was reported for the BC derived from stone fruit pits at 300 °C (Hale et al. 2015), while 528 $m^2 g^{-1}$ (via CO_2 sorptometry) was reported for oakwood BC pyrolyzed at 650 °C (Mukherjee et al. 2011). Intriguingly, while surface area typically escalates with increasing pyrolysis temperature up to a specific temperature limit, excessively high temperatures can induce BC with diminished surface area due to internal pore space deformation. For instance, Jeong et al. (2016) observed an increase in BC surface area when pyrolysis temperature increased from 450 °C to 650 °C but detected marginal decline in surface area at 750 °C. However, in another study, BCs produced between 650 and 850 °C were reported to exhibit higher surface area relative to those produced at lower pyrolysis temperatures (Mukherjee and Lal 2013).

Biochar's inherent pore characteristics—including total pore space, pore size and pore distribution —significantly influence soil water retention, availability, and gas fluxes. The pore structure within BC particles exhibits variability in internal diameters, contingent upon the specific feedstock and pyrolysis temperature. Typically categorized, these pores encompass macropores (> 50 nm), mesopores (2–50 nm), and micropores (< 2 nm). Both intrapores and interpores affect BC's surface area, gas diffusivity, soil water storage, as well as the sorption and molecular transport mechanisms therein (Atkinson et al. 2010).

The heating rate and pressure during the pyrolysis influence the mass transfer dynamics of volatile compounds, as well as the resultant BC's surface area, pore volume, and pore size distribution (Tripathi et al. 2016). Typically, BCs derived from higher temperatures exhibit higher internal pore volume (Brewer et al. 2014; Keiluweit et al. 2010); however, higher temperatures can instigate the thermal cracking of heavy hydrocarbons, leading to alterations in macro-porosity and a potential decline in overall BC yield (Tripathi et al. 2016). Furthermore, pyrolysis conditions characterized by higher heating rate, elevated pressure and extended retention time can induce molecular rearrangements within the BC matrix, subsequently influencing the surface area and porosity (Bikbulatova et al. 2018; Gray et al. 2014). Pyrolysis above 400 °C could increase skeletal density and yield of aromatic and quinone compounds. It could also reduce O-containing and aliphatic functional groups, and the crystalline nature of BC (Brewer et al. 2014; Gray et al. 2014; Kameyama et al. 2019; Keiluweit et al. 2010).

Biochars produced at lower temperatures typically exhibit increased ion-exchange groups. Additionally, the physicochemical attributes of BC can evolve over time; freshly produced BCs generally possess a reduced CEC relative to aged BCs (Liang et al. 2006). Cation exchange capacity of BCs can undergo modifications within soil environments due to carboxylation process induced by abiotic oxidation and the loss of hydrophobic compounds (Verheijen et al. 2010). CEC exerts an influence on O to C ratios, with higher CEC correlating to an elevated O/C ratio. This relationship is inherently associated with hydrophobicity (Batista et al. 2018). Overall, CEC plays a crucial role in enhancing soil structure and retaining soil nutrients, demonstrating importance in water-filtration applications.

3 Biochar impacts on soil properties that influence water dynamics

Biochar has garnered significant attention as a soil amendment to harness a wide range of functions and benefits including increased yield and water retention (Ahmed et al. 2016; Bohara et al. 2019; Igalavithana et al. 2017; Liu et al. 2017a, b; Salinas et al. 2018). While many studies have reported positive effects of BCs on crop yield (Agegnehu et al. 2017; Jeffery et al. 2011; Uzoma et al. 2011; Xiao et al. 2016), mechanisms that govern yield benefits are not yet fully understood. Water holding capacity and liming effects are considered two of the mechanisms by which BC may boost crop yields (Jeffery et al. 2011). Several studies have documented the substantial influence of BC application on soil water dynamics including improvements in soil WHC (Blanco-Canqui 2017; Bohara et al. 2019). For instance, Zhou et al. (2018) observed higher WHC and an increase in PAW by 18% with 9 Mg ha^{-1} maize cob BC application compared to the control plot in a sandy loam soil. The potential improvement in WHC of BC-amended soils emanates from significant changes in various soil physicochemical properties influencing soil water dynamics such as soil bulk density (BD), pore volume and size, infiltration, hydraulic conductivity (K), water potential, water repellency, and soil thermal properties (Fig. 2) (Blanco-Canqui 2017; Hardie et al. 2014). These properties are discussed in detail next.

3.1 Biochar impacts on soil bulk density and porosity

Bulk density and porosity characteristics of soil influence soil water dynamics. Various studies, both field and laboratory studies, have elucidated alterations in soil BD with BC application (Additional file 1: Table S1) resulting from changes in porosity and soil structure (Blanco-Canqui 2017). In South Korea, Park et al. (2023a, b) reported that corn waste BC significantly reduced soil BD and increased near-surface porosity, CEC, and soil water content in both dry and wet years within upland

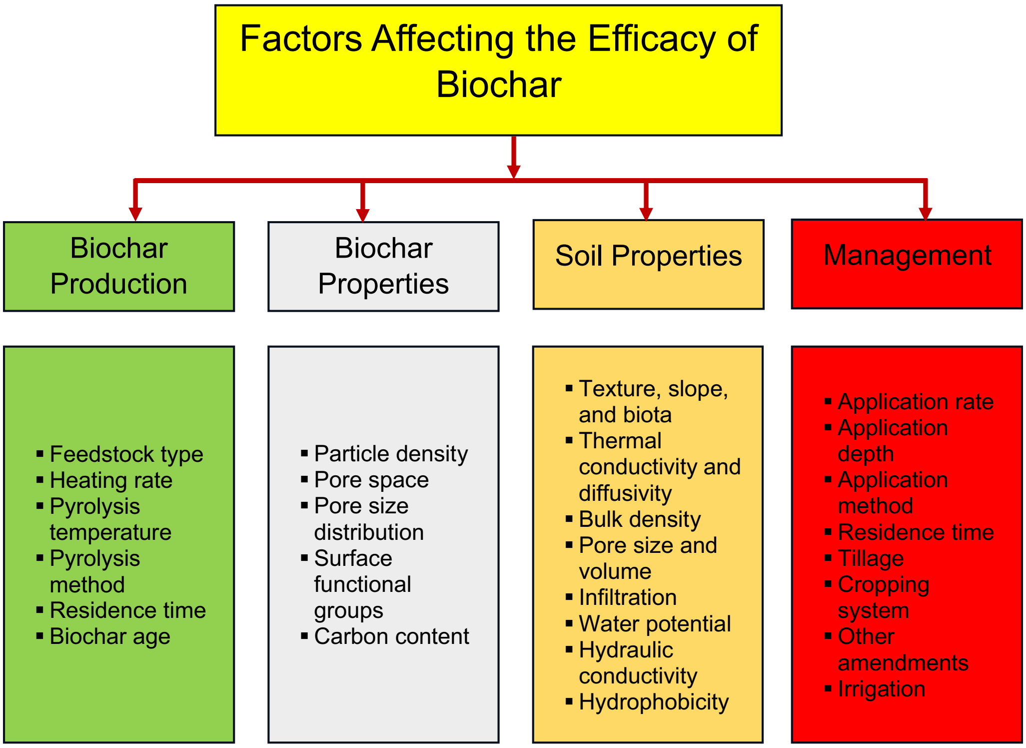


Fig. 2 Factors influencing the efficacy of BC in influencing soil water dynamics (Adapted and modified from Blanco-Canqui 2021)

corn production. Generally, BC reduces soil BD (Blanco-Canqui 2017; Park et al. 2023b) with reported decreases ranging from 1 to 73% compared to unamended soils, contingent upon soil texture and the rate of BC application (Zhao et al. 2016). The decrease in BD has demonstrated a linear correlation with the increasing rate of BC application. Generally, positive effects were apparent in fields when the BC application rate was > 7.5 Mg ha^{-1} (e.g., Ma et al. 2016) and in laboratories when the rate was above 0.1% w/w (~ 2.1 Mg ha^{-1}) (Gamage et al. 2016). In addition to the BC application rate and soil texture, the effects on BD vary with BC feedstock type and pyrolysis temperature. While Liu et al. (2016) observed reduced BD with mesquite BC (pyrolyzed at 400 °C) at 2% application rate, Igalavithana et al. (2017) and Pratiwi and Shinogi (2016) observed no significant effect at this rate with rice husk BC derived from pyrolysis at 750 °C.

Similarly, the majority of studies indicate an increase in total porosity of soil varying from less than 1% to 55% following the application of BC (Additional file 1: Table S1). It must be noted that most of those studies demonstrating increased porosity with BC applications were conducted in coarse-textured soils. Studies suggest a decrease in BD and an increase in porosity in the sand, loamy sand, and sandy loam soils (Abel et al. 2013; Gamage et al. 2016; Githinji 2014; Glab et al. 2016; Novak et al. 2016; Obia et al. 2016). However, a study by Villagra-Mendoza and Horn (2018) reported inconsistent effects of BC on soil porosity in sandy and sandy loam soil with the application of mango tree BC (pyrolyzed at 600 °C) at 2.5 and 5% rates. They reported that wide coarse pores decreased, and narrow pores increased after BC applications.

Biochar could reduce soil BD through two mechanisms: dilution effects and increased soil porosity (Blanco-Canqui 2017; Herath et al. 2013). Biochars, possessing lower density than the soil, act as amendments that, upon incorporation, result in dilution and reduction of the ensuing BD. Moreover, BC appears to increase soil porosity through differential mechanisms, including the direct introduction of new pores (Atkinson et al. 2010; Downie et al. 2009), reduction in BD and increase in soil aggregation (Verheijen et al. 2010), formation of accommodating pores between BC particles and soil aggregates (Jones et al. 2010; Novak et al. 2012), reduction of soil packing and restructuring of pore distribution (Sun et al. 2018), and an increase in the population of burrowing invertebrates (Lehmann et al. 2011). Andrerenelli et al. (2016) reported that the addition of wheat bran derived pelletized BC enhanced pore space by improving both soil aggregation and BC's internal pore space. However, the improvement in pore space from soil aggregation is likely to be a more enduring effect. Also, BC forms accommodation pores depending upon soil texture, size of BC particles, and degree of settling (Hardie et al. 2014). Green waste BC derived from pyrolysis at 450 °C significantly increased the meso-porosity of bauxite processing sand by filling large pores between sand particles with BC particles, thereby positively influencing available WHC and water retention at field capacity (Jones et al. 2010). In addition, BC application may improve the population of earthworms and other soil biota, contributing to modifications in BC's particle size and soil structure that influence porosity (Thies and Rillig 2009).

A few studies also showed limited to adverse effects of BCs on porosity in certain soil types (Jien and Wang 2013; Verheijen et al. 2010; Villagra-Mendoza and Horn 2018). According to Jien and Wang 2013, higher rates of BC amendments can prompt macroaggregate formation, shifting from micro-aggregate dominance over time, resulting in decreased porosity. In a few cases, BC-amended soils showed no significant effect on soil porosity. For example, mango-wood BC from pyrolysis at 600 °C showed no significant impact on the total porosity of sandy soil (Villagra-Mendoza and Horn 2018). Obia et al. (2016), however, observed an increased proportion of pores between 10 and 100-μm radius with smaller particle sizes of maize cob BC (≤ 0.5 mm) produced at 350 °C in loamy sand compared to coarse BC particles (1–5 mm). In sandy soils, both fine and coarse BCs decreased the proportion of pores between 10 and 100-μm radius. The effects of BC on soil porosity hinge on BC's internal porosity influenced by production conditions such as gasification, pyrolysis temperature, and particle size. Higher pyrolysis temperatures and gasification conversion generally increase porosity, as discussed earlier, irrespective of feedstock types due to a rise in the production of volatiles (Verheijen et al. 2010). Bikbulatova et al. (2018) observed that freezable free water decreased from 58 to 21% in peanut shell BC, and from 64 to 34% in palm kernel shell BC pyrolyzed at 800 °C with increasing gasification conversion from 28 to 75% due to increased micropore volume when gasification conversion increased from 28 to 75%. In summary, BC applications generally reduce soil BD and increase porosity particularly in coarse-textured soils, but outcomes vary, underscoring the need for context-specific considerations in BC strategies.

Enhanced porosity resulting from BC amendments is beneficial for improving water retention in soils, as will be discussed later in a different sub-section. This improvement is particularly vital for plants in low rainfall zones. The change in soil water-retention capacity has been demonstrated as a function of soil porosity, influenced by factors such as textures, organic matter content, and the specific properties of the BC utilized (Blanco-Canqui 2017; Hardie et al. 2014; Joseph et al. 2010; Mangrich et al. 2015. For example, dried corn residue BC pyrolyzed at 500 °C increased soil porosity in coarse-textured soil compared with fine-textured soil (Igalavithana et al. 2017). Generally, BCs contain high total internal porosity. Larger-sized BC particles exhibit a higher proportion of mesopores and macropores compared to their smaller counterparts, depending on the types of biomass feedstocks (Wang et al. 2019). According to Chen et al. (2017), smaller-sized BC particles could increase water retention due to their greater surface area. Conversely, larger particles (> 0.5 mm) might amplify water retention, particularly in drier and saturated conditions. It is noteworthy that small pores in BCs generally retain water for an extended duration compared to macropores (Blanco-Canqui 2017). Arthur and Ahmed (2017) reported 20–150% higher water retention with the application of rice straw—BC pyrolyzed at 550 °C in sandy soil due to an increased fraction of soil pores < 30 μm. Mangrich et al. (2015) posited that polarity and micropores constituted pivotal factors influencing the augmentation of soil water-holding following BC applications in their study.

3.2 Biochar impacts on soil hydrophobicity and hydrophilicity

Application of BC could significantly impact soil water dynamics by modifying the hydrophobic/hydrophilic properties of soil, based on the surface properties of BC (Kameyama et al. 2019; Novak et al. 2012). Soil hydrophobicity or water repellency results from non-polar coatings of hydrophobic organic compounds on soil and water repellent particulate organic matter (Doerr et al. 2000). Biochar's water repellency is contingent on BC's feedstock material, pyrolysis temperature, and the residence time of BC in the soil (Jeong et al. 2016; Laird et al. 2009). Biochar's surface chemistry such as alkyl (C–H) functional groups can induce water repellency (Jeffery et al. 2015; Kinney et al. 2012). Repellency can prevent diffusion of water in soil and BC intrapores (Liu et al. 2017a, b) reduce infiltration of water into mineral soil and induce overland flow. As a result, water repellency affects crop productivity by influencing nutrient cycling, greenhouse gas emissions, and PAW. Laird et al. (2009) reviewed the effect of pyrolysis and reported hydrophobicity of fresh BC under low-temperature pyrolysis, which tends to develop ketones, quinones, carboxylic C, and aromatic compounds. The hydrophobic properties of BC are likely predominantly determined by the pyrolysis temperature, as it affects the quantity of surface carboxylic groups and surface area. While hydrophobicity occurs in BC produced at 300 °C, BC could lose hydrophobic property at temperatures > 500 °C due to the loss of hydrophobic compounds, predominantly aliphatic functional groups, as well as non-polar semi volatile compounds (Gray et al. 2014; Zornoza et al. 2016). Kinney et al. (2012) reported that BCs produced from the same feedstock displayed hydrophobicity when pyrolyzed at 300 °C, but not when pyrolyzed at 500 °C. Similarly, hydrophobicity decreases with decreasing particle size (Gray et al. 2014). Further, while freshly produced BC tends to exhibit higher hydrophobicity due to a lower number of polar surface functional groups, prolonged exposure to water and oxygen subsequent to soil application may result in a shift towards hydrophilic properties. This transformation occurs due to the formation of new carboxyl and other polar functional groups through surface oxidation (Laird et al. 2009). Accordingly, lower hydrophobicity for older BCs compared to fresh BCs has been reported in other studies due largely to an increase in O:C ratio, negative surface charge and CEC as the aging level intensifies (Aller et al. 2017; Mia et al. 2017; Ojeda et al. 2015).

Biochar may lead to a decrease in repellency, an increase in repellency, or, in some cases, no significant effect, depending on soil type, BC feedstock, and pyrolysis temperature. Devereux et al. (2012) observed that the application of wood charcoal at a 5% rate reduced water repellency by five times compared to the control (classified as water repellent) in sandy loam soil. In contrast, Glab et al. (2016) observed a slight increase in water repellency. However, Villagra-Mendoza and Horn (2018) reported no clear response of BC on the water repellency of sandy soil, possibly due to a constrained increase in surface area. Glab et al. (2018) observed that amending willow BC pyrolyzed at 350 °C to soil supplied with organic amendments such as maize straw and sewage sludge reduced repellency to values below maize straw treatments (315 s). Hallin et al. (2015) also observed that the application of finely ground pine and spruce BC pyrolyzed at 700 °C at a 10% and 25% rate reduced repellency by 50% and 100%, respectively. This reduction could arise from water absorption into soil pores and a decrease in soil–water interfacial energy and an increase in the effective soil surface area in contact with water (Hallin et al. 2015). In summary, studies suggest a mixed effect of BC on water repellency. Therefore, further research could enhance our understanding of the mechanisms and consequences of water repellency in BC-amended soils.

3.3 Biochar impacts on soil hydraulic conductivity

Hydraulic conductivity plays a pivotal role in governing infiltration, soil water retention in the vadose zone, and the overall dynamics of soil water recharge from rainfall and irrigation. Understanding of changes in K is critical for unraveling water flow patterns, solute and pollutant transport, and for enhancing the management of irrigation and drainage in BC-amended soils. The determination of K stands as a key input parameter in rainfall-runoff models. Several factors affect K values, including soil particle size distribution, intra-aggregate porosity, effective porosity, pore throat size, pore connectivity, pore density, surface area of grains, shrink-swelling, BD, degree of saturation, microbial activity, bioturbation, extrinsic factors such as temperature, and management practices like tillage, among others. By affecting many of these critical soil properties, the incorporation of BCs into soils has the potential to significantly alter soil K (Table 1).

In general, the application of BCs tends to result in a decrease in K_{sat} in coarse-textured soils and an increase in fine-textured soils (Blanco-Canqui 2017). Reduced

Table 1 Impact of BC derived from different feedstocks and pyrolysis temperature on K_{sat} across different soils

Location	Soil	BC type	Pyrolysis temp (°C)	BC rate	Effect	References
Germany	Sand and sandy loam	Mango-wood	600	0%, 2.5%, and 5%	Decreased K_{sat}	Villagra-Mendoza and Horn (2018)
Czech Republic	Sandy loam and loam	Grape-stalks	600	0%, 2%, and 5%	Decreased K_{sat}	Jacka et al. (2018)
China	Sandy loam	Maize-cob	360	0 and 9 Mg ha^{-1}	Increased K_{sat}	Zhou et al. (2018)
Korea	Sandy loam	Dried corn residue	500	0%, 2%, 5%, 7.5%, and 10%	Decreased K_{sat}	Igalavithana et al. (2017)
Saudi Arabia	Sandy loam	Conocarpus tree waste	400	22 Mg ha^{-1}	Decreased K_{sat}	Ibrahim et al. (2017)
USA	Sandy loam	Red oak	500	0%, 3%, and 6%	Decreased K_{sat}	Dokoohaki et al. (2017)
Iran	Sandy loam	Apple wood chips	550	2%	Decreased K_{sat}	Esmaeelnejad et al. (2017)
USA	Portneuf silt loam	Oak and hickory hardwood sawdust	500	0%, 1%, and 2%	No significant effect	Lentz et al. (2019)
Hong Kong	Compacted clay	Peanut shells	500	0%, 5%, and 20%	Increased K_{sat}	Wong et al. (2017)

K_{sat} is likely to occur in coarse-textured soils when BCs fill macropore spaces between soil particles, leading to increased tortuosity and decreased pore diameter, particularly with BCs composed of smaller particles (Esmaeelnejad et al. 2017; Igalavithana et al. 2017). For example, Lim et al. (2016) reported a decreased K_{sat} in both coarse and fine sand as BC particles induced soil tortuosity. In certain cases, BCs may induce swelling in coarser soils through polar hydrogen bonding of O–H and C-O–H groups, potentially altering the orientation of soil particles and BD (Jacka et al. 2018). Githinji (2014) observed a linear decrease in K_{sat} with increasing application rates of peanut hull BC pyrolyzed at 500 °C, primarily attributed to the water repellency of organic matter in BC-amended soils. Also, Zhang et al. (2016) reported a gradual decline in K_{sat} in sandy soil with increasing ratios of poplar BC pyrolyzed at 550 °C, linked to the loss of macropores. In certain soil mixtures, K_{sat} decreases due to the internal structure and higher field capacity of BCs (Barnes et al. 2014). Blanco-Canqui (2017) reported a 7 to 2270% decrease in K_{sat} with BC applications to coarse-textured soils with sandy-to-sandy loam texture.

Biochar applications may increase K_{sat} depending on soil type, BC rate, and BC particle size (Herath et al. 2013; Moutier et al. 2000; Trifunovic et al. 2018). Zhou et al. (2018) reported a notable 106% increase in K_{sat} in sandy loam soils with the application of maize cob BC pyrolyzed at 360 °C at 9 Mg ha^{-1} compared to the control. Barnes et al. (2014), however, observed increased K_{sat} in clay-rich soil but decreased K_{sat} in sandy and organic soils. Increased K_{sat} in fine-textured soils may occur due to an increase in microporosity, possibly facilitated by increased earthworm activities under BC application (Hardie et al. 2014). In certain cases, BC may initially decrease K_{sat} values in coarse-textured soils due to particle structure disruption and macropores clogging in the early stages. However, over subsequent wetting–drying cycles, K_{sat} could exhibit an increase (Villagra-Mendoza and Horn 2018). Lim et al. (2016) found that BCs with larger particle sizes (e.g., > 1 mm) reduced K_{sat} more significantly than BCs with small particles in sandy soils. While BCs increased K_{sat} in clay loam soils, higher BC rates were required for this effect (Lim et al. 2016). According to Blanco-Canqui (2017), a minimum BC rate as low as 10 Mg ha^{-1} is necessary to induce either an increase or decrease in K_{sat} values. A few studies have also reported limited to no effect of BCs on K_{sat} values. For example, Laird et al. (2010) observed no significant effect of mixed hardwood BC amendment on K_{sat} in fine-loamy soil, indicating that BC does not consistently induce changes in K_{sat}.

In summary, BC generally results in a reduction in K_{sat}, but the effects may vary with soil types, BC feedstocks, BC particle size, and application rates (Table 1). It is noteworthy that BC induced changes in K_{sat} can have important implications for the irrigation management of agroecosystems. For example, in sandy soils, a decreased K_{sat} could presumably reduce pore water loss during droughts and alleviate soil eluviation during intense rainstorms (Jacka et al. 2018). Similarly, reduction in K_{sat} lowers soil water infiltration, which holds the potential to facilitate an increase in biomass production (Lim et al. 2016). In poorly drained soils, an increase in K_{sat} has positive effects on soil aeration. Overall, in-depth exploration of BC's interaction with various soil types and its influence on K_{sat} is essential for improving the accuracy of computer models estimating soil water recharge and stormwater runoff.

3.4 Biochar impacts on soil infiltration

Infiltration is one of the vital soil hydrological properties affecting soil water content, water redistribution, nutrient leaching, runoff, erosion, and groundwater levels (Sun et al. 2018; Wang et al. 2017a, b). The impact of BC on infiltration, as evidenced by multiple field and modeling studies, is contingent on factors including feedstock type, production temperature, particle size of BC, and soil type (Table 2). In a study utilizing five different infiltration models, the addition of mixed tree residue BC enhanced infiltration in loamy clay soil but decreased it in sandy soil (Wang et al. 2017a). Sun et al. (2018) reported a significant alteration in soil infiltration capacity with BC particle size, noting that sieved corn straw BC of particle size ≤ 0.25 mm, produced at 450 °C, improved infiltration in coastal silty loam, likely by enhancing pores connectivity and the density of effective pores. The application of BC to different soil layers (surface layer: 0–10 cm, underlying soil: 10–20 cm and plow layer: 0–20 cm) may yield varying effects on water infiltration and evaporation. Li et al. (2016) observed that applying 1% BC to the top 10 cm of soil decreased infiltration by 12.5% while a 4% BC application rate increased infiltration by 10.6% compared to unamended soil. This variability could potentially be attributed to BC's differential effects on soil homogeneity, structure, and water flow pathways at different soil layers.

Biochar applications exhibit a dual impact on infiltration, with potential positive and negative outcomes dependent on BC properties and soil type (Table 2). Positive effects include the reduction of penetration resistance, surface crusting, and the enhancement of soil aggregation and macro-porosity (Bohara et al. 2019; Prober et al. 2014; Sandhu and Kumar 2017). For example, Bohara et al. (2019) reported that applying pinewood BC produced at 550 °C to a fine sandy loam soil at a 10% rate increased the unsaturated infiltration rate to

Table 2 Impact of BC derived from different feedstock and pyrolysis temperature on water infiltration for different soils and study types

Location	Soil	Study type	Study duration	BC type	Pyrolysis temp (°C)	BC rate	Effect	References
Israel	Loamy sand	Rainfall simulation	–	Wood chips	620	0 to 2%	1.7 fold increase in final infiltration rates	Abrol et al. (2016)
USA	Loamy sand	Incubation	96d	Pecan	700	0, 11, 22, and 44 Mg ha^{-1}	No effect	Busscher et al. (2010)
Germany	Sand and sandy loam	Rainfall simulation	–	Mango wood	600	0%, 2.5%, and 5%	Decreased	Villagra-Mendoza and Horn (2019)
USA	Sandy loam	Greenhouse	< 2 mo	Peanut hulls	500	0%, 25%, 50%, 75%, and 100%	Gradually decreased	Githinji (2014)
USA	Compacted horizon of sandy loam	Incubation	128 d	Pine chips, poultry litter and as blend	500	0%	0.095 mL min^{-1}	Novak et al. (2016)
						2%	0.165–0.22 mL min^{-1}	
USA	Fine sandy loam	Plexiglas column	8 wk	Pinewood	550	0%, 2.5%, 5%, and 10%	Increased†	Bohara et al. (2019)
Australia	Sandy loam	Field	31 mo	Acacia green waste	550	0 and 47 Mg/ha	No significant effect	Hardie et al. (2014)
Saudi Arabia	Sandy loam	Pot	5 wk	Wood	400	0%	0.763a	Ibrahim et al. (2013)
						0.50%	0.761a	
						1.00%	0.548b	
						1.50%	0.564c	
						2%	0.534d	
China	Aeolian sandy	Laboratory/PVC pots	–	Mixed trees residue (polar, elm, pagoda, and apple tree)	550	0, 10, 50, 100, and 150 g kg^{-1}	Reduced infiltration	Wang et al. (2017a, b)
	Loamy clay						Increased infiltration	
Australia	Clay loam	Field	2 yr	Tree residues	600	0 and 20 Mg ha^{-1}	Increased	Prober et al. (2014)
USA	Loam	Field plots	2 yr	Mixed hardwood (oak, elm, and hickory)	500–575	0 and 96 Mg ha^{-1}	No consistent effect	Rogovska et al. (2014)
China	Silty loam	Laboratory/Soil column	–	Corn straw (Non-sieved BC)	450	0.5%, 1%, 2%, 5%, and 10%	10% rate of non-sieved BC decreased infiltration	Sun et al. (2018)
			–	Sieved BC		1% and 10%	≤ 0.25 mm BC improved infiltration	
China	Silt loam	Rainfall simulation	–	Cotton straw	400	0%, 3%, and 5%	Infiltration rate decreased with increasing BC rate	Wei et al. (2023a, b)
USA	Portneuf silt loam	Field	6 yr	Oak and hickory hardwood sawdust		0%, 1%, 2%, 1% biochar + 2% manure	Combined 1% biochar + 2% manure increased infiltration	Lentz et al. (2019)
China	Eum-Orthric	Soil column simulation	–	Apple woods	450–480	0%, 1%, 2%, and 4%	Mixed effect	Li et al. (2016)

† Infiltration in the study refers to the unsaturated and saturated water permeability rate (cm h^{-1})

– Not available

10.65 cm h^{-1}, compared to 4.1 cm h^{-1} in an untreated soil, attributed to a decrease in BD and surface crusting. Similarly, in non-calcareous loamy sand, Abrol et al. (2016) observed increased infiltration rate with the application of 2% mixed woodchips BC produced at 620 °C as it reduced clay dispersion, surface sealing, and aggregate loss. Although BC addition improves water infiltration rate in the short-term, the increase may be transient because gradual filling of pore spaces in BC and their physical disintegration may lead to a reduction in infiltration rates over time (Novak et al. 2016). Second, BC applications could reduce infiltration by clogging soil voids. Wang et al. (2017a, b) reported reduced infiltration with tree residue BC pyrolyzed at 550 °C in aeolian sandy soils. Wei et al. (2023a, b) reported a decrease in infiltration rate with an increase in cotton straw BC amount under artificial rainfall experiments. Biochar particles are small enough to fill macro spaces of soil particles and alter soil hydraulic properties. They modify soil pore size and distribution, which has direct repercussions on percolation, residence time, and water flow paths (Atkinson et al. 2010). On the other hand, some studies reported negligible effects of BCs on infiltration. Busscher et al. (2010) observed no significant effect of pecan BC pyrolyzed at 700 °C on infiltration in a Norfolk loamy sand soil. Also, Hardie et al. (2014) observed no significant effect of Acacia green waste BC pyrolyzed at 550 °C on infiltration of sandy loam soil because of no observed change in soil porosity. Rogovska et al. (2014), however, observed inconsistent effects of hardwood BC produced at temperature between 500 and 575 °C on infiltration rates of Clarion loam soil. Overall, the impact of BC applications on infiltration rates appears to be mixed, influenced by soil type, BC particle size, production temperatures, and depth of placement. Long-term field studies are, however, necessary to validate and refine these findings. In general, BC application holds the potential to improve infiltration in loamy to clay soils, while its effects on sandy to fine sandy loams may result in decreased infiltration. Understanding these dynamics is crucial for optimizing agroecosystem management, particularly with respect to the influencing factors such as irrigation quantity and timing. The reduction in infiltration observed in sandy and sandy loam soils, as facilitated by BCs, may offer benefits in minimizing leaching losses and maximizing nutrients bioavailability. In arid and semi-arid regions, the strategic utilization of BC holds promise for conserving soil water resources by enhancing infiltration rates.

3.5 Biochar impacts on soil thermal properties

Biochars alter soil thermal properties, including thermal conductivity and diffusivity (Liu et al. 2018; Usowicz et al. 2016; Zhang et al. 2013; Zhao et al. 2016). These changes can impact soil evaporation losses (Bohara et al. 2019), soil WHC, and water movement. Generally, BCs exhibit lower thermal conductivity than soil, resulting in a reduction in soil thermal conductivity upon application (Zhao et al. 2016). Soil thermal properties are intricately linked to soil texture, BD, and soil water content (Liu et al. 2018; Zhang et al. 2016). Zhao et al. (2016) observed strong correlations between soil volumetric heat capacity and soil water content ($r=0.79$), soil thermal conductivity and soil water content ($r=0.69$), and soil thermal conductivity and soil BD ($r=0.58$). They noted a decrease in thermal conductivity with increasing corncob BC amendment in sandy loam soil. Bohara et al. (2019) observed lower soil evaporation rates under pinewood BC application compared to control plots, presumably due to the development of aggregates and soil pores. Also, the color of BCs, dependent on feedstock types and production conditions, contributed to higher thermal absorbance. The general tendency of BCs to reduce BD, coupled with their poor thermal diffusivity, leads to lower thermal conductivity in soils (Zhao et al. 2016). Zhao et al. (2016) reported that aromatic compounds formation, induced by BCs produced at temperatures below 500 °C, can lead to water repellency, potentially lowering WHC and, consequently, thermal conductivity. Biochar may also indirectly impact soil thermal conductivity and soil WHC by influencing enzymatic activity, habitat, soil microstructure, and nutrient bioavailability crucial to soil microorganisms. Overall, the effect of BC on soil thermal conductivity is a function of interactions and changes in soil BD, soil WHC, and soil thermal diffusivity.

Certain studies suggest that BC can alter soil albedo and heat fluxes, influencing soil moisture, surface energy balance, global radiative forcing, and climatic feedback (Genesio et al. 2012; Verheijen et al. 2013). Two critical factors affecting soil albedo are soil color and soil moisture content. Biochar may darken soil color based on several factors, including initial soil color, BC color, application rate, surface roughness, and soil water retention characteristics (Verheijen et al. 2010). Therefore, in bare soil, BC amendments could potentially reduce albedo. Lower albedo generally means higher soil temperature, and vice versa. Global energy balance models indicate that applying BC at 120 t ha^{-1} to global croplands could reduce the negative radiative forcing of farmlands by 5% (Verheijen et al. 2013), suggesting the climate change mitigation potential of BCs. The soil albedo may decrease with increasing BC rates, dependent on soil water content (Usowicz et al. 2016). However, Genesio et al. (2012) observed no significant difference in albedo as BC rates increased from 30 to 60 t ha^{-1}. While there are opportunities to mitigate albedo effects of BC through soil management practices like deep tillage and incorporation into the topsoil, it is crucial to acknowledge that such management regimes could exacerbate water loss, nutrient leaching, and carbon mineralization and emissions.

3.6 Biochar impacts on soil water holding capacity

The impact of BC on soil WHC exhibits variability, ranging from short-term to long-term effects, depending on BC properties and soil types. Many researchers have consistently reported an increase in soil WHC following BC applications (Table 3) in multiple field-based studies (Karhu et al. 2011; Liang et al. 2014) and laboratory investigations (Bohara et al. 2019; Duong et al. 2017; Igalavithana et al. 2017; Jones et al. 2010). Biochar has been documented to increase soil WHC at a rate of as high as 4 Mg ha^{-1} (de Sousa Lima et al. 2018). However, some studies indicate improvements in WHC only at higher BC rates, reaching 20 Mg ha^{-1} or beyond (Amoakwah et al. 2017; Siltecho et al. 2022). This increase in WHC is primarily governed by two mechanisms, as discussed earlier: (i) an increase in soil-specific surface area and (ii) an increase in soil porosity. Further, the water retention capacity of the soil is influenced by the soil texture, the type of feedstock, and the rate of BC applications (Dugan et al. 2010; Gunal et al. 2018). In a recent meta-analysis by Wei et al. (2023a, b), the assessment of BC's impact on soil water retention across various textures revealed a notably greater influence on field capacity (23.8%) and available water capacity (25.6%) in coarse-textured soils compared to medium (5%, 20.9%) and fine (7.2%, 11%) textured soils, emphasizing the textural dependency of BC effects. In an organically managed farm, Karhu et al. (2011) showed that 9 Mg ha^{-1} BC application, a by-product of birch produced at 400 °C, increased soil WHC by 11% compared to control plots in the same application year. Indeed, BC application could increase soil WHC by reducing BD (Githinji 2014; Novak et al. 2016; Usowicz et al. 2016), increasing porosity (Abel et al. 2013; Gamage et al. 2016; Obia et al. 2016), increasing surface area (Laird et al. 2010), and promoting soil aggregation (Blanco-canqui et al. 2020; Herath et al. 2013), especially in coarse-textured soils.

A few studies also demonstrate the positive effects of BC on WHC in fine-textured soils. For example, bamboo-derived BC pyrolyzed at 600 °C exhibited an increased water retention capacity in low plastic clay soil, potentially attributed to an increase in smaller pores (Yadav and Bag 2023). Additionally, some studies have shown that a BC-mediated increase in WHC can positively influence soil functions and crop productivity (Bohara et al. 2019; Glab et al. 2018; Liu et al. 2016). According to Bohara et al. (2019), an increased soil WHC leads to a reduction in water stress and a subsequent decrease in irrigation water requirement by lowering evaporation loss during surface irrigation. These factors collectively contribute to an increase in plant available water and crop yield (Jeffery et al. 2011). Generally, BCs may potentially increase PAW (Table 4) and crop yields in soils characterized by low WHC, such as sandy to loamy sand soils (Obia et al. 2016). For example, Aller et al. (2017) reported an increase in PAW and soil water retention with fresh BC produced from corn stover, switchgrass, soybean, and hardwoods at temperatures ranging from 500–600 °C in sandy loam soil. The impact of BC on PAW varies depending on whether it is applied as a single treatment or through reapplication. In the silty loam soils of Slovakia, a single application of 10 t ha^{-1} and 20 t ha^{-1} of BC, derived from cereal husks and paper fiber sludge at a pyrolysis temperature of 550 °C, led to improvements of 8–51% and 18–21%, respectively, while reapplication further enhanced PAW by 18–34% (10 t ha^{-1}) and 19–31% (20 t ha^{-1}) (Tokova et al. 2023).

The impact of BC on PAW is a function of BC's particle size, shape, and internal structure. Finer particles of BC may mix more effectively with the soil than coarser particles, positively impacting soil pore size distribution and PAW. Liao and Thomas (2019) demonstrated a substantial increase in water retention capacity (91–258%) with sieved sugar maple wood BC in comparison to ground BC of equivalent particle size. This enhancement was attributed to the elongated particles of the sieved BC, leading to an augmentation of soil interpore volume. A study by Liu et al. (2017a, b) on the effect of mesquite BC pyrolyzed at 400 °C on soil water retention curves indicated that particle size modifies inter-pores and adds intra-pores to alter soil water content. Pores within BC (intra-pores) control water retention at lower suctions, increasing field capacity, permanent wilting point, and PAW for medium and coarse BC-sand media. Additionally, inter-pores regulate water retention at higher suctions in fine BC-sand media (Liu et al. 2017a, b). Therefore, BC-induced changes in WHC and PAW are often associated with BC properties, pore morphology and distribution, and soil aggregation (Mukherjee and Lal 2013).

The physical characteristics of BCs often serve as prime factors controlling WHC in diverse soils. As a result, soil WHC depends on the type of material used to produce BC and the conditions applied for pyrolysis. Water absorption rates increase with prolonged BC gasification conversion times under high-temperature pyrolysis, such as in the case of peanut shell and palm kernel shell BC pyrolyzed at 900 °C, possibly due to higher pore volume (Bikbulatova et al. 2018). The internal porosity of BC and grain-to-grain interaction frequently contribute to an increase in WHC (Barnes et al. 2014). Further, certain additive compounds

Table 3 Impact of BC derived from different feedstocks and pyrolysis temperature on WHC across different soils

Location	Soil	Study type	Study duration	BC type	Pyrolysis temp (°C)	BC rate	WHC (%)	Effect	References
Denmark	Sandy	Pots/Greenhouse-		Wheat straw	500	0%, 1%, 2%, and 3%		Increased	Ahmed et al. (2016)
Canada	Loamy Sand	Column and incubation	6 wk	Switchgrass	300,400	0%,1% and 2%		Increased	Mohamed et al. (2016)
USA	Loamy sand	Incubation	96d	Pecan	700	0, 11, 22, and 44 Mg ha^{-1}		Mixed	Busscher et al. (2010)
USA	Loamy Sand		-	Eastern hemlock and switchblade grass				Increased	Yu et al. (2017)
USA	Sandy loam	Columns, incubation	91 d	Red-oak	500	0%, 3% and 6%		Increased	Basso et al. (2013)
USA	Loamy sand	Lab	~3d	Yellow pine scrap lumber	400	0% to 100%		Increased	Yu et al. (2013)
Korea	Sandy loam	Incubation	~1 mo	Dried corn residue	500	0%	30.1c		Igalavithana et al. (2017)
						2%	37.0b	Increased	
						5%	35.7bc		
						7.5%	39.6ab		
						10%	43.3a		
Saudi Arabia	Sandy loam	Pot	5 wk	Wood	400	0%			Ibrahim et al. (2013)
						0.5%		Increased	
						1.0%			
						1.5%			
						2%			
Ghana	Sandy loam, silt loam, and loamy sand	Lab	~2d	Sawdust, maize stover and charcoal	420 and 450	0, 5,10 and 15 Mg ha^{-1}		Increased	Dugan et al. (2010)
Spain	Sandy loam	Greenhouse	2 mo	Greenhouse plant debris	500	600 g soil, 200 g marble sludge + 400 g soil, and 150 g marble sludge + 50 g BC + 400 g soil		Increased	Salinas et al. (2018)
	Sandy								
UK	Sandy loam	Lab/ incubation	~8 wk	hardwood (oak, cherry and ash)	400	Field moist control	61.0a	Increased	Case et al., (2012)
						0%	61.0a		
						1%	65.0a		
						2%	65.0a		
						5%	68.0b		
						10%	73.0b		
China	Silt loam	Field mesocosm	~7 mo	Maize straw	400	0, 48 Mg ha^{-1}		Increased	Liu et al. (2017a, b)
Finland	Silt loam	Field	-	Birch-charcoal		0	0.49		
					400	9 Mg ha^{-1}	0.54	Increased	Karhu et al. (2011)
China	Loamy	Field plot	–	Mixed crop straw	500	16 Mg ha^{-1}		Increased	Liu et al. (2016)
China	Fluvisols with 17.3 g/kg of CaCO3 on the surface	Field	3 yr	Rice husk and shell of cotton seed	400	WM† (0 Mg ha^{-1})	285c	Increased	Liang et al. (2014)
						WM-F††	295bc		

Table 3 (continued)

Location	Soil	Study type	Study duration	BC type	Pyrolysis temp (°C)	BC rate	WHC (%)	Effect	References
						WM-F-30 Mg ha^{-1}	291bc		
						WM-F-60 Mg ha^{-1}	320ab		
						WM-F-90 Mg ha^{-1}	321a		
Vietnam	Gray soil	Lab	28 d	Rice husk	550	0%	19.5d	Increased	Duong et al. (2017)
						1%	26.1 cd		
						3%	29.1c		
						9%	56.5a		
				Coffee husk		1%	24.7 cd		
						3%	30.9c		
						9%	46.9b		
	Basalt			Rice husk		0%	70.6e		
						1%	75.6 cd		
						3%	78.5c		
						9%	79.8c		
				Coffee husk		1%	73.8de		
						3%	86.1b		
						9%	101a		
Brazil	Quartzarenic Neosols		140 d	Green coconut shells, orange peel, oil palm bunch, sugarcane bagasse and water hyacinth	350	5%		Increased	Mangrich et al. (2015)
Australia	Bauxite-processing residue sand	Lab	6 wk	Municipal green waste	450	40 and 80 Mg ha^{-1}		Increased	Jones et al. (2010)
India	Nutrient poor	Field	-	Rice husk	250–300	10 Mg ha^{-1}		Increased	Singh et al. (2018)

– Not available; †wheat and maize straw incorporated separately; †† wheat and maize straw with inorganic chemical fertilizer

during the pyrolysis process could enhance the porosity and WHC of the resulting BC. Mohamed et al. (2016) observed increased porosity (micropore volume increased by > 1400%) and, consequently, higher WHC with switchgrass BC. Also, water retention increases with oxidation of the BC surface. In a microcosms study, Suliman et al. (2017) used the molarity of ethanol droplet test and reported higher hydrophilicity in BC produced from pine wood at high-temperature pyrolysis (600 °C) compared to pine bark BC produced at low temperature (350 °C). The particle size of the BC can significantly affect WHC, influencing surface area and exposure of internal pore space. Liao and Thomas (2019) reported maple wood BC produced at 363–374 °C with particle size of 0.06 mm to 0.5 mm exhibited 91 to 258% higher WHC compared to BC with a particle size of 2 mm to 4 mm.

Porosity and surface area remain pivotal controlling factors in determining soil WHC but additional factors such as CEC and negative zeta potential also contribute to enhancing the soil WHC (Batista et al. 2018). The diverse surface functional groups of BCs are influenced by the feedstock used and production conditions, exerting a significant impact on BCs' WHC. Kinney et al. (2012) established a positive correlation between hydrophobicity and alkyl functional groups in BC. The varied functional groups facilitate the retention of nutrient and water on BC surfaces. Biochars are characterized by a predominant aromatic C structure, encompassing both aromatic (amorphous phase) and polyaromatic rings (crystalline

Table 4 Impact of BC derived from different feedstocks and pyrolysis temperature on PAW across different soils and study types

Location	Soil	Study type	BC type	Pyrolysis temp (°C)	BC rate	Effect on PAW	References
China	Sandy	Indoor simulation	Cotton straw	400	0%, 1%, 2%, 4%, and 6%		Pu et al. (2019)
Ghana	Sandy loam	Field	Corn cob	500–550	0, 10 and 20 Mg ha^{-1}	–	Amoakwah et al. (2017)
China	Sandy loam	Field (measured after 8 yr)	Maize cob	360	0, 4.5, 9 Mg ha^{-1}	Increased by 10% and 18% under 4.5 and 9 t ha^{-1}, respectively	Zhou et al. (2018)
USA	Sandy loam	Greenhouse	Corn stover, switchgrass, soybean and hardwood	500–650	1% w/w (field rate 22 Mg ha^{-1})	Increased under fresh BC but no effect under aged BC	Aller et al. (2017)
	Silt loam					No effect for both BC	
	Clay loam					Decreased PAW for both BC	
Turkey	Sandy loam	Greenhouse	Rice husks, common bean, corn cobs	500	0%, 0.5%, 1%, 2%, and 3% (field rates 0, 11.25, 22.5 45 and 67.5 Mg ha^{-1})	–	Gunal et al. (2018)
	Loamy					–	
Iberian Peninsula	Loamy	Field (measured after 15 mo)	Miscanthus	450	0, 3.5 and 10 Mg ha^{-1}	No effect	Moragues-Saitua et al. (2017)
	Sandy loam				0, 10, and 20 Mg ha^{-1}	No effect	
Ghana	Sandy	Field study (after 3 and 15 mo)	Rice straw	550	3%	–	Arthur and Ahmed (2017)
Saudi Arabia	Desert soil/sandy	Column/incubation	Date palm tree residues	300,400, 500, 600	0, 50 t ha^{-1}		Alotaibi and Schoenau (2019)
Germany	Sand	Lab	Mango-wood	600	0%, 2.5%, and 5%	Increased with increasing rate	Villagra-Mendoza and Horn (2018)
	Sandy loam					Increased at 5% rate only	
Brazil	Sandy	Greenhouse	Coffee husks	530	4, 8, 12, and 16 Mg ha-1	Increased	de Sousa Lima et al. (2018)
Brazil	Sandy loam	Greenhouse	Eucalyptus bark	350	0, 5, 10, 20, 40, 60 g kg^{-1}		Tanure et al. (2019)
Poland	Loamy sand	Pot	Willow	350	0.5%, 1%, 2% and 4%	Increased	Glab et al. (2018)
Poland	Loamy sand	Pot	Miscanthus and wheat straw	300	0, 5, 10, 20, 40 g kg^{-1}	–	Glab et al. (2016)
USA	Maddock and Brookings (sandy and fine-silty)	Field	Corn stover, Ponderosa pine and switchgrass	150–850	10 Mg ha^{-1}	–	Sandhu and Kumar (2017)
USA	Caplis very fine sandy loam	Lab	Pinewood	550	0%, 100%, 2.5%, and 5%	Increased	Bohara et al. (2019)
Denmark	Sandy and sandy loam	PVC pots	Wheat straw and pine wood	750 and 1200	0% and 1%	Increased	Hansen et al. (2016)

Table 4 (continued)

Location	Soil	Study type	BC type	Pyrolysis temp (°C)	BC rate	Effect on PAW	References
Germany	Sand, loamy sand	Column and field	Feedstock maize and beachwood	750, 550	0%, 1%, 2.5%, and 5%	Increased	Abel et al. (2013)
USA	Sandy loam	Columns	Red-oak	500	0%, 3% and 6%	Increased	Basso et al. (2013)
Australia	Sandy loam	Field	Acacia green waste	550	0 and 47 Mg ha^{-1}	No effect	Hardie et al. (2014)
Hong Kong	Clay	Lab	Peanut shell	500	0%, 5% and 20%	–	Wong et al. (2017)
Brazil	Sandy, and clay loam	Lab	*Miscanthus*	450	6.25, 12.5, 25 Mg ha^{-1}	Increased	de Jesus Duarte et al. (2019)
China	Clay loam	Field	Maize straw and peanut hulls	n/a	0, 7.8 Mg ha^{-1}	Increased	Ma et al. (2016)
China	Clay loam	Lab	Straw, woodchips, wastewater sludge	500	0%, 2%, 4%, and 6%	No effect	Zong et al. (2016)
USA	Sandy loam and clay loam	Lab	Corn stover and switchgrass	650 (fast pyrolysis), 400 to 800 (slow)	0, 104 Mg ha^{-1}	Increased	Mollinedo et al. (2015)
China	Loam	Field	Mixed crop straw	500	0, 16 Mg ha^{-1}	No effect	Liu et al. (2016)
China	Loam	Field	Maize straw	400	0, 10, 20, 30 Mg ha^{-1}	–	Xiao et al. (2016)
USA	Portneuf silt loam	Field	Oak and hickory hardwood sawdust	500	0%, 1%, 2%, 1% BC + 2% manure	Increased; 1% BC + 2% manure had largest effect	Lentz et al. (2019)
Brazil	Sandy clay loam	Lab incubation	Sugarcane filter-cake	575	0%, 5%, and 10%	Increased	Eykelbosh et al. (2014)
Ghana	Sandy clay loam	Field	Rice straw	550	0, 15, 30 Mg ha^{-1}		Obour et al. (2019)
USA	Silt loam and Fine sandy soil	Lab and field	Softwood and walnut shell	600–700, and 900	0, 10 and 20 Mg ha^{-1}	Increased under walnut BC at 10 and 20 Mg ha^{-1} rates in sandy soil No long-term effect of walnut BC in silty loam under field condition	Wang et al. (2019)
Taiwan	Mudstones	Lab incubation	Rice hull	400	0%, 2.5%, 5%, and 10%	Increased	Hseu et al. (2014)
China	Frozen soil (50% sand, 36% silt, 14% clay)	Field	Corn straw	500	0, 3, 6, 9, 12 kg m^{-2}	Increased	Fu et al. (2019)

– Not available

phase) (Brewer et al. 2014; Keiluweit et al. 2010). The presence of polar oxygen-containing functional groups increases hydrogen bonding, thereby enhancing the WHC of BCs. Suliman et al. (2017) reported a positive relationship between total acidic functional groups and soil WHC. During pyrolysis and gasification at very high temperatures, the decomposition of functional groups may occur in biomass, potentially minimizing BCs' interaction with water (Bikbulatova et al. 2018). Understanding these intricate relationships between BC properties and WHC is crucial for optimizing soil management practices and enhancing water retention in agricultural systems.

Additionally, management factors, such as the depth and method of BC applications, also play a crucial role in affecting soil WHC. The mechanical disturbance of soil may stimulate the decomposition of BCs by exposing them to the surface of soil aggregates and increasing their availability to microorganisms (Kuzyakov et al. 2009). This process can consequently reduce aggregation and porosity, essential for water retention. Basso et al. (2013) observed that uniform surface application with topsoil mixing of BC resulted in a reduction of drainage loss of water and, therefore, improved water retention compared to deep and band application of BC.

A few studies also report no significant effect of BC on soil water retention. In a long-term field experiment, Wang et al. (2019) found that BC application had no significant impact on water retention in silty clay loam soil after six years of management, compared to control plots. This lack of impact was attributed to decreased porosity resulting from the infilling of BC pores with smaller particles. Similarly, another field study involving Miscanthus BC pyrolyzed at 450 °C observed no effect of BC on loamy and sandy loam soils (Moragues-Saitua et al. 2017). Overall, studies indicate that BC has the potential to improve water retention in coarse and medium-textured soils, with minimal effect in fine-textured soils. This increase in water retention with BC amendment is particularly beneficial for minimizing water stress in non-irrigated crops under rainfed cultivation, especially in arid and semi-arid regions (Herath et al. 2013).

4 Research gaps and opportunities

While the application of BC has demonstrated significant benefits for soil health and sustainability, challenges associated with large-scale production and agricultural utilization pose potential impediments. The scale-up of BC production and its incorporation into agriculture can be hindered by the considerable time and cost involved. Additionally, transportation costs associated with moving biomass to pyrolysis facilities and distributing end products to farmland present logistical challenges. The pyrolysis process, integral to BC production, has the potential to generate harmful chemicals such as polycyclic aromatic hydrocarbons (PAH), cresols, xylenols, and acrolein ash. The impact of these by-products on public health and soil ecosystems necessitates thorough investigation. Furthermore, the use of heavy machinery for BC application or the utilization of finer BC may induce soil compactions, thereby altering infiltration rates and WHC. This emphasizes the need for a comprehensive understanding of the potential field impacts of different BCs to optimize water use efficiency and prevent degradation of croplands. Overall, there are several research gaps that need to be addressed by future research to improve our understanding of soil water dynamics in BC-amended soils.

(i) The majority of studies examined in the review are laboratory-based, with only a limited number of field studies available, and these tend to be predominantly short-term (1–2 years). Also, several inconsistent results are evident between field and laboratory studies, arising from variations in soil properties and environmental conditions (Edeh et al. 2020). Therefore, there is a critical need for further long-term field-based investigations spanning diverse management regimes, soils, and pedoclimatic conditions to comprehensively understand the behavior and effects of BC on water dynamics. Long-term studies should extend their focus beyond near-surface soil properties, delving into deeper layers, while also investigating the differential effects of single versus multiple applications on soil hydrological properties. Additionally, large-scale applications of BC require careful consideration to minimize disturbance to both soil physical properties and biota. Environmental aspects like surface runoff and nutrient leaching to groundwater should also be considered. Overall, the potential enhancements in soil water dynamics through BC amendment offer promising opportunities to reduce irrigational water use in agricultural systems and to revitalize or rehabilitate degraded croplands.

(ii) A comprehensive understanding of how BC impacts soil water availability necessitates a deeper exploration of field capacity and wilting point dynamics. Unfortunately, limited long-term studies addressing these soil quality indicators and/or water characteristics impede our ability to unravel the intricate mechanisms governing BC's influence on soil water availability for optimal plant water use (Razzaghi et al. 2020), highlighting the need for additional scientific inquiry in this crucial domain. Advanced tools such as stable water isotopes (^{18}O and ^2H) and drones with multispectral, hyperspectral, or thermal remote sensing enable precise assessment of crop water status and soil water distribution, offering valuable insights into field-scale responses to BC amendments (Acharya et al. 2021; Fischer et al. 2019).

(iii) The dynamic impact of BC on soil properties is likely attributed to variations in size, intra-porosity, and hydrophobicity. Currently, the available research is inadequate to comprehensively elucidate how water retention modifies the fate of BC within the vadose zone and its interaction at the plant-soil interface across varying temporal and spatial scales (Lehmann et al. 2011). Also, there is a notable gap in understanding the interplay between water and BC, as well as the influence of BC structure on WHC. Therefore, it is imperative to undertake additional studies focusing on the mechanisms governing water retention in BC-amended soils. Similarly, the temporal evolution of BC properties during aging necessitates long-term field studies to elucidate how BC properties change after a single BC application and how this transformation influences soil water dynamics (Edeh et al. 2020).

(iv) Research on the interactions between BC and microorganisms in soils has predominantly centered around small-scale laboratory incubation and greenhouse pot experiments. There is a compelling need to shift focus towards large-scale field trials (Palansooriya et al. 2019). The interrelationship between WHC and the microbial community under BC applications is not well-understood. Future research should aim to unveil and address the potential effects of soil microorganism activity, abundance, and diversity on WHC.

(v) While BCs increase PAW and WHC due to an increased specific surface area and increased volume of mesopores and macropores, in some cases, BCs become hydrophobic. More studies on water repellency at the molecular level, encompassing a range of BC and soil types, are necessary.

(vi) The importance of soil water dynamics in BC-amended soils under future climate change, and their interconnections with plant water use, irrigation management, tillage systems, and crop rotation deserves considerable attention.

5 Summary

Agricultural water demand for on-farm irrigation is on the rise, driven by the expansion of arable land and changes in global, regional, and localized hydrological cycles. Therefore, management practices that improve irrigation water-use efficiency, soil water retention, and crop productivity are essential. Biochar, as a soil amendment, holds the potential to significantly influence soil water dynamics, and the magnitude of these impacts is dependent on factors such as feedstock, pyrolysis temperature, and soil type. Biochar application generally increases porosity, soil water retention, and PAW, but reduces K_{sat} in coarse-textured soils such as sand, loamy sand, and sandy loams. Biochar amendment may increase infiltration in clay loam soils and decrease infiltration in sandy loam soils. Biochars appear to have a mixed effect on soil water repellency, although studies are very few. Overall, the positive impact of BC on soil functions, particularly soil water dynamics, bears significant implications for irrigation and nutrient management in agricultural systems. There is a critical need for more long-term, field-based studies encompassing diverse management regimes, pedoclimates, and soil types to better inform the effects of different kinds of BC on soil hydrology. Additionally, the impact of BC on soil thermal properties warrants further investigation. Overall, BC applications should be more targeted, accounting for the specific characteristics of sites, soil types, and BC properties.

Supplementary Information

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Additional file 1: Table S1. Impact of BC derived from different feedstocks and pyrolysis temperatures on soil bulk density and porosity for different soils.

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Competing interests

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