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Impact of Bentonite, Biochar and Compost on Physical and Hydro-Physical Properties of a Sandy Soil

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SANDY soils have a coarse texture with large particles, which results in large pores that allow water to drain quickly through the soil profile. This makes sandy soils prone to dryness, as they do not retain water and, consequently, do not retain nutrients. The objective of this study was to investigate the effect of bentonite, biochar, and compost as soil amendments on particle size distribution, organic matter, bulk density, particle density, total porosity, soil water retention, available water, hydraulic conductivity, and pore size distribution of sandy soil. Application rates were (T1: control; T2: bentonite 2%; T3: bentonite 3%; T4: bentonite 4%; T5: biochar 0.5%; T6: biochar 1%; T7: biochar 1.5%; T8: compost 5 ton fed^{-1}; T9: compost 10 ton fed^{-1}; T10: compost 15 ton fed^{-1}). Furthermore, mixtures (T11: bentonite 3% + biochar 1%; T12: biochar 1% + compost 10 ton fed^{-1}; T13: bentonite 3% + compost 10 ton fed^{-1}; T14: bentonite 3% + biochar 1%+ compost 10 ton fed^{-1}). The results revealed that adding soil amendments improves soil's physical and hydro-physical properties compared to the control (without application). The application of amendments has reduced soil bulk density (BD), hydraulic conductivity (HC), and quickly drainable pores (QDP). Conversely, there was a significant increase in soil organic matter (OM), available water (AW), water holding pores (WHP), soil water retention (SWR), and improving particle size distribution compared to the untreated soil (T1). These results indicate that adding soil amendment enhances the texture of the sandy soil by increasing the fine colloidal particles in the soil complex, thus enhancing pore size distribution (PSD), improving soil properties, and retaining soil water. This ultimately reflects positively on the soil quality and crop production.

Keywords: Soil quality, Amendments, Soil water retention, Available water, Pore size distribution, and Sandy soil.

1. Introduction

Sandy soil, known for its coarse texture and low organic matter content, poses significant challenges to agricultural productivity due to their poor water retention and nutrient-holding capacities (Musei et al., 2024). Sandy soil has low water holding capacity, resulting in low yield (Ibrahimi & Alghamdi, 2022). It typically has less clay, organic matter, and nutrient retention but exhibits higher pH, calcium carbonate content, and infiltration rates (Alghamdi et al., 2018). This limitation challenges sustainable agriculture, especially in regions prone to drought and erratic rainfall patterns (de Holanda et al., 2023).

Bentonite, a type of clay primarily composed of montmorillonite, has unique properties that make it an excellent soil amendment (Nath et al., 2023). Its high activity for cation exchange capacity (CEC) and ability to swell upon wetting enable it to improve soil physical properties significantly (Karbout et al., 2021). Bentonite has been utilized as a soil amendment, particularly in sandy soils, due to its unique physicochemical properties (El-Nagar & Sary, 2021; El Refaey, 2021). Many researches have shown that adding bentonite to sandy soils can increase the proportion of fine particles, enhancing soil texture and structure (Zhou et al., 2022; Wahba et al., 2020). This improvement reduced bulk density and increased water retention and nutrient availability (Czaban & Siebielec, 2013). Hussain et al. (2022) attributed this to bentonite's activity to increase the proportion of fine particles and improve soil aggregation. Additionally, long-term experiments have shown that bentonite can enhance soil chemical properties, such as pH and nutrient content, further improving soil fertility (Czaban & Siebielec, 2013).

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Adding bentonite to sandy soils can decrease hydraulic conductivity by filling the voids between sand particles, creating a more tortuous path for water flow (Sobti & Singh, 2017).

Applying biochar to sandy soil has garnered significant attention due to its potential to enhance soil water retention, improving agricultural productivity and resilience to climate variability (Malik et al., 2024; Pandian et al., 2024). Biochar, a carbon-rich product derived from the pyrolysis of organic materials, has been identified as a promising soil amendment (Chagas et al., 2022; Gyanwali et al., 2024). Its porous structure and high surface area can improve soil physical properties, including water retention, porosity, and low bulk density (Leng et al., 2021; Singh et al., 2024). Moreover, biochar application can significantly increase the water retention capacity of sandy soils under both dry and wet conditions (Chen et al., 2018). For instance, higher biochar application rates (3-5%) have been associated with increased water retention, mainly when larger particle sizes and higher pyrolysis temperatures are used (Li et al., 2021). Biochar can improve water retention, increase soil aggregation, and enhance nutrient availability in sandy soils (Šurda et al., 2024). For instance, high biochar doses have increased water retention in dry and wet conditions (Chen et al., 2018). Additionally, biochar application can alter soil hydraulic properties by increasing porosity and decreasing bulk density (Šurda et al., 2024; Alghamdi, 2018). Moreover, biochar's ability to enhance soil structure and reduce evaporation rates further contributes to its effectiveness in improving soil water dynamics (Vitková et al., 2024). Incorporating biochar into sandy soils boosts water retention and enhances soil fertility by reducing nutrient leaching and increasing microbial activity (Lustosa Carvalho et al., 2020). Research indicates that biochar can alter the PSD of sandy soils, leading to improved water retention and aeration (Liu et al., 2017). Adding biochar increases the number of mesopores and macropores, which are crucial for water storage and root penetration (Singh et al., 2022). Smaller biochar particles tend to increase the proportion of mesopores, enhancing soil water retention and reducing bulk density (Vitková et al., 2024). Conversely, larger particles contribute to the formation of macropores, which improve soil aeration and drainage (de Jesus Duarte et al., 2019). The pyrolysis temperature during biochar production also influences its properties, with higher temperatures generally resulting in greater porosity and stability (Lustosa Carvalho et al., 2020). Research has shown that biochar can significantly enhance the texture of sandy soils by increasing the proportion of fine particles and improving soil aggregation (Gerges et al., 2023). This leads to better water retention, reduced bulk density, and enhanced nutrient availability (Bekchanova et al., 2024). Additionally, incorporating biochar into sandy soils has increased soil organic carbon content, which is crucial for maintaining soil structure and fertility (Singh et al., 2022).

Compost, an organic amendment derived from the decomposition of plant and animal residues, has unique properties that make it an excellent soil conditioner (Elsonbaty & El-Sherpiny, 2024; Singh et al., 2020). Its high organic matter content and nutrient availability enable it to improve soil physical properties significantly (Lehmann & Kleber, 2015). Research has shown that adding compost to sandy soils can increase the proportion of fine particles, enhancing soil aggregation and improving soil texture (Cooper et al., 2020; Duong et al., 2012). This improvement leads to better water retention, reduced bulk density, and increased nutrient availability (Kheir et al., 2023). Additionally, long-term experiments have shown that compost can enhance soil chemical properties, such as pH and cation exchange capacity (CEC), further improving soil fertility (Farrell & Jones, 2009). Higher compost application rates have been associated with more pronounced improvements in SWR, transforming sandy soils into loamy textures (Curtis & Claassen, 2005; Şeker & Manirakiza, 2020). Adding compost to sandy soils can increase the proportion of fine particles, thereby enhancing soil aggregation and modifying PSD (Duong et al., 2012). Therefore, this research aims to improve the physical and hydro-physical characteristics of sandy soil by using some natural soil amendments and to study the addition of these amendments to see if they can increase soil moisture content (SMC) so that water availability for plants is fulfilled and soil water loss is reduced.

2. Materials and Methods

2.1. Experimental site

A pot experiment was conducted at the Desert Research Center during winter 2022 in pots with a diameter of 30 cm and a depth of 35 cm. The soil in the pot was 10 kg. Wheat grains cultivar Gemiza-12 variety suitable for the area was sown on December 11th in the season. Irrigation was carried out using fresh water, and the soil moisture content (SMC) was maintained at approximately 100% field capacity by weighing the pots. In this experiment, sandy soil from areas of agricultural expansion in Egypt was selected from the Ahmed Orabi Agricultural Association site, located along the Cairo-Ismailia agricultural road at line 7 in the association. Before starting the experiment, some physical and chemical soil analysis was conducted, according to Dane & Topp (2020) and Sparks et al. (2020), and the results are shown in Table 1.

Table 1. Some physical and chemical characteristics of the studied soil.

Soil property	Unit	Value	
Particle size distribution:			
Coarse sand	(%)	81.53	
Fine sand		8.82	
Silt		6.84	
Clay		2.81	
Texture class		Sand	
Bulk density (BD)	(Mg m^{-3})	1.54	
Particle density (Pd)		2.59	
Total porosity (TP)	(%)	40.54	
pH (1:2.5 soil water suspension)		8.27	
ECe (dS m^{-1}, soil paste extract)	(dS m^{-1})	0.72	
Organic matter (OM)	(g kg^{-1})	2.50	
$CaCO_3$	(%)	4.11	
Soluble cations (mmolc L^{-1})		Soluble anions (mmolc L^{-1})	
Ca^{2+}	1.72	CO_3^{2-}	0.00
Mg^{2+}	1.61	HCO_3^{-}	2.62
Na^{+}	2.53	Cl^{-}	2.47
K^{+}	1.35	SO_4^{2-}	2.12

2.2. Treatments

Three types of natural soil amendments were used for the sandy soil: bentonite mineral, biochar, and compost—each treatment involved three different concentrations in addition to the control treatment (without application). Then, a mixture of the amendments was applied at a medium concentration to study the improvement in soil texture and other physical properties, especially soil water retention (SWR). The various treatment combinations are tested, and their codes are shown in Table 2. The analyses of the amendments used for the soil are presented in Tables 3 and 4.

Table 2. Treatments used description and their codes.

Treatments	Description
T1	Control (without amendments)
T2	Bentonite applied at 2%
T3	Bentonite applied at 3%
T4	Bentonite applied at 4%
T5	Biochar applied at 0.5%
T6	Biochar applied at 1%
T7	Biochar applied at 1.5%
T8	Compost applied at 5 ton fed^{-1}
T9	Compost applied at 10 ton fed^{-1}
T10	Compost applied at 15 ton fed^{-1}
	Mixtures of bentonite, biochar, and compost, as follows:
T11	Bentonite 3% + biochar 1%
T12	Biochar 1% + compost 10 ton fed^{-1}
T13	Bentonite 3% + compost 10 ton fed^{-1}
T14	Bentonite 3% + biochar 1% + compost 10 ton fed^{-1}

Table 3. Some physical and chemical characteristics of the bentonite.

Property	Value	Chemical composition (%):	
Particle size distribution:		SiO_2	54.98
Sand (%)	7.36	TiO_2	1.49
Silt (%)	13.71	Al_2O_3	17.34
Clay (%)	78.93	Fe_2O_3	9.40
Texture class	Clay	MnO	0.07
Bulk density (Mg m^{-3})	0.58	MgO	2.49
Field capacity (FC, %)	45.42	CaO	0.97
Permanent wilting point (PWP, %)	16.75	Na_2O	2.80
Available water (AW, %)	28.67	K_2O	1.02
pH (1:2.5 soil water suspension)	7.81	P_2O_5	0.17
EC (dS m^{-1}, soil paste extract)	0.76	Cl	1.15
Cation exchange capacity (CEC, $cmol_c$ kg^{-1})	94.35	SO_3	0.47
Specific surface area (SSA, m^2 g^{-1})	562	LOI	7.65
Soluble cations (mmolc L^{-1})		Soluble anions (mmolc L^{-1})	
Ca^{2+}	4.07	CO_3^{2-}	0.00
Mg^{2+}	2.79	HCO_3^-	2.53
Na^+	0.51	Cl^-	0.81
K^+	0.23	SO_4^{2-}	4.26

LOI: loss of incendiaries.

Table 4. Some physical and chemical properties of compost and biochar.

Amendments	Bulk density (Mg m^{-3})	pH	EC (dS m^{-1})	Organic carbon (%)	Moisture content (%)	C/N ratio	Total N (%)	Total P (%)	Total K (%)
Compost	0.60	7.4	2.4	25.75	12.5	17.05	1.51	0.25	0.50
Biochar	0.38	8.65	1.88	19.85	8.5	19.46	1.02	0.19	0.32

2.3. Statistical analyses

The experiment used a randomized complete block design (RCBD) with three replicates. The data was statistically analyzed using ANOVA in SPSS. Significant differences between treatment means were compared by Tukey's HSD test at $P < 0.05$ (Snedecor & Cochran, 1980).

3. Results

3.1. Particle size distribution, organic matter, bulk density, particle density, and total porosity

Soil texture is one of the most important indicators of soil physical properties. Results presented in Table 5 reveal that all the amendment treatments showed improved soil texture (loamy sand) compared with unamended soil (sand). At the same time, the application of amendments increased organic matter (OM). A higher OM value was observed under the T7 treatment (6.50 g kg^{-1}) compared to the control (T1) treatment (2.50 g kg^{-1}). Conversely, data in Table 5 showed that the application of amendments resulted in a decrease in the bulk density values, and the decrease was all the amendment treatments. The higher BD value was observed under the T1 treatment (1.54 Mg m^{-3}), while the lowest BD value was gained by the T7 treatment (1.37 Mg m^{-3}).

Regarding particle density (Pd), data in Table 5 revealed that the highest values of Pd were observed at the T4 treatment (2.62 Mg m^{-3}). In contrast, the lowest Pd values were reported at the T14 treatment (2.41 Mg m^{-3}). Concerning the effect of the applied amendment on total porosity (TP), data in Table 5 shows soil was highly affected by amendment addition. The TP of the experimental soil responded positively to the amendment treatments, reaching the highest 44.66% when treated soil received T4 application compared with T1 treatment (40.54%). Therefore, the TP enhancement in the sandy soil studied may be attributed to the inverse relationship between BD and TP.

3.2. Soil water retention

Soil water retention (SWR) property is a significant indicator of soil hydro-physical properties. The retained moisture in sandy soil differs at suction as affected by the application rates of amendments, as represented in Fig. 1. The data reveal that adding any of the amendments, at any rate, increases the retained moisture at any suction. The highest values of 0.001, 0.10, 0.33, 1.00, and 15.00 bar were 29.67, 16.24, 13.43, 12.86, and 5.69 % at the T12, T4, T12, T12, and T12 treatments, respectively. In contrast, the lowest values of 0.001, 0.10, 0.33, 1.00, and 15.00 bar were 25.67, 8.89, 6.32, 6.21, and 2.61% under the untreated soil treatment (T1).

Table 5. Effect of different soil amendments on particle size distribution, organic matter, bulk density, particle density, and total porosity of the studied soil.

Treatments.	Particle size distribution (%)				Texture class	OM (g kg^{-1})	BD (Mg m^{-3})	Pd (Mg m^{-3})	Total porosity (TP, %)
	Coarse sand	Fine sand	Silt	Clay					
T1	81.53	8.82	6.84	2.81	S	2.50e	1.54a	2.59b	40.54m
T2	74.25	12.34	9.61	3.80	L S	3.20e	1.44e	2.58c	44.19c
T3	73.02	12.16	10.42	4.40	L S	2.80e	1.44e	2.59b	44.40b
T4	73.43	9.24	11.41	5.92	L S	2.90e	1.45d	2.62a	44.66a
T5	74.93	9.34	12.60	3.13	L S	5.30bc	1.41g	2.48g	43.15g
T6	76.25	9.75	10.81	3.19	L S	5.70ab	1.39i	2.47h	43.72e
T7	75.23	9.15	12.40	3.22	L S	6.50a	1.37j	2.45i	44.08d
T8	74.09	9.22	12.75	3.94	L S	4.10d	1.48b	2.52f	41.27l
T9	74.05	9.73	12.01	4.21	L S	4.20d	1.47c	2.53e	41.90k
T10	74.10	9.40	12.09	4.41	L S	4.50cd	1.42f	2.52f	43.65f
T11	75.35	9.15	11.31	4.19	L S	5.60b	1.42f	2.48g	42.74i
T12	74.13	9.75	11.30	4.82	L S	4.10d	1.45d	2.54d	42.91h
T13	74.23	9.54	11.68	4.55	L S	4.90bcd	1.41g	2.47h	42.91h
T14	74.68	9.31	11.56	4.45	L S	4.20d	1.40h	2.41j	41.91j

S: sand; LS: loamy sand; OM: organic matter; BD: bulk density; Pd: particle density.

3.3. Available water and hydraulic conductivity

Data presented in Fig. 2 indicated the effect of treatments on available water (AW) and hydraulic conductivity (HC). The AW was calculated as the difference between moisture content at field capacity (FC) and permanent wilting point (PWP). The higher AW values were detected at 11.58% at the T4 treatment. Conversely, the lowest values of AW were 6.28% under the T1 treatment. On the other hand, a comparison between the amendments indicated that bentonite 4% (T4) was more efficient than other amendments in increasing the amount of AW in the studied soil. At the same time, soil treatment with amendments decreased the values of HC. The value of untreated soil was 10.91cm h^{-1}, which decreased upon treating the soil with bentonite at a rate of 4% (T4) to 3.11cm h^{-1}. Additionally, these results indicated that the bentonite at a rate of 4% had the lowest value decrease than the other treatments for HC.

3.4. Pore size distribution

Pore size distribution (PSD) is considered a method of characterizing soil structure. It could be derived from soil moisture curves, which show the volume of water removed from a given volume of soil at a specific tension. Fig. 3 shows the effect of the applied soil amendments on the PSD of sandy soil. The application of amendments resulted in increased slowly drainable pores (SDP), water holding pores (WHP), and fine capillary pores (FCP). On the other hand, this application of amendments decreased quickly drainable pores (QDP). The maximum values of QDP, SDP, WHP, and FCP were 16.78, 2.94, 11.58, and 5.69% at the T1, T9, T4, and T12 treatments, respectively. In contrast, the minimum values of QDP, SDP, WHP, and FCP were 12.43, 2.30, 6.28, and 2.61% under the T4, T1, T1, and T1 treatments, respectively.

4. Discussion

Applying amendments significantly improves the soil's physical and hydro-physical attributes, such as soil texture, organic matter, and total porosity (Das & Ghosh, 2024). In our study, Biochar amendment at a rate of 1.5% (T7) produced the best results regarding reduced soil bulk. In contrast, bentonite at a rate of 4% (T4) amendment produced the best results regarding increased total porosity compared with unamended soil (control). Fu et al. (2021) reported that improving the texture of sandy soil increases the fine colloidal particles and enhances the fine pores, thus improving the soil's ability to retain moisture and nutrients. Botková et al. (2023) also reported that biochar application reduces bulk and particle densities, increasing porosity in sandy soils.

Adding biochar modifies the soil's particle size distribution, enhancing the soil's overall structure and texture (Liu et al., 2017). Applying bentonite to sandy soils improves soil physical properties, including soil texture, water retention, available water, pore size distribution, and hydraulic conductivity (Alghamdi et al., 2023).

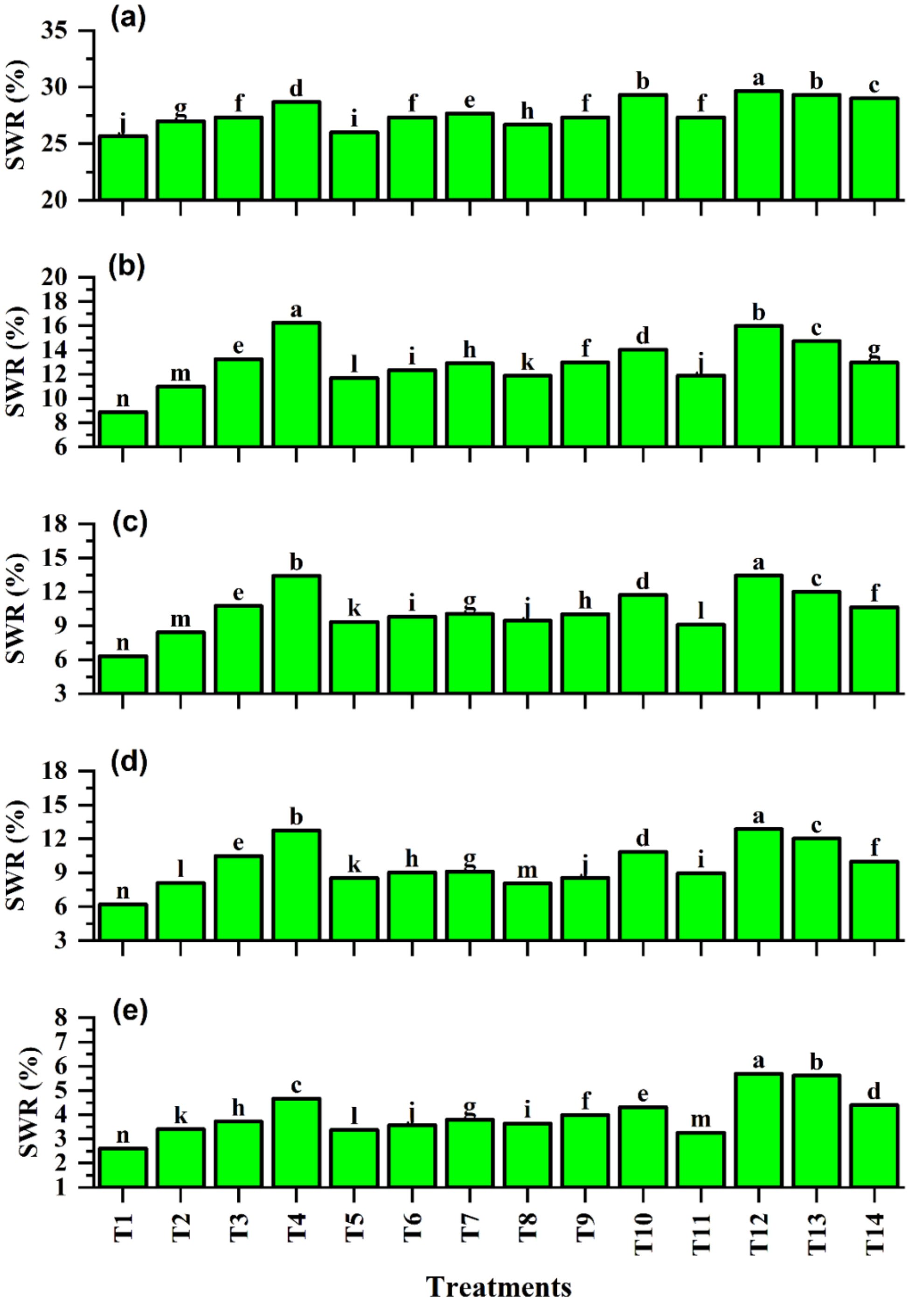

Fig. 1. Effect of different soil amendments on soil water retention (SWR, %) of the studied soil under different applied suction pressures. (a) 0.001 bar, (b) 0.10 bar, (c) 0.33 bar, (d) 1.00 bar, (e) 15.00 bar, (T1) control, (T2) bentonite 2%, (T3) bentonite 3%, (T4) bentonite 4%, (T5) biochar 0.5%, (T6) biochar 1%, (T7) biochar 1.5%, (T8) compost 5 ton fed^{-1}, (T9) compost 10 ton fed^{-1}, (T10) compost 15 ton fed^{-1}, (T11) bentonite 3% + biochar 1%, (T12) biochar 1% + compost 10 ton fed^{-1}, (T13) bentonite 3% + compost 10 ton fed^{-1}, (T14) bentonite 3% + biochar 1%+ compost 10 ton fed^{-1}. Columns with different letters are significantly different (*P* < 0.05 level), while the same letters represent no significant difference.

In this study, the addition of bentonite showed satisfactory results for enhancing soil texture by increasing the proportion of fine particles and improving soil aggregation (Wahba et al., 2020). This leads to better water retention, reduced bulk density, and increased nutrient availability (Czaban & Siebielec, 2013). In compost treatment, the application has significantly improved the hydro-physical properties of sandy soils (Das & Ghosh, 2024).

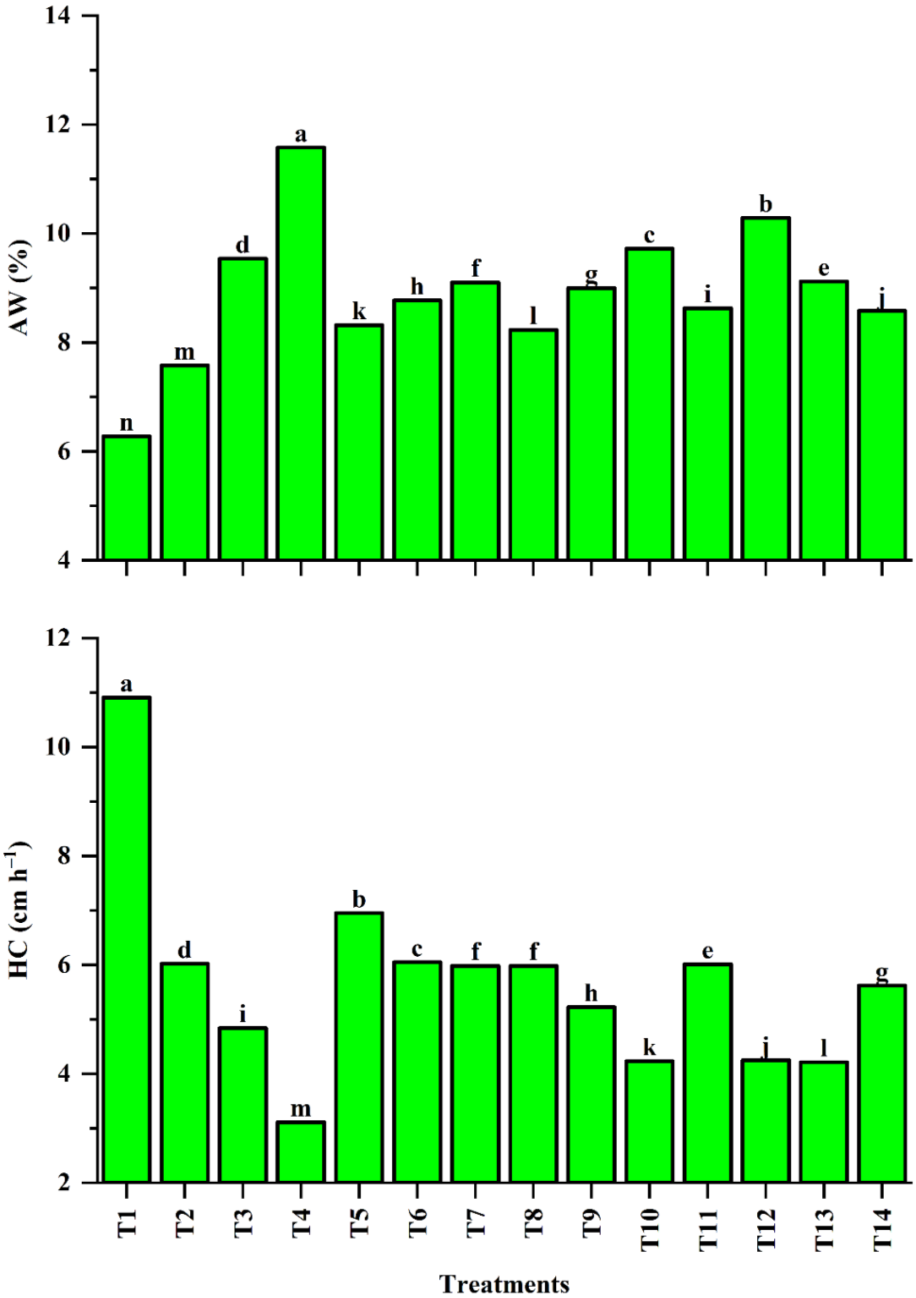

Fig. 2. Effect of different soil amendments on the studied soil's available water (AW) and hydraulic conductivity (HC). (T1) control, (T2) bentonite 2%, (T3) bentonite 3%, (T4) bentonite 4%, (T5) biochar 0.5%, (T6) biochar 1%, (T7) biochar 1.5%, (T8) compost 5 ton fed^{-1}, (T9) compost 10 ton fed^{-1}, (T10) compost 15 ton fed^{-1}, (T11) bentonite 3% + biochar 1%, (T12) biochar 1% + compost 10 ton fed^{-1}, (T13) bentonite 3% + compost 10 ton fed^{-1}, (T14) bentonite 3% + biochar 1%+ compost 10 ton fed^{-1}. Columns with different letters are significantly different ($P < 0.05$ level), while the same letters represent no significant difference.

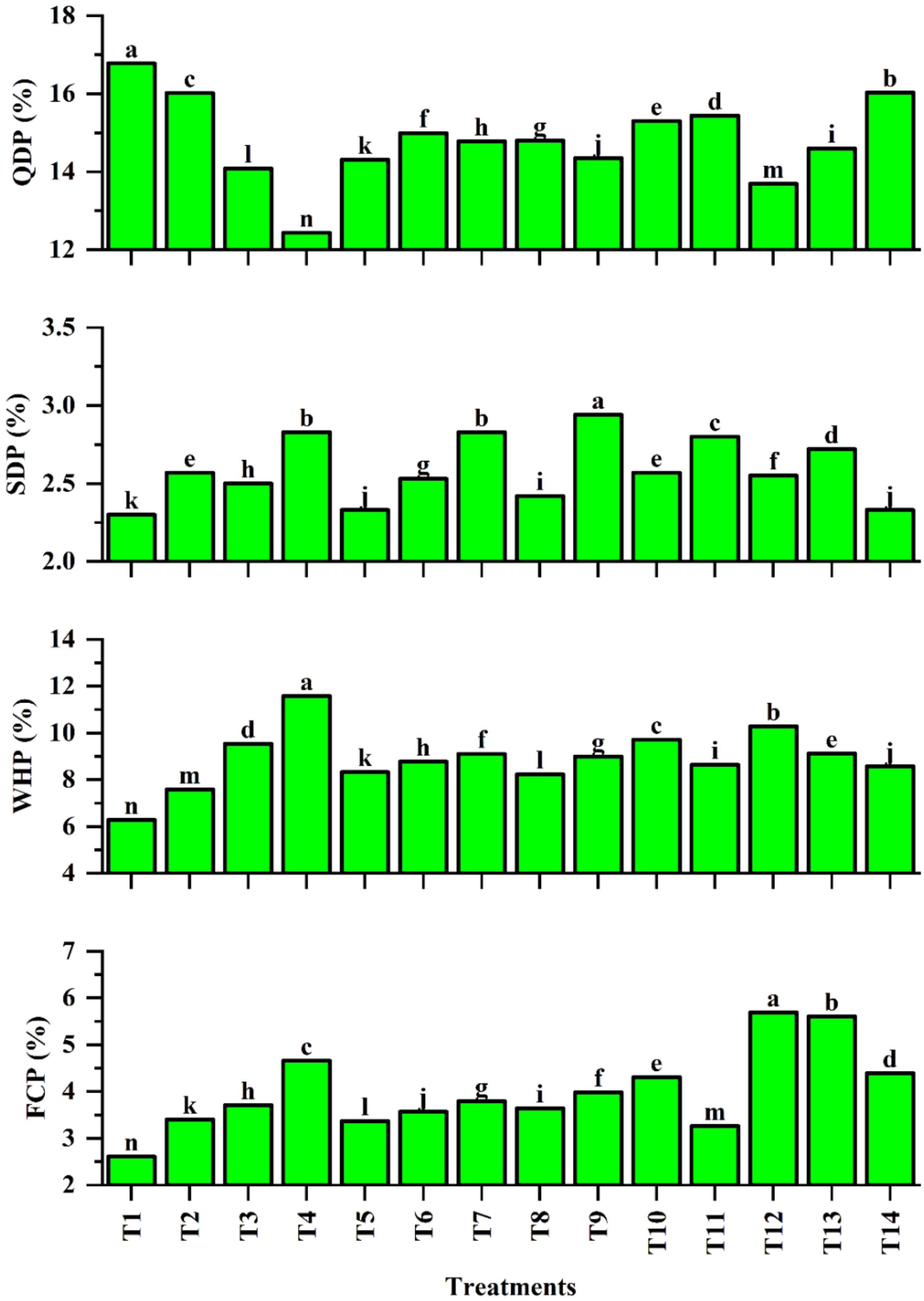

Fig. 3. Effect of different soil amendments on the studied soil's pore size distribution (PSD). (QDP) quickly drainable pores, (SDP) slowly drainable pores, (WHP) water holding pores, (FCP) fine capillary pores, (T1) control, (T2) bentonite 2%, (T3) bentonite 3%, (T4) bentonite 4%, (T5) biochar 0.5%, (T6) biochar 1%, (T7) biochar 1.5%, (T8) compost 5 ton fed^{-1}, (T9) compost 10 ton fed^{-1}, (T10) compost 15 ton fed^{-1}, (T11) bentonite 3% + biochar 1%, (T12) biochar 1% + compost 10 ton fed^{-1}, (T13) bentonite 3% + compost 10 ton fed^{-1}, (T14) bentonite 3% + biochar 1%+ compost 10 ton fed^{-1}. Columns with different letters are significantly different (P< 0.05 level), while the same letters represent no significant difference.

Soil amendments also positively impacted SWR in sandy soils (Kang et al., 2022). Like the findings of this experiment, Botková et al. (2023) and Šurda et al. (2024) also observed that biochar significantly increases the available water content (AWC) in sandy soils, which is crucial for plant growth. The type and particle size of biochar influence its effectiveness; smaller particle sizes tend to yield better results in enhancing water retention (Botková et al., 2023). In this experiment, the bentonite application can significantly increase SWR and AW by improving the soil's ability to hold moisture (Mancy & Sheta, 2021; Mi et al., 2020). This result could be explained based on the effect of the bentonite on increasing WHP and decreasing QDP. Moreover, the fine particles in bentonite block the macropores between the sand particles due to binding several grains to aggregates. Compost application can increase water-stable aggregates, improve PSD, and increase soil available water in sandy soils (Ibrahim et al., 2021).

Pore size distribution significantly influences water retention and movement in the soil and is heavily impacted by the soil's texture and structure (Gao et al., 2019). To enhance water retention in sandy soil, efforts should be directed toward redistributing the pores, which involves increasing WHP while reducing QDP (El-Ngar & Abu El-Ezz, 2021). Generally, improving PSD in the studied soil can be linked to increased storage pores. It also boosts the number of inter-aggregates and reduces QDP while increasing WHP, SDP, and FCP (Sheta et al., 2019). This is crucial for improving water movement and retention in sandy soil, where it's essential to minimize water movement and enhance moisture retention (Ghanem et al., 2022). It was observed that the soil amendments significantly improved the sandy soil's hydraulic conductivity and PSD (Dong et al., 2022). Biochar alters PSD, with optimal biochar content differing based on soil type, affecting water retention capabilities (Alghamdi et al., 2020). This could be due to the biochar's porous structure and ability to alter PSD, collectively contributing to better plant moisture retention and availability.

Conversely, while biochar shows promise in improving sandy soil properties, excessive application may lead to adverse effects, such as pore blockage and reduced water flow, highlighting the need for balanced application strategies (Acharya et al., 2024). Recently, Šurda et al. (2024) found that the impact of biochar on hydraulic conductivity varies; while wettable biochar maintains conductivity, water-repellent biochar can decrease due to blockage of water pathways. In our investigation, modifying PSD through bentonite application results in a higher proportion of mesopores and micropores, which are crucial for water storage (Abdelfattah & Mostafa, 2024). Additionally, bentonite has been shown to reduce hydraulic conductivity, thereby decreasing the rate of water loss through drainage and improving overall soil water dynamics (Demdoum et al., 2021). In this study, the decrease in HC might be due to bentonite blocking the macropores between the sand particles and binding several particles to form aggregates. The binding effect would partially shift the pore size from non-capillary to capillary, decreasing the HC. The improvement in soil functions due to compost addition is mainly attributed to modifying soil structure parameters, such as increased mesopores and improved pore continuity (Al-Omran et al., 2019).

5. Conclusions

This study aims to comprehensively analyze how different amendments affect the physical and hydrological properties of sandy soils—examining parameters such as TP, BD, WHC, and hydraulic conductivity values. This study concluded that adding 4% bentonite to sandy soil significantly boosted the value content of WHP and decreased QDP. Thus, the soil's moisture content increased at FC and AW. Over and above, bentonite is widely available and economically reasonable, making it an excellent option for soil amendment. The findings of this research will contribute to the development of sustainable soil management practices, particularly in regions where sandy soils predominate and water scarcity is a critical concern. This approach aligns with the current circumstances, which require minimizing water wastage and maintaining the appropriate soil moisture level to meet crop needs, achieving optimum production.

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