scientific reports

Check for updates

OPEN

Spent coffee waste-derived biochar improves physical properties, water retention, and maize (*Zea mays* L.) growth in sandy soil

Abdulaziz G. Alghamdi✉**, Abdulrasoul Alomran, Hesham M. Ibrahim, Arafat Alkhasha & Mosaed A. Majrashi**

Adding organic soil amendments can improve the physical and hydrological properties of soil, subsequently enhancing fertility for better crop production. In this study, spent Arabica and Columbian coffee wastes and their respective biochars were evaluated as soil amendments to improve the physical and hydrological properties of loamy sand soil and enhance maize (*Zea mays* L.) crop growth. Spent Arabica coffee (AC) and Columbian coffee (CC) wastes were collected and transformed into biochar through pyrolysis process at 550 °C with a residence time of 3 h and pyrolysis rate of 5 °C per minute. The AC and CC derived biochar were termed as ABC and CBC, respectively. The produced soil amendments were applied to soil at 0% (control), 1%, 3%, and 5% in a column setup. The moisture characteristics, including water infiltration, evaporation, and water retention, were investigated. Thereafter, the prepared amendments were applied to loamy sand soils at 0% (control), 1%, 3%, and 5% (w/w) application rates. Maize growth was then observed for a period of 30 days under greenhouse conditions. Results of the column trials showed that ABC and CBC applied at 5% reduced the cumulative water evaporation by 57%–66% and cumulative infiltration by 124%–181% compared to control. Likewise, 5% application of ABC and CBC resulted in 101 to 130% higher water retention in loamy sand soil. Results of the greenhouse experiment showed that 5% application of ABC and CBC amendments resulted in root biomass of 2.12 and 2.38 g, respectively, as compared to 0.51 g in control treatment. Similar treatments resulted in shoot biomass of 9.70 and 9.93 g respectively, as compared to 7.37 g in control. Likewise, 5% application of CBC and ABC increase plant height from 15.71 to 30.94 cm in ABC and 33.23 cm in CBC. Overall, 5% application of coffee waste-derived biochars significantly reduced water evaporation and infiltration, while increasing soil water retention and maize plant height, root biomass, and shoot biomass. Therefore, spent coffee waste-derived biochar could effectively be employed to improve physical and hydrological properties of loamy sand soils for better crop productivity.

Keywords Water conservation, Infiltration and evaporation, Maize growth, Waste-derived biochar, Arid regions

A general concept of soil quality describes the "capacity of soil to function in a natural or controlled ecosystem for sustainable biological and agricultural productivity, better environment quality, and viable fauna and flora health"[1] Soil quality is crucial in assessing soil's environmental impact, such as soil erosion and degradation, and ascertaining managing practices for sustainable land use for agricultural practices and other soil-related activities. Several parameters are responsible for optimizing better soil quality, including soil moisture regulation, nutrient retention and bioavailability, soil structure, soil texture, bulk density, and soil aeration[2]. Sandy soils are typically characterized by a high percentage of sand, a coarse texture, poor aggregate stability, and a lower water table, ultimately leading to lower soil moisture. Additionally, these soils have low organic matter and nutrient availability, high soil temperature, and low fertility. According to an estimate, about 6% of global soils (900 million hectares) are naturally sandy[3]. In contrast, non-natural sandy soils result from anthropogenic activities, climate change, and intensive agricultural activities[4]. Rigorous agricultural activities generally result in infertile soil with

Soil Sciences Department, College of Food and Agricultural Sciences, King Saud University, P.O. Box 2460, 11451 Riyadh, Saudi Arabia. ✉email: agghamdi@ksu.edu.sa

exhausted nutrients, while climate change affects the water cycle in soil and deteriorates water dynamics and soil moisture. Water regulation and nutrient availability in sandy soils are significant concerns that the scientific community and policymakers need immediate attention.

Restoration of natural and non-natural sandy soils to their original productive level would be a lucrative development[5]. Making sandy soil suitable for farming requires a considerable amount of external input, such as organic and inorganic fertilizers and soil amendments. Coarse textured soil usually requires a higher application of inorganic fertilizers, which is not an ideal scenario for an ordinary farmer since higher application of inorganic fertilizers not only increases production cost but also results in secondary pollution due to abundant nutrient loss by soil leaching, surface run-off, and volatilization[6]. On the other hand, commonly practiced organic fertilizers and soil amendments face numerous challenges, including massive and continuous application throughout the cropping season, a higher decomposition rate, and quick mineralization in the small cropping season[7]. A possible solution could be the application of a more stable organic material. Recently, biochar has gained desirable attention as an organic soil amendment since it has excellent soil stability, better nutrient-holding ability, and a hydrophilic nature[8].

Biochar is a solid carbonaceous material obtained through the pyrolysis of organic materials[9]. It has excellent sorptive characteristics, porous surface, a higher specific surface area, excellent recalcitrant potential, aromatic crystalline carbon structures, and a plausible potential to improve soil quality and remove soil and water-borne pollutants[10]. Biochar is a relatively new development and got the ultimate attention of the scientific community as a feasible and sustainable soil management practice to improve soil physical and chemical properties and remove many organic and inorganic pollutants[11]. In addition to soil abiotic parameters, biological parameters (microorganisms) showed promising responses towards biochar addition as a soil amendment, including increased microbial biomass and more activity. Previous research showed biochar's positive effects on crop production by ensuring essential nutrient availability and improving soil structure, ultimately improving soil moisture and water permeability[12]. Scientists have stated a significant increase in maize (*Zea mays* L.) production by applying biochar at 10–15 t ha^{-1}[13]. The higher yield of maize was mainly due to a sufficient supply of essential nutrients, especially phosphorus.

Biochar characteristics and field performance largely depend on feedstock type and thermal treatment. Coffee is a significant socio-economic crop that has a tremendous global history. The Kingdom of Saudi Arabia showed great potential in meeting global consumption of coffee by producing 80.07 thousand tons of coffee annually[14]. Spent coffee waste, which is the powdered remnants of coffee extracted from beans, is an efficient adsorbent and has diverse soil and aquatic applications, including pollutant remediation, proper metal extraction, and a barrier to pesticide mobility in the soil and aquatic environment[15]. Using spent coffee waste as feedstock to produce biochar has been reported to have promising effects on soil physical quality, improving crop productivity, and plummeting metal toxicity[16].

Sandy soils pose significant challenges for sustainable agriculture, especially in arid and semi-arid regions like Saudi Arabia. These soils typically have poor water retention, nutrient deficiency, and are subjected to harsh climatic conditions. Biochar derived from spent coffee waste could offer a promising solution to improve soil properties and moisture retention, thereby enhancing crop growth. This represents a novel approach to addressing the limitations of sandy soils and improving crop production in such environments through the cost-effective utilization of waste materials. In this perspective, this research was designed to transform spent coffee waste into biochar. The raw, spent coffee waste and derived biochar were applied to a loamy sand soil to investigate the impacts of such soil amendments on the hydro-physical characteristics of soil and maize plant growth.

Material and method

Preparation of biochar

Spent coffee waste was collected from coffee shops in Riyadh. Briefly, the spent coffee waste comprised Arabica coffee (AC) and Columbian coffee (CC). The collected samples were washed with deionized water (DI) to remove impurities, air-dried, grinded, and sieved by a 2-mm size aperture and stored in an air-tight container. Additionally, the moisture content of coffee waste samples was analyzed by oven drying at 105 °C until constant weight was achieved. A slow pyrolysis process produces biochar. The spent coffee waste was pyrolyzed at 550 °C in a digital muffle furnace (Wisetherm FH14, Germany) with a residence time of 3 h and 5 °C per minute temperature rise. Freshly produced biochar was collected, cooled, grinded, and sieved through a 1 mm mesh aperture, stored in an air-tight container, and tagged as ABC (Arabica-coffee waste-derived biochar) and CBC (Columbian-coffee waste-derived biochar).

Characterization of biochar

The biochar produced and their feedstocks (coffee waste) were analyzed to interpret physio-chemical characteristics. The pH, electrical conductivity (EC), and cation exchange capacity (CEC) were determined by following standard procedures[17]. Briefly, the pH and EC values of the produced biochar and feedstock were determined in a solid-to-DI water ratio 1:10 (w/v) suspension. The functional groups were assessed with FTIR (Bruker Alpha-Eco ATR-FTIR, Bruker Optics, Inc).

Soil samples: collection and preparation

Soil samples (agricultural soil) were collected from the Derab Agriculture Research Center, King Saud University. Collected soil samples were stored in air-tight bags and shifted to the laboratory for physio-chemical analyses. The soil samples were air-dried and sieved through a 2 mm sieve. Sieved soil samples were analyzed chemically (pH, electrical conductivity, cation exchange capacity, cations, and anions) following standard procedures[17]. A soil suspension was prepared at a 1:2.5 ratio (w/v). The prepared suspension was analyzed for pH using a pH meter (WTW-pH 523) and electrical conductivity (EC) by EC meter (YSI Model 35). Soil texture was determined by following Bouyoucos's[18] method.

Column experiment

Transparent plastic columns were used in this study. The internal diameter of the columns was 5 cm, and the length was 40 cm. The columns were closed from the bottom to avoid the loss of soil. The soil was filled into the columns to 30 cm height. The untreated soils were added in each column with a bulk density of 1.4 g/cm^3 (825 g of soil), while the treated soils with biochar were added with a bulk density of 1.4 g/cm^3 (550 g of soil). The soil was amended with the soil amendments (AC, CC, ABC, and CBC) at 0%, 1%, 3%, and 5% (0 g, 10 g, 30 g, and 50 g of either AC, CC, ABC, and CBC per kg of soil). The soil mixed with amendments was filled on the top 10 cm height of the column. A control treatment was added without amendments, and all treatments were performed in triplicate. All the columns were arranged in a completely randomized design and placed vertically under 22 °C ± 2 °C. Twenty-five mL of tap water was added weekly to complete 5 wetting/drying cycles. The soil columns' weight was measured daily to estimate the cumulative evaporation. After 5 weeks, the soil columns were cut into number of segments at 2.5-cm intervals up to a depth of 10 cm, followed by 5-cm intervals afterward. The gravimetric method was used to determine the soil's water contents and lateral movement of water. Cumulative evaporation and water content data were used to estimate water retention in soil. A mini disk infiltrometer (M12, 2-cm suction; Decagon Devices, Pullman, WA, USA) was used to analyze water infiltration in soil. The constant head method was used to determine the saturated hydraulic conductivity of soil.

Greenhouse experiment

A greenhouse experiment investigated the effects of added soil amendments on the growth of maize (*Zea mays* L.) plants. This study was carried out according to the national and international guidelines for collecting plant samples. Moreover, it followed the guidelines outlined in the IUCN Policy Statement on Research Involving Species at Risk of Extinction and the Convention on the Trade in Endangered Species of Wild Fauna and Flora. Plastic pots (13.2 cm inside diameter and 14.0 cm height) were selected; each pot was filled to a height of 11.0 mm with 2500 g soil, already sieved by a 2 mm sieve. Amendments (AC, CC, ABC, and CBC) were added at four different application rates, which were 0% (CK), 1% (AC1, CC1, ABC1, and CBC1), 3% (AC3, CC3, ABC3, and CBC3) and 5% (AC5, CC5, ABC5, and CBC5). Maize was used as a test crop. 10 seeds of maize were sown in each pot after amending the soil with the prepared amendments. The soil moisture was adjusted at field capacity throughout the experiment, and pots were irrigated with tap water. The changes in water contents at room temperature were measured daily for 30 days. A control treatment was added without amendments, and all treatments were performed in triplicate. Plants were harvested after 30 days of germination and were analyzed for growth parameters. Pots were irrigated with tap water before harvesting to avoid damaging plant roots. Initially, plant height and fresh weight were determined, and later, plant samples were oven-dried at 60 °C until a constant weight, and the dry weight was measured.

Statistical analyses

The obtained data were statistically analyzed using a computer software Statistix 8.1 and Microsoft Excel. The original data were presented using the means of three replicates and standard deviations. The influence of the various treatments was compared using the Least Significant Difference (LSD) test with a 5% probability level[19].

Results and discussion

Characteristics of soil, coffee waste, and biochar

Physio-chemical properties of the soil, spent coffee waste, and produced biochar used in this study are shown in Table 1. The results showed that the soil was loamy sand in texture with a slightly acidic pH (6.37). The EC of the soil was 3.22 dS m^{-1}, with higher SO_4^{2-} (4.75 meq L^{-1}) and Ca^{2+} (18.33 meq L^{-1}) concentrations. The CEC

Parameters	Unit	Soil	AC	CC	ABC	CBC
Texture	–	Loamy sand	–	–	–	–
pH	–	6.37	4.68	4.55	9.42	8.86
Electrical conductivity	dS m^{-1}	3.22	1.47	2.17	4.46	4.74
Cation exchange capacity	cmol kg^{-1}	23.14	19.21	20.01	14.91	15.00
Ca^{2+}	meq L^{-1}	18.33	5.22	5.44	–	–
Mg^{2+}	meq L^{-1}	8.33	5.78	7.56	–	–
Na^{+}	meq L^{-1}	4.87	0.12	0.51	–	–
K^{+}	meq L^{-1}	0.82	5.18	9.91	–	–
Cl^{-}	meq L^{-1}	7.33	7.22	7.67	–	–
HCO_3^{-}	meq L^{-1}	0.27	0.27	0.27	–	–
CO_3^{-}	meq L^{-1}	0.00	0.00	0.00	–	–
SO_4^{2-}	meq L^{-1}	24.75	8.81	15.48	–	–

Table 1. Selected physio-chemical properties of soil, Arabica coffee waste (AC), Colombian coffee waste (CC), AC-derived biochar (ABC), and CC-derived biochar (CBC).

of the used soil was 23.14 cmol kg^{-1}. The spent coffee wastes showed an acidic pH, while the biochar showed an alkaline pH. The pH of AC was 4.68, while that of CC was 4.55, suggesting a great potential of such biomass for the alkaline soils of Saudi Arabia. The pyrolysis process resulted in a twofold higher pH, reaching 9.42 in ABC and 8.86 in CBC. The spent coffee waste showed lower EC values (1.47 dS m^{-1} for AC and 2.17 dS m^{-1} for CC). The higher EC of the CC as compared to the AC could be due to higher SO_4^{2-} (15.48 meq L^{-1}), K^+ (9.91 meq L^{-1}), and Mg^{2+} (7.56 meq L^{-1}) concentrations than AC, which showed 8.81 meq L^{-1} of SO_4^{2-}, 5.18 meq L^{-1} of K^+ and 5.78 meq L^{-1} of Mg^{2+}. The EC of the produced biochar increased significantly and reached 4.46 and 4.74 dS m^{-1} in AC and CC, respectively. It was observed that the CEC of the biochar was lower than that of feedstocks. The CEC of AC and CEC was 19.21 and 20.01 cmol kg^{-1}, which were reduced to 14.91 and 15.00 cmol kg^{-1} in ABC and CBC, respectively. The decline in CEC in ABC and CBC could be due to the loss of volatile compounds such as surface functional groups and organic matter[20].

Further, the higher aromaticity in the resultant biochar could be a reason for the reduction in CEC[20]. These results suggest that spent coffee waste can be a promising precursor for biochar production, which may be used to enhance soil properties in sandy and alkaline soils commonly found in arid and semi-arid regions like Saudi Arabia. Most soils in Saudi Arabia are alkaline in nature, so acidic soil amendments could be more effective than alkaline ones. Since the coffee wastes analyzed in this study were acidic, they have the potential to serve as beneficial soil amendments.

FTIR spectra of the synthesized ABC and CBC as studied from 500 to 4000 cm^{-1} are provided in Fig. 1. Some small bands in the 690–780 cm^{-1} range were observed in both samples, showing the presence of Si–O, which were sharper in CBC compared to ABC. Both samples showed a band at 1093 cm^{-1}, ascribed as C–O–C stretches due to polysaccharide cellulose. The presence of hemicellulose and cellulose was evident with the two bands between 2800 and 2950 cm^{-1}[21,22]. Similarly, the two bands at 1490 cm^{-1} and 1750 cm^{-1} were due to the presence of C=C in both produced biochars. A vast band was found at 3350–3450 cm^{-1} in both produced biochar, indicating the presence of O–H stretches associated with water molecules and some volatile functional groups[20]. The higher broadness of these bands showed that both biochars had more moisture content.

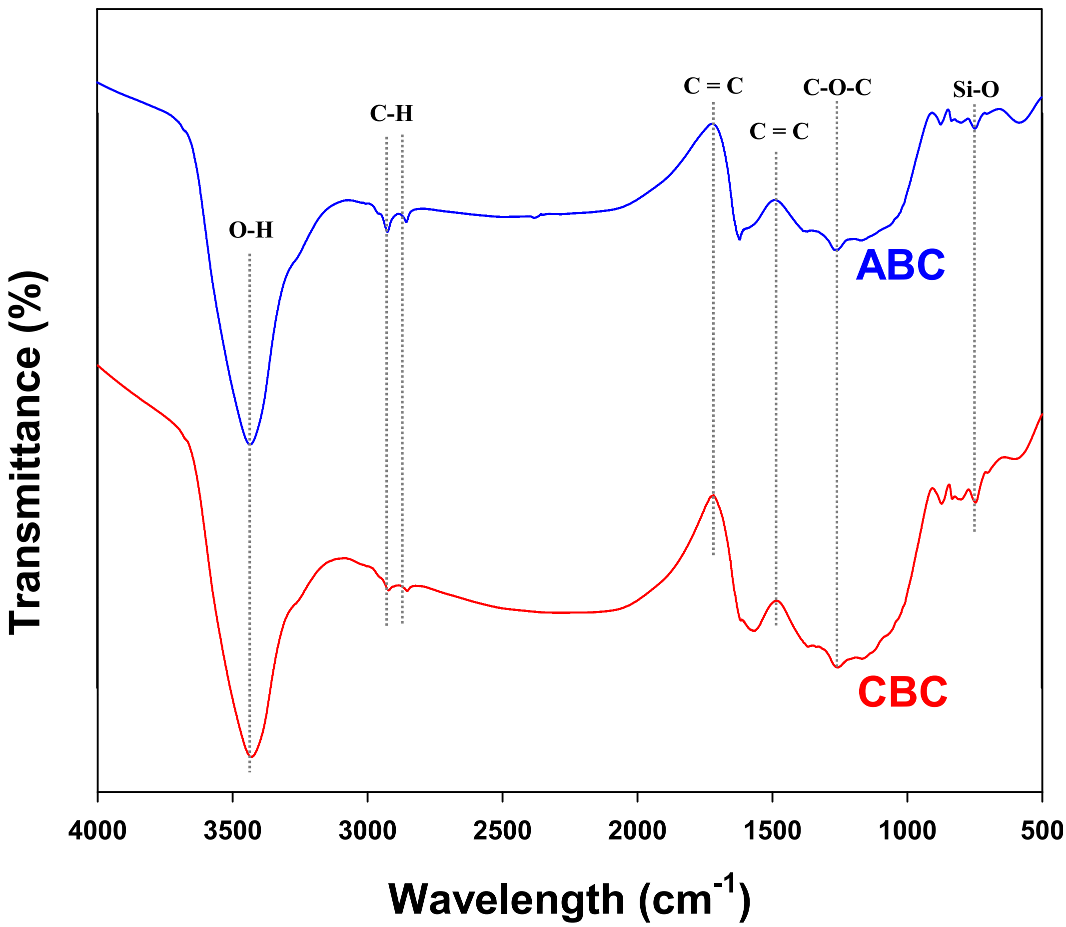

Fig. 1. Fourier-transform infrared spectroscopy analyses of Arabica coffee waste derived biochar (ABC) and Colombian coffee waste derived biochar (CBC).

Impacts of synthesized amendments on soil properties

Soil hydraulic conductivity and bulk density

The impacts of the synthesized amendments on soil hydraulic conductivity are shown in Fig. 2a. The results showed the highest hydraulic conductivity in CK treatment (0.044 cm min^{-1}) compared to the synthesized amendments. Overall, 1% application of AC and CC and their derived biochar (ABC and CBC) resulted in higher hydraulic conductivity as compared to the other application rates. In contrast, an increase in the application rate resulted in the lowest hydraulic conductivity. Moreover, the spent coffee application resulted in slightly higher hydraulic conductivity than their respective biochar. The lowest hydraulic conductivity was exhibited by ABC5 and CBC5, reaching 0.019 and 0.020 cm min^{-1}, respectively. Previously, Hassan and Mahmoud[23] reported a significant reduction in soil hydraulic conductivity by applying organic amendments. Likewise, Li et al.[12] stated

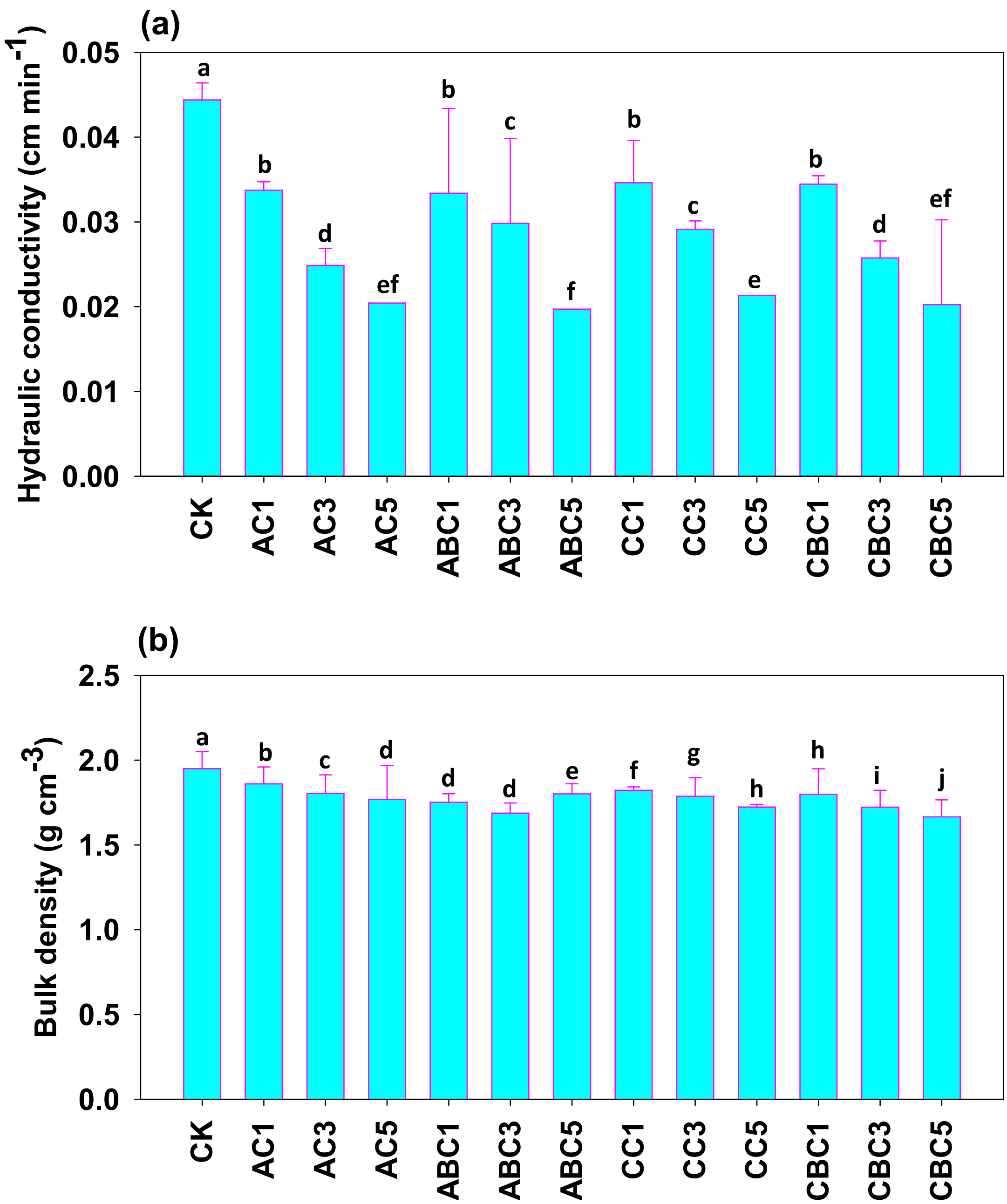

Fig. 2. Impacts of the synthesized amendments (AC1: Arabica coffee applied at 1%, AC3: Arabica coffee applied at 3%, AC5: Arabica coffee applied at 5%, AC1: Arabica coffee-derived biochar applied at 1%, AC3: Arabica coffee-derived biochar applied at 3%, AC5: Arabica coffee-derived biochar applied at 5%, CC1: Colombian coffee applied at 1%, CC3: Colombian coffee applied at 3%, CC5: Colombian coffee applied at 5%, CBC1: Colombian coffee-derived biochar applied at 1%, CBC3: Colombian coffee-derived biochar applied at 3%, and CBC5: Colombian coffee-derived biochar applied at 5%) along with control (CK) on soil hydraulic conductivity (**a**) and bulk density (**b**). Different letters displayed above the bars indicate a statistically significant difference ($p < 0.05$ level), while same letters represent no significant difference.

that biochar application reduced soil hydraulic conductivity in silty clay soil. Similar to the soil's hydraulic conductivity, the soil's bulk density was decreased with applying soil amendments (Fig. 2b). The highest bulk density was observed in CK (1.95 g cm^{-3}), while the lowest was observed with ABC5 and CBC5, reaching 1.80 and 1.67 g cm^{-3}, respectively.

Raw coffee waste amendments showed a higher bulk density than their respective biochars. Soil amendments such as biochar can potentially impact the physical properties of soil, inducing soil structure, bulk density, and hydraulic conductivity. Due to its higher stability and minimum degradation, biochar can stay in the soil for hundreds of years and maintain its structure[20]. Therefore, the application of biochar changes the aggregate stability and pore distribution of soil, consequently impacting soil hydraulic conductivity and bulk density[24]. The addition of biochar to soil could alter soil aggregation and stabilize the larger aggregates, consequently improving pore volume and reducing soil bulk density[25–27]. Therefore, these findings suggested that the application of biochar produced significantly improved soil structure, which is of critical importance for transporting water and solutes, exchanging gases, and developing roots.

Evaporation and infiltration

Changes in cumulative water evaporation and infiltration in soil after the application of amendments (coffee wastes and their derived biochar) were investigated in this study. The impacts of the applied soil amendments on cumulative evaporation are shown in Fig. 3. Significant reductions in cumulative evaporation were observed with the application of amendments. Overall, CK showed the highest cumulative evaporation of all the applied amendments, while ABC5 and CBC5 showed the lowest. The rate of amendment application had a significant impact on soil physical properties in this study. The cumulative evaporation is reduced with an increase in the rate of application. The application of amendment at 5%, i.e., ABC5 and CBC5, resulted in the highest reduction in cumulative evaporation (57% and 66%, respectively, compared to CK). Applying biochar resulted in up to 12% more reduction in cumulative evaporation than their respective feedstock waste. Colombian coffee waste and its derived biochar performed better than Arabica coffee waste and its derivative biochar in reducing cumulative evaporation. The applications of Colombian coffee-derived biochar exhibited up to 6% more reduction in cumulative evaporation than Arabica coffee waste-derived biochar.

Soil evaporation is an essential aspect of studying water relations in sandy soil. It has been reported that adding biochar to soil could reduce evaporation and enhance the soil's water-holding capacity[28]. Pore structure and pore volume are critical for water retention-evaporation in soil. Due to finer particles, biochar can potentially absorb higher amounts of water in the soil, reducing the water loss due to evaporation[29]. The reason for reduced water evaporation in soils amended with biochar compared to those amended with pristine spent coffee waste is higher water absorption.

Additionally, finer biochar particles can enter the pore spaces in the soil, resulting in the clogging of pores and subsequently reducing the hydraulic conductivity of the soil. The significant reduction in hydraulic conductivity with the application of biochar was responsible for the reduced water evaporation[8]. Therefore, biochar performed better than CK and raw coffee wastes in reducing water loss from the soil in this study.

The impacts of the synthesized amendments on cumulative infiltration are shown in Fig. 4. All the amendments exhibited significant implications for cumulative infiltration. The highest cumulative infiltration was observed under CK during all the time intervals, whereas the lowest cumulative infiltration was demonstrated when biochar was applied from 3 to 5%. Overall, the lowest cumulative infiltration was observed with the application of CBC5, which was 181% lower than CK, followed by CBC3 and ABC5 (124% and 96% lower than CK, respectively), suggesting the outclass performance of both biochars at the highest application rates. Similarly, other amendments showed that the increase in application rate resulted in a decrease in the cumulative infiltration. It was observed that the application of biochar resulted in a 43%–105% decline in cumulative infiltration as compared to their respective feedstocks with a similar application rate, suggesting that converting coffee waste into biochar could be a better option for improving soil physical properties than applying the pristine coffee waste. Finer and lighter biochar particles could penetrate the pore spaces of soil, reducing water flow and infiltration[30].

Furthermore, the fine biochar particles enhance the intraparticle porosity of the soil, which could increase air entrapment and delay the wetting process, resulting in a reduced infiltration rate[31]. Moreover, the variations in the infiltration rate as a function of the applied soil amendments were also studied, and the results are shown in Fig. 5. Overall, the infiltration rate reduced with time's passage towards equilibrium. All the applied amendments showed a lower infiltration rate than CK. Likewise, the increase in the application rate resulted in a reduction in infiltration rate, reaching the lowest with a 5% application rate. All the synthesized biochar showed lower infiltration rates than their respective feedstocks with the same application rate. The lowest infiltration rate was exhibited by ABC5 and CBC5, which were 193% and 161%, respectively, lower than CK's. Overall, the application of CC-derived biochar showed 46%–74% lower infiltration rate, while AC-derived biochar showed 36%–123% lower infiltration rates than pristine CC and AC, respectively.

The infiltration of water in soil is one of the crucial factors for delivering water and nutrients to plants. The reduction in cumulative infiltration and infiltration rate in soil with the application of soil amendments in this study could be due to the changes in soil structure. The entrapment of biochar particles within the pore spaces in soil could have reduced water infiltration[30,31]. Moreover, the hydrophobic properties of the produced biochar could have resulted in water repellence and reduced the infiltrate of water in soil; however, the water repellency persists for a short time only[32]. Previously, various researchers have reported a reduction in water infiltration in sandy soil with biochar-based soil amendments[33–35.] Barnes et al.[34] conducted a study that demonstrated the effectiveness of applying biochar in reducing water infiltration and mitigating the impacts of soil erosion. Similarly, Subedi et al.[36] observed a decline in soil infiltration rates following the application of biochar. Wallach

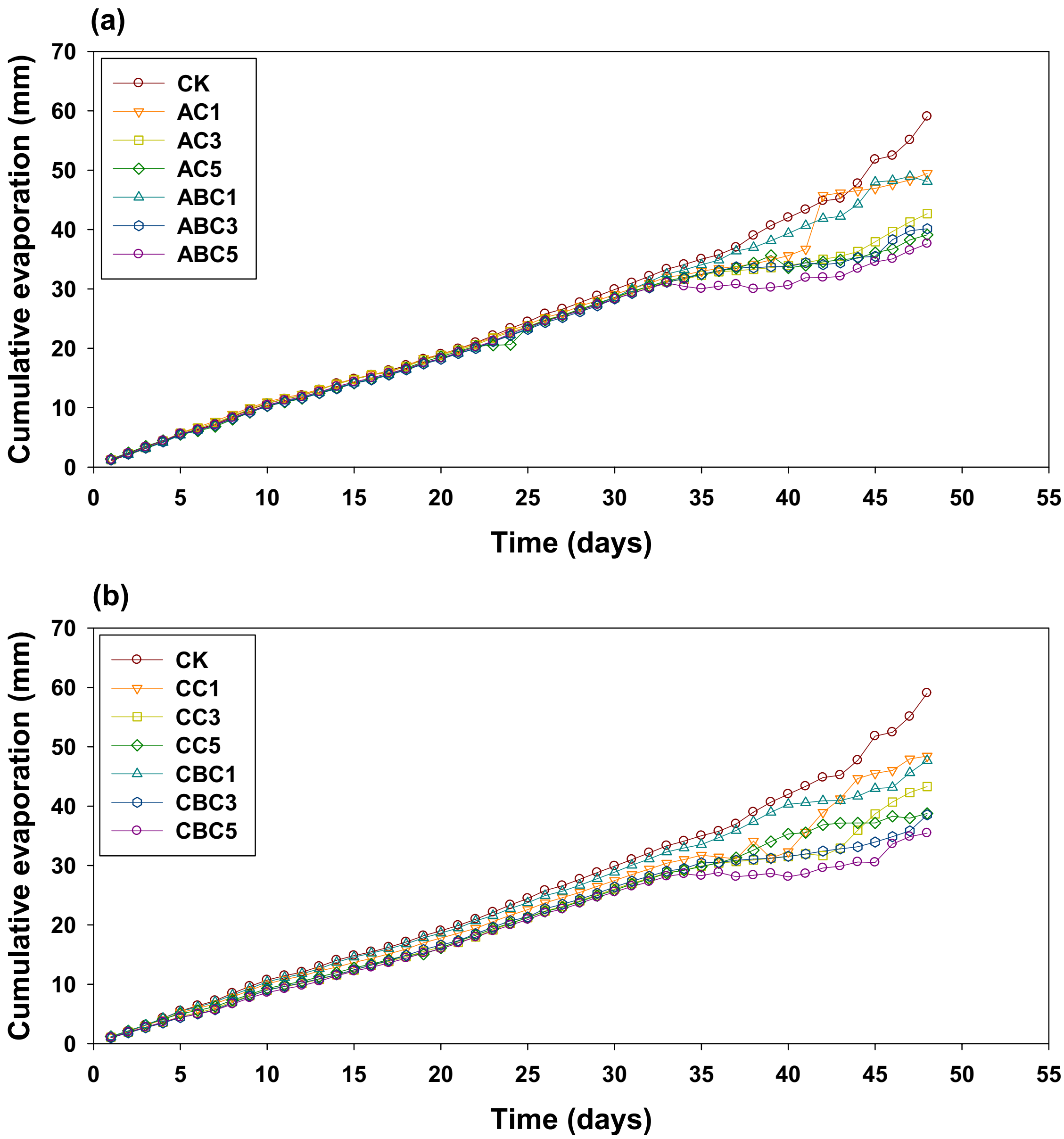

Fig. 3. Impacts of the synthesized amendments (AC1: Arabica coffee applied at 1%, AC3: Arabica coffee applied at 3%, AC5: Arabica coffee applied at 5%, AC1: Arabica coffee-derived biochar applied at 1%, AC3: Arabica coffee-derived biochar applied at 3%, AC5: Arabica coffee-derived biochar applied at 5%, CC1: Colombian coffee applied at 1%, CC3: Colombian coffee applied at 3%, CC5: Colombian coffee applied at 5%, CBC1: Colombian coffee-derived biochar applied at 1%, CBC3: Colombian coffee-derived biochar applied at 3%, and CBC5: Colombian coffee-derived biochar applied at 5%) along with control (CK) on soil cumulative evaporation (a: Arabica coffee waste and its derived biochars and b: Colombian coffee waste and its derived biochars).

et al.[37] explained that the hydrophobic (water-repelling) properties of biochar, as well as the changes it can induce in soil structure, were responsible for the hindrance of infiltration in soils amended with charred materials. Therefore, transforming spent coffee waste into biochar could efficiently reduce water infiltration and enhance water retention in sandy soils in arid and semi-arid regions.

Water retention

The impacts of the applied amendments on soil water contents are shown in Fig. 6. All the applied amendments exhibited significant impacts on soil water contents. CK demonstrated the highest water evaporation (5.90 mm) and the lowest water retention (2.13 mm). The amendments' application rate was essential in enhancing soil water retention. With the increase in the application rate, water evaporation was decreased, whereas the retention was increased. The highest water retention was observed with the higher application rate (5%). The highest water retention was observed in CBC5 (4.87 mm) and ABC5 (4.26 mm), which were 130% and 101% higher, respectively, compared to CK. Results revealed that applying AC-derived biochar increased water retention by

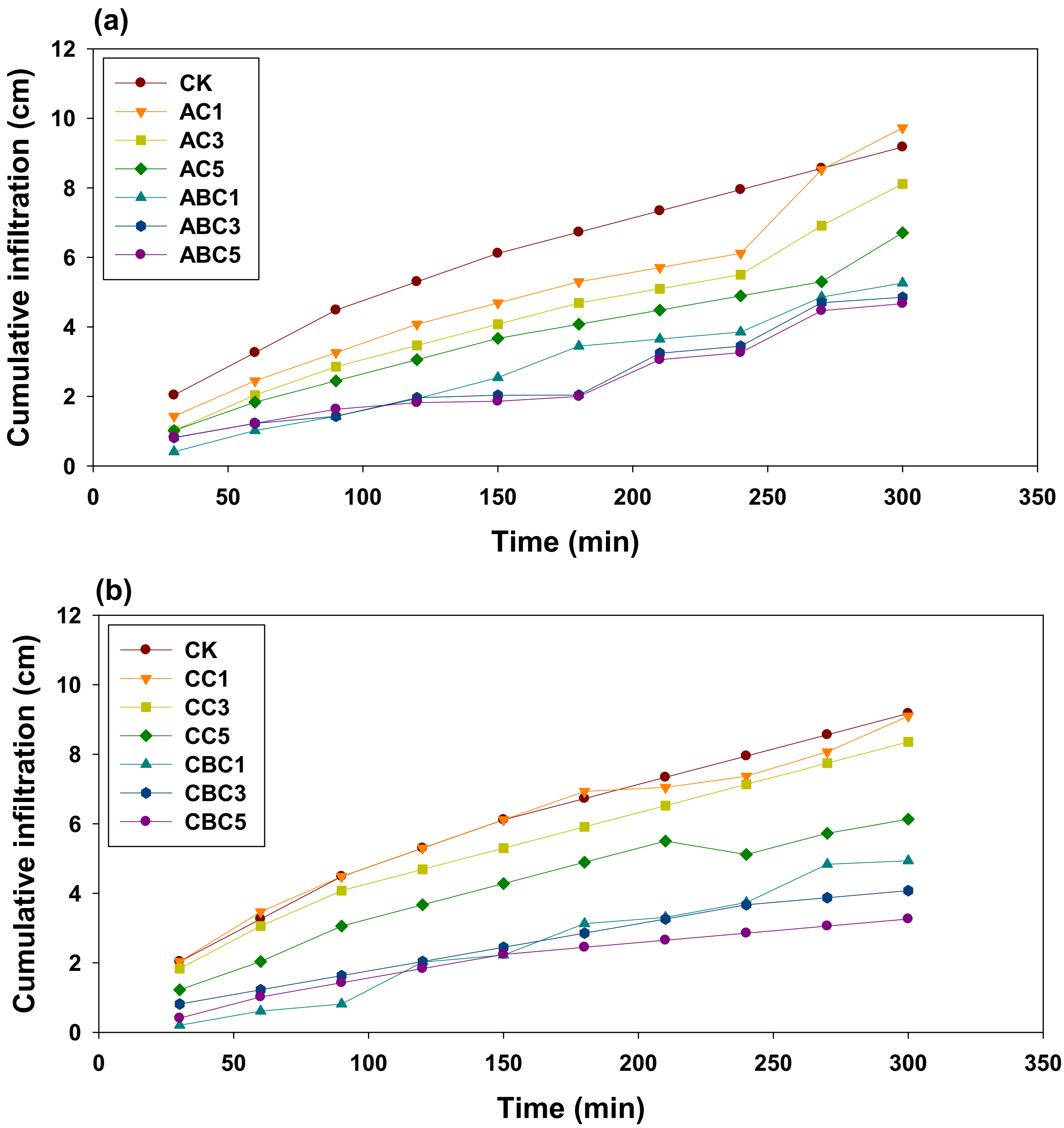

Fig. 4. Impacts of the synthesized amendments (AC1: Arabica coffee applied at 1%, AC3: Arabica coffee applied at 3%, AC5: Arabica coffee applied at 5%, AC1: Arabica coffee-derived biochar applied at 1%, AC3: Arabica coffee-derived biochar applied at 3%, AC5: Arabica coffee-derived biochar applied at 5%, CC1: Colombian coffee applied at 1%, CC3: Colombian coffee applied at 3%, CC5: Colombian coffee applied at 5%, CBC1: Colombian coffee-derived biochar applied at 1%, CBC3: Colombian coffee-derived biochar applied at 3%, and CBC5: Colombian coffee-derived biochar applied at 5%) along with control (CK) on soil cumulative infiltration (**a**: Arabica coffee waste and its derived biochars and **b**: Colombian coffee waste and its derived biochars).

up to 11%. In comparison, the application of CC-derived biochar showed up to 26% higher water retention than pristine AC and CC with the same application rates. Overall, CC-derived biochar performed better than AC-derived biochar in reducing evaporation and enhancing soil water retention.

The significance of biochar in improving soil water retention and decreasing water evaporation has been extensively studied[38–40]. Overall, a significant improvement in the water retention capacity of soil has been demonstrated with the application of charred materials[41–44]. However, the extent of the impact of biochar on water retention of soil varies with the soil type, biochar type, atmospheric conditions, and biochar application rate[8]. The porosity, pore volume, and surface area are the critical characteristics of the biochar in determining its efficiency in improving the soil's water retention capacity. Biochar can absorb water within its pores through capillary action, reducing water transport and enhancing its retention[45]. Therefore, higher porosity of biochar is responsible for higher water holding capacity. Moreover, adding biochar to soil improves soil structure, such as hydraulic conductivity, soil aggregation, and pore size distribution, resulting in higher soil water retention capacity[46]. Therefore, due to biochar's higher recalcitrance and stability, enhancing the water retention capacity

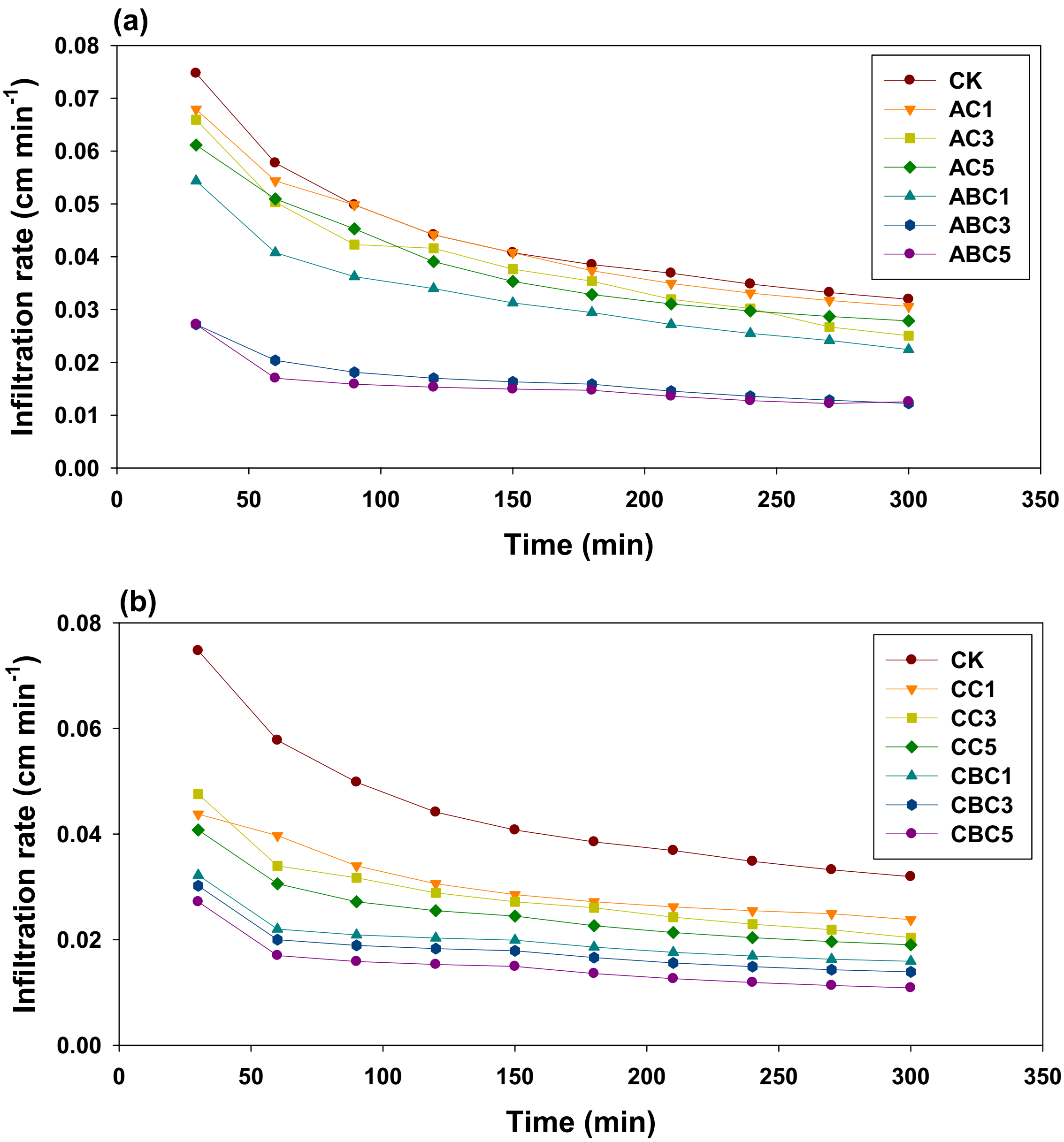

Fig. 5. Impacts of the synthesized amendments (AC1: Arabica coffee applied at 1%, AC3: Arabica coffee applied at 3%, AC5: Arabica coffee applied at 5%, AC1: Arabica coffee-derived biochar applied at 1%, AC3: Arabica coffee-derived biochar applied at 3%, AC5: Arabica coffee-derived biochar applied at 5%, CC1: Colombian coffee applied at 1%, CC3: Colombian coffee applied at 3%, CC5: Colombian coffee applied at 5%, CBC1: Colombian coffee-derived biochar applied at 1%, CBC3: Colombian coffee-derived biochar applied at 3%, and CBC5: Colombian coffee-derived biochar applied at 5%) along with control (CK) on soil infiltration rate (a: Arabica coffee waste and its derived biochars and b: Colombian coffee waste and its derived biochars).

of sandy soils of arid and semi-arid regions using biochar-based soil amendments is a greener and more cost-effective approach.

Impacts of synthesized amendments on maize plant growth

Figure 7 represents the potential effect of biochar derived from Arabic and Columbian coffee on plant biomass and height. Figure 7a,b represent the effect of coffee-derived biochar with 1%, 3%, and 5% application rates on the root and shoot biomass, respectively. The 5% and 3% application rates of biochar performed significantly better than the CK. The application of CBC5 performed excellently compared to CBC3 and CBC1 and produced more root biomass, while the same trend was observed in ABC5, where it performed better, followed by ABC1 and ABC3. CBC5 and ABC5 resulted in fivefold higher root biomass and 1.5-fold higher shoot biomass than CK. The increased root biomass by applying CBC5, CBC3, ABC5, and ABC1 indicated the potential of biochar for improving plant biomass by supplying the available nutrients to the plant root[47]. The increased root biomass indicates more available nutrients associated with biochar application rates. It was reported by Rafique et al.[48] that a 1.5%

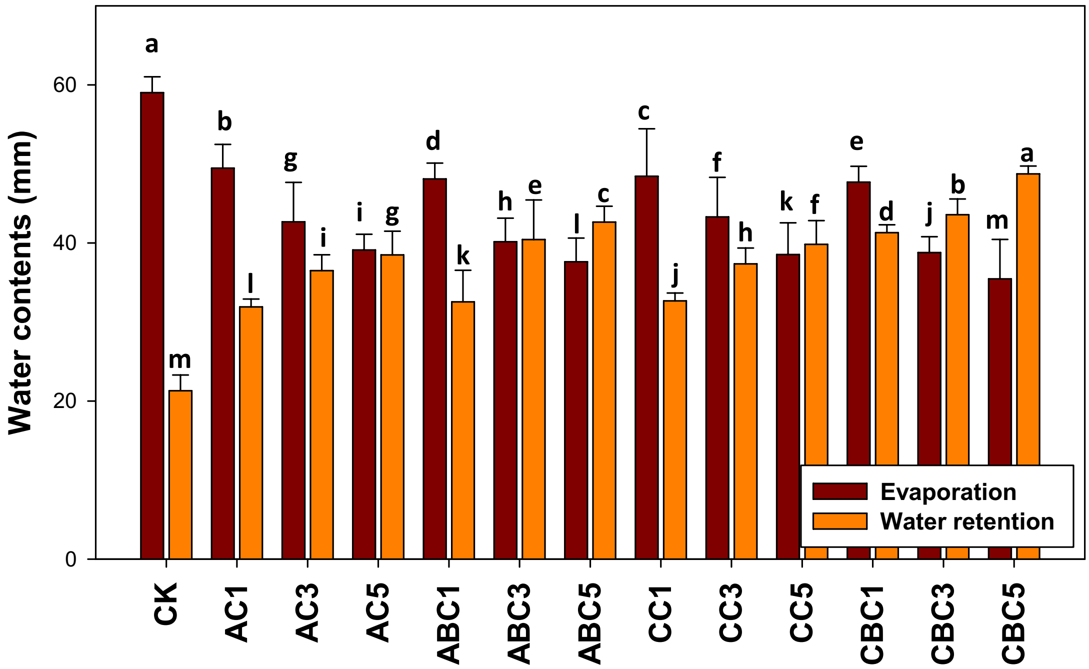

Fig. 6. Impacts of the synthesized amendments (AC1: Arabica coffee applied at 1%, AC3: Arabica coffee applied at 3%, AC5: Arabica coffee applied at 5%, AC1: Arabica coffee-derived biochar applied at 1%, AC3: Arabica coffee-derived biochar applied at 3%, AC5: Arabica coffee-derived biochar applied at 5%, CC1: Colombian coffee applied at 1%, CC3: Colombian coffee applied at 3%, CC5: Colombian coffee applied at 5%, CBC1: Colombian coffee-derived biochar applied at 1%, CBC3: Colombian coffee-derived biochar applied at 3%, and CBC5: Colombian coffee-derived biochar applied at 5%) along with control (CK) on soil water contents. Different letters displayed above the bars indicate a statistically significant difference ($p < 0.05$ level), while same letters represent no significant difference.

to 3% application rate of biochar could increase the plant's fresh biomass by 76%. In a study, Rajkovich et al.[49] also reported an increase in the biomass of maize plants by 30%-40% with the application of different biochars.

The findings of increased biomass through the application of biochar and its modified versions have been corroborated by other studies. Ruqin et al.[50] and Wang and Xu[24] have also reported similar results, where they observed increased biomass following the application of biochar and its modified forms. A comparable trend was observed in the shoot biomass as well. Here, the 5% and 3% application rates of biochar performed significantly better than the control (CK). Among the modified biochars, the application of AC5 resulted in the maximum shoot biomass, followed by CBC5 and ABC5. Interestingly, the 3% application rate of CBC produced slightly higher shoot biomass compared to the 3% application rate of ABC. This consistent pattern of improved biomass production, both in terms of total biomass and shoot biomass, across multiple studies highlights the potential benefits of using spent coffee waste derived biochar and its modified variants as soil amendments to enhance plant growth and productivity.

On the other hand, a similar pattern was also observed in the plant height (Fig. 7c), where CBC5 showed the maximum plant height, followed by CBC3, ABC5, and ABC3. Overall, the application of ABC5 and CBC5 resulted in up to twofold higher plant height than CK. Plant height was observed to be better in the plants where biochar application rates were higher because of the improved bioavailability of the essential nutrients to the plants[51].

Biochar incorporation into the soil helps to increase soil fertility and exchangeable acidity because of the presence of oxides and hydroxides of the alkali metals present in the biochar ashes[52]. It has been reported that nutrient availability is positively affected in soils treated with biochar[53,54]. Puga et al.[55] reported that nitrogen availability was increased with applying biochar, while Usman et al.[56] stated that applying biochar increased the P, Fe, K, Zn, Cu, and Mn concentrations in the soil. The plants uptake these nutrients, which ultimately causes better plant growth by increasing biomass and plant height. Application of biochar to the soil causes increased nutrient availability because of increased pH, improved physio-chemical characteristics of the soil, increased soluble nutrients because of the greater biochar surface area, and nutrient contribution from the biochar in the ash form, which increases the available nutrients for the plants[57]. Therefore, spent coffee waste biochar could be used as an efficient and cost-effective approach to improve plant growth under sandy soils in arid and semi-arid regions.

Conclusion

The present study investigated the potential of spent coffee wastes (Arabica coffee waste and Columbian coffee waste) and their respective biochars as soil amendments to improve the physical properties of loamy sand soil and maize growth. The results demonstrated that all the soil amendments significantly enhanced soil physical

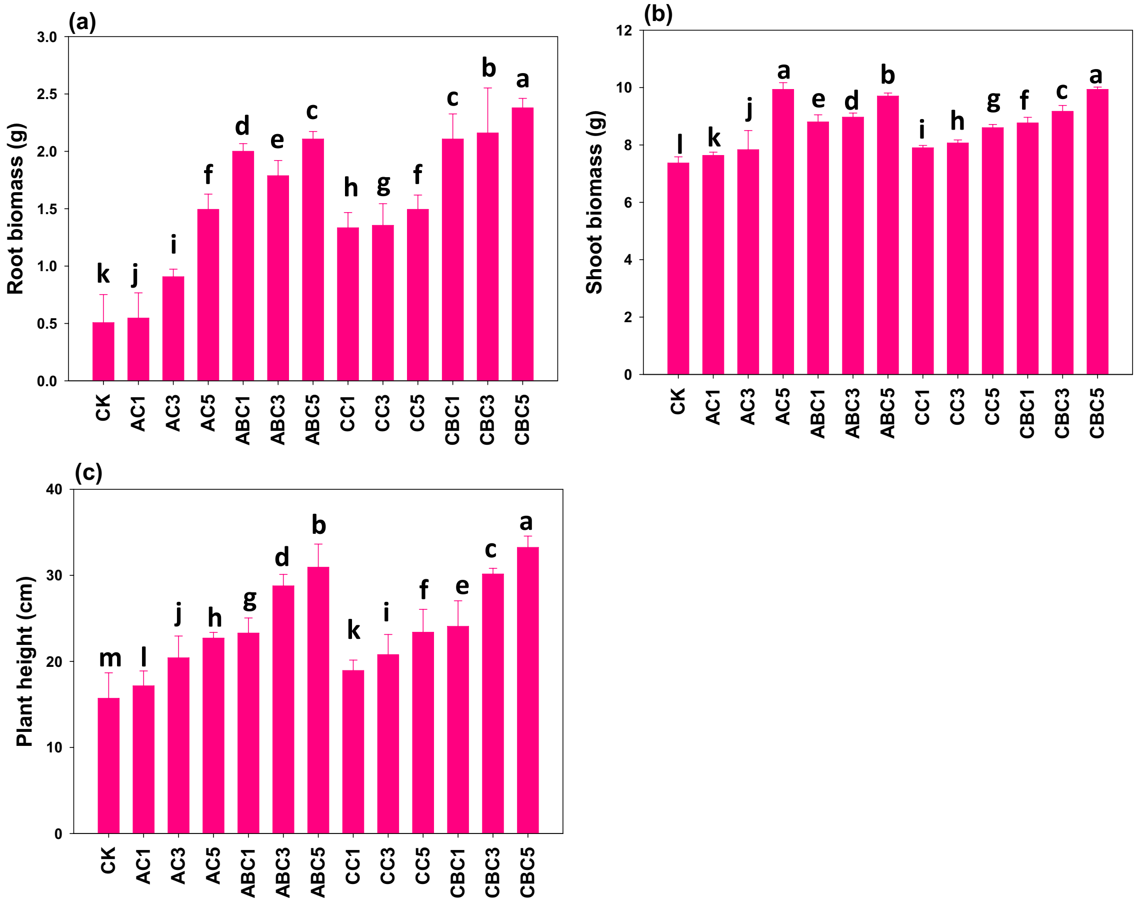

Fig. 7. Impacts of the synthesized amendments (AC1: Arabica coffee applied at 1%, AC3: Arabica coffee applied at 3%, AC5: Arabica coffee applied at 5%, AC1: Arabica coffee-derived biochar applied at 1%, AC3: Arabica coffee-derived biochar applied at 3%, AC5: Arabica coffee-derived biochar applied at 5%, CC1: Colombian coffee applied at 1%, CC3: Colombian coffee applied at 3%, CC5: Colombian coffee applied at 5%, CBC1: Colombian coffee-derived biochar applied at 1%, CBC3: Colombian coffee-derived biochar applied at 3%, and CBC5: Colombian coffee-derived biochar applied at 5%) along with control (CK) on maize root dry biomass (**a**), shoot dry biomass (**b**), and plant length (**c**). Different letters displayed above the bars indicate a statistically significant difference ($p < 0.05$ level), while same letters represent no significant difference.

characteristics and maize performance compared to the unamended control. Notably, the coffee waste-derived biochars, specifically ABC5 and CBC5 (5% application rate), outperformed the pristine coffee waste-based amendments. The application of ABC5 and CBC5 led to a 57%–66% reduction in cumulative evaporation and a 124%–181% reduction in infiltration rate compared to the control. Furthermore, these biochar treatments improved soil water retention by 101%–130% relative to the control. In terms of plant growth, ABC5 and CBC5 doubled the plant height, increased root biomass by fivefold, and enhanced shoot biomass by 1.5-fold compared to the control. The findings of this study indicate that Arabica and Colombian coffee wastes can be effectively converted into biochar and used as potent soil amendments. These coffee waste-derived biochars can help improve soil physical properties and enhance maize productivity in arid and semi-arid regions. The superior performance of the coffee waste biochars demonstrates their potential as sustainable and cost-effective alternatives to traditional soil management practices.

Data availability

Data Availability: The data presented in this study are not available in the public domain due to privacy and ethical restrictions, but are available from the corresponding author on a reasonable request.

Received: 4 April 2024; Accepted: 18 August 2024
Published online: 26 August 2024

References

1. Bekchanova, M. *et al.* Biochar's effect on the ecosystem services provided by sandy-textured and contaminated sandy soils: a systematic review protocol. *Environ. Evidence* **10**(1), 1–12 (2021).
2. Reynolds, W. D., Bowman, B. T., Drury, C. F., Tan, C. S. & Lu, X. Indicators of good soil physical quality: density and storage parameters. *Geoderma* **110**(1–2), 131–146 (2002).

3. Van Asperen, H. L., Bor, A. M. C., Sonneveld, M. P. W., Bruins, H. J. & Lazarovitch, N. Properties of anthropogenic soils in ancient run-off capturing agricultural terraces in the Central Negev desert (Israel) and related effects of biochar and ash on crop growth. *Plant Soil* **374**(1), 779–792 (2014).
4. Hartemink, A. E. & Huting, J. Land cover, extent, and properties of Arenosols in Southern Africa. *Arid Land Res. Manage.* **22**(2), 134–147 (2008).
5. Kang, S. *et al.* Marginal lands: concept, assessment and management. *J. Agricult. Sci.* **5**(5), 129 (2013).
6. Meena, R. S. *et al.* Impact of agrochemicals on soil microbiota and management: A review. *Land* **9**(2), 34 (2020).
7. Uzoma, K.C., Inoue, M., Andry, H., Zahoor, A. and Nishihara, E. Influence of biochar application on sandy soil hydraulic properties and nutrient retention. Journal of Food, Agriculture & Environment, 9(3/4 part 2), pp.1137–1143 (2011).
8. Zhang, J., Qun, C. H. E. N. & Changfu, Y. O. U. Biochar effect on water evaporation and hydraulic conductivity in sandy soil. *Pedosphere* **26**(2), 265–272 (2016).
9. Ghorbani, M. *et al.* How do different feedstocks and pyrolysis conditions effectively change biochar modification scenarios? A critical analysis of engineered biochars under H2O2 oxidation. *Energy Convers. Manage.* **300**, 117924 (2024).
10. Lehmann, J. A handful of carbon. *Nature* **447**(7141), 143–144 (2007).
11. Agbede, T. M., Odoja, A. S., Bayode, L. N., Omotehinse, P. O. & Adepehin, I. Effects of biochar and poultry manure on soil properties, growth, yield, and quality of cocoyam (Xanthosoma sagittifolium Schott) grown in sandy soil. *Commun. Soil Sci. Plant Anal.* **51**(7), 932–947 (2020).
12. Li, L., Zhang, Y. J., Novak, A., Yang, Y. & Wang, J. Role of biochar in improving sandy soil water retention and resilience to drought. *Water* **13**(4), 407 (2021).
13. Medyńska-Juraszek, A. *et al.* Biochar improves maize growth but has a limited effect on soil properties: Evidence from a three-year field experiment. *Sustainability* **13**(7), 3617 (2021).
14. Al-Abdulkader, A. M., Al-Namazi, A. A., AlTurki, T. A., Al-Khuraish, M. M. & Al-Dakhil, A. I. Optimizing coffee cultivation and its impact on economic growth and export earnings of the producing countries: The case of Saudi Arabia. *Saudi J. Biol. Sci.* **25**(4), 776–782 (2018).
15. Serna-Jiménez, J. A. & Siles, J. A. A review on the applications of coffee waste derived from primary processing: strategies for revalorization. *Processes* **10**(11), 2436 (2022).
16. Kim, M. S. *et al.* The effectiveness of spent coffee grounds and its biochar on the amelioration of heavy metals-contaminated water and soil using chemical and biological assessments. *J. Environ. Manage.* **146**, 124–130 (2014).
17. Sparks, D. L. *Methods of soil analysis* (Soil Society of American, 1996).
18. Bouyoucos, G. J. Hydrometer method improved for making particle size analysis of soils. *Agronomy J.* **54**, 464–465 (1962).
19. Steel, R. G. D., Torrie, J. H. & Dickey, D. A. *Principles and Procedures of Statistics: a Biometrical Approach* 3rd edn, 400–428 (McGraw Hill Book Co., 1997).
20. Ahmad, M. *et al.* Date palm waste-derived biochar composites with silica and zeolite: synthesis, characterization and implication for carbon stability and recalcitrant potential. *Environ. Geochem. Health* **41**, 1687–1704 (2019).
21. Usman, A. R. A. *et al.* Biochar production from date palm waste: Charring temperature induced changes in composition and surface chemistry. *J. Anal. Appl. Pyrolysis* **115**, 392–400 (2015).
22. Jouiad, M., Al-Nofeli, N., Khalifa, N., Benyettou, F. & Yousef, L. F. Characteristics of slow pyrolysis biochar produced from rhodes grass and fronds of edible date palm. *J. Anal. Appl. Pyrolysis* **111**, 183–190 (2015).
23. Hassan, A. Z. & Mahmoud, A. W. The combined effect of bentonite and natural zeolite on sandy soil properties and productivity of some crops. *Topclass J. Agricult. Res.* **1**(3), 22–28 (2013).
24. Wang, G. & Xu, Z. The effects of biochar on germination and growth of wheat in different saline-alkali soil. *Asian Agricult. Res.* **5**(11), 116–119 (2013).
25. Tejada, M. & Gonzalez, J. L. Influence of organic amendments on soil structure and soil loss under simulated rain. *Soil Tillage Res.* **93**(1), 197–205 (2007).
26. Jien, S. H. & Wang, C. S. Effects of biochar on soil properties and erosion potential in a highly weathered soil. *Catena* **110**, 225–233 (2013).
27. Amin, A. E. E. A. Z. Impact of some amendments on kinetics of leaching dissolved organic carbon and ammonium in calcareous sandy soil under vinasse addition. *Sci. Rep.* **14**(1), 4233 (2024).
28. Basso, A. S., Miguez, F. E., Laird, D. A., Horton, R. & Westgate, M. Assessing potential of biochar for increasing water-holding capacity of sandy soils. *Gcb Bioenergy* **5**(2), 132–143 (2013).
29. Zhang, J. & You, C. F. Water holding capacity and absorption properties of wood chars. *Energy Fuels* **27**, 2643–2648 (2013).
30. Liu, Z. *et al.* Impacts of biochar concentration and particle size on hydraulic conductivity and DOC leaching of biochar–sand mixtures. *J. Hydrol.* **533**, 461–472 (2016).
31. Eibisch, N. *et al.* Does water repellency of pyrochars and hydrochars counter their positive effects on soil hydraulic properties?. *Geoderma* **245**, 31–39 (2015).
32. Githinji, L. Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. *Arch. Agronomy Soil Sci.* **60**(4), 457–470 (2014).
33. Laird, D. A. *et al.* Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma* **158**(3–4), 443–449 (2010).
34. Barnes, R. T., Gallagher, M. E., Masiello, C. A., Liu, Z. & Dugan, B. Biochar-induced changes in soil hydraulic conductivity and dissolved nutrient fluxes constrained by laboratory experiments. *PloS ONE* **9**(9), 108340 (2014).
35. Xiao, Q., Zhang, H., Shen, Y. & Li, S. Effects of biochar on water infiltration, evaporation and nitrate leaching in semi-arid loess area. *Transact. Chinese Soc. Agricult. Eng.* **31**(16), 128–134 (2015).
36. Subedi, R. *et al.* Does soil amended with biochar and hydrochar reduce ammonia emissions following the application of pig slurry?. *Eur. J. Soil Sci.* **66**(6), 1044–1053 (2015).
37. Wallach, R., Margolis, M. & Graber, E. R. The role of contact angle on unstable flow formation during infiltration and drainage in wettable porous media. *Water Resources Res.* **49**(10), 6508–6521 (2013).
38. Gaunt, J. L. & Lehmann, J. Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environ. Sci. Technol.* **42**, 4152–4158 (2008).
39. Kinney, T. J., Masiello, C. A., Dugan, B., Hockaday, W. C. & Dean, M. Hydrologic properties of biochar produced at different temperatures. *Biomass Bioenergy* **41**, 34–43 (2012).
40. Beck, D. A., Johnson, G. R. & Spolek, G. A. Amending greenroof soil with biochar to affect run-off water quantity and quality. *Environ. Pollut.* **159**, 2111–2118 (2011).
41. Novak, J. M. & Watts, D. W. Augmenting soil water storage using uncharred switchgrass and pyrolyzed biochar. *Soil Use Manage.* **29**, 98–104 (2013).
42. Baronti, S. *et al.* Impact of biochar application on plant water relations in *Vitis vinifera* (L). *Eur. J. Agronomy* **53**, 38–44 (2014).
43. Amin, A. E. E. A. Z. Effects of saline water on soil properties and red radish growth in saline soil as a function of co-applying wood chips biochar with chemical fertilizers. *BMC Plant Biol.* **23**(1), 382 (2023).
44. Tammeorg, P. *et al.* Short-term effects of biochar on soil properties and wheat yield formation with meat bone meal and inorganic fertiliser on a boreal loamy sand. *Agricult. Ecosyst. Environ.* **15**(191), 108–116 (2014).

45. Karhu, K., Mattila, T., Bergström, I. & Regina, K. Biochar addition to agricultural soil increased CH4 uptake and water holding capacity–Results from a short-term pilot field study. *Agricult. Ecosyst. Environ.* **140**(1–2), 309–313 (2011).
46. Soinne, H., Hovi, J., Tammeorg, P. & Turtola, E. Effect of biochar on phosphorus sorption and clay soil aggregate stability. *Geoderma* **219–220**, 162–167 (2014).
47. Rafique, M. I., Ahmad, M., Al-Wabel, M. I., Ahmad, J. & Al-Farraj, A. S. Mitigating the toxic effects of chromium on wheat (*Triticum aestivum* L.) seed germination and seedling growth by using biochar and polymer-modified biochar in contaminated soil. *Sustainability* **14**(23), 16093 (2022).
48. Rafique, M. I., Usman, A. R., Ahmad, M., Sallam, A. & Al-Wabel, M. I. In situ immobilization of Cr and its availability to maize plants in tannery waste–contaminated soil: effects of biochar feedstock and pyrolysis temperature. *J. Soils Sediments* **20**, 330–339 (2020).
49. Rajkovich, S. *et al.* Corn growth and nitrogen nutrition after additions of biochar with varying properties to a temperate soil. *Biol. Fertility Soils* **48**, 271–284 (2012).
50. Ruqin, F. A. N., Jia, L. U. O., Shaohua, Y. A. N., Yunlai, Z. H. O. U. & Zhang, Z. Effects of biochar and super absorbent polymer on substrate properties and water spinach growth. *Pedosphere* **25**(5), 737–748 (2015).
51. Ahmad, M. *et al.* Effects of soil dilution and amendments (musselshell, cowbone, and biochar) on Pb availability and phytotoxicity in military shooting range soil. *Ecotoxicol. Environ. Safety* **79**, 225–231 (2012).
52. Tanure, M. M. C. *et al.* Soil water retention, physiological characteristics, and growth of maize plants in response to biochar application to soil. *Soil Tillage Res.* **192**, 164–173 (2019).
53. Karimi, A., Moezzi, A., Chorom, M. & Enayatizamir, N. Application of biochar changed the status of nutrients and biological activity in a calcareous soil. *J. Soil Sci. Plant Nutrition* **20**, 450–459 (2020).
54. Gupta, R. K. *et al.* Rice straw biochar improves soil fertility, growth, and yield of rice–wheat system on a sandy loam soil. *Exp. Agricult.* **56**(1), 118–131 (2020).
55. Puga, A. P. *et al.* Nitrogen availability and ammonia volatilization in biochar-based fertilizers. *Arch. Agronomy Soil Sci.* **66**(7), 992–1004 (2020).
56. Usman, A. R., Al-Wabel, M. I., Abdulaziz, A. H. & Mahmoud, W. A. Conocarpus biochar induces changes in soil nutrient availability and tomato growth under saline irrigation. *Pedosphere* **26**(1), 27–38 (2016).
57. Sánchez-Reinoso, A. D., Ávila-Pedraza, E. Á., Lombardini, L. & Restrepo-Díaz, H. The application of coffee pulp biochar improves the physical, chemical, and biological characteristics of soil for coffee cultivation. *J. Soil Sci. Plant Nutrit.* **23**(2), 2512–2524 (2023).

Acknowledgements
Researchers Supporting Project number (RSPD2024R825), King Saud University, Riyadh, Saudi Arabia.

Author contributions
Conceptualization, A.G.A., A.A. and H.M.I; methodology, A.G.A., and A.A.; software, A.G.A. and A.A., and A.A.A.; validation, A.G.A., and A.A.; formal analysis, A.G.A. and A.A., and A.A.A.; investigation, A.G.A., A.A., H.M.I., and M.A.M; resources, A.G.A.; data curation, A.G.A. and A.A., and A.A.A.; writing—original draft preparation, A.G.A., and A.A.; writing—review and editing, A.G.A., A.A., H.M.I., A.A.A., and M.A.M; visualization, A.G.A., and A.A,; supervision, A.G.A.; project administration, A.G.A.; funding acquisition, A.G.A., H.M.I., and M.A.M. All authors have read and agreed to the published version of the manuscript.

Funding
Researchers Supporting Project number (RSPD2024R825), King Saud University, Riyadh, Saudi Arabia.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to A.G.A.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.