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S. I. BIOCHAR

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Impact of biochar with different organic materials on carbon fractions, aggregate size distribution, and associated polysaccharides and soil moisture retention in an arid soil

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Abstract

Biochar and organic amendments manipulate numerous soil properties but limited research has been done on the combined effect of biochar and different organic materials in an arid soil. The current study focuses on the distribution of dry soil aggregate size and associated polysaccharides by the application of biochar and its combination with other organic amendments. The treatments were the following: (i) control, (ii) biochar, (iii) poultry litter, (iv) sugarcane bagasse, (v) crop residue, (vi) biochar + poultry litter (B + PL), (vii) biochar + sugarcane bagasse (B + SB), and (viii) biochar + crop residue (B + CR). Amendments were applied on 1% total organic carbon based on soil weight. Mung bean (*Vigna radiata* L.) crop was sown as a test crop. The highest total organic carbon (TOC) was in biochar and crop residues (11.42 g kg^{-1} and 11.04 g kg^{-1} respectively); POC highest stocks were also under the same combination with similar quantity (3.80 g kg^{-1} and 3.80 g kg^{-1} respectively). The MBC stocks (0.25 g kg^{-1}) were highest in biochar along other combinations. In organic amendments, poultry litter produced relatively higher macroaggregation than other treatments. Polysaccharides contents had the following incremental trend: sugarcane bagasse > biochar + sugarcane bagasse > poultry litter > biochar + crop residue > crop residue alone > biochar + poultry residue > biochar > control. The highest digest plant available moisture content (θ_{AMC}) 14.3% was recorded in the biochar applied with the combination of sugarcane bagasse. However, the highest plant biomass (61.33 g) was in biochar + poultry litter and plant height (37.67 cm) was in biochar. Overall biochar application with crop residues is effective in improving the carbon fractions and its combination with sugarcane bagasse improves polysaccharides and soil moisture content in the arid soil.

Keywords Biochar · Soil aggregate sizes · Polysaccharides · Organic carbon · Soil moisture retention

This article is part of the Topical Collection on *Implications of Biochar Application to Soil Environment under Arid Conditions*

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Introduction

Biochar is the product of thermal degradation of organic materials in pyrolysis and is used as a soil conditioner to improve crop production and remediate soil pollution (Lehmann 2007; Al-Wabel et al. 2013; Rehman et al. 2017; Abbas et al. 2018a, b). Biochar produced from pyrolysis of corn stover feedstock at 350 °C has been found to extensively enhance aggregate stability and soil moisture retention (Herath et al. 2013). Biochar can increase soil aggregation as it affects the soil moisture retention pattern (Li et al. 2018). Stimulation in soil biological community and aggregation abundance with the application of biochar have been observed (Liang et al. 2006; Grossman et al. 2010; Wei et al. 2014) that ultimately affect nutrient cycles and plant growth (Wardle et al. 2008; Kuzyakov et al. 2014). Biochar addition improves the rate of photosynthesis and plant growth under water stress conditions by increasing soil moisture retention capacity of the soil (Ali et al. 2017: Paneque et al. 2016). Crop yield reduces under water stress because of interference in the transport of carbon (Muller et al. 2011). Application of biochar increased the biomass of wheat in a field under semi-arid climatic condition (Olmo et al. 2014). Application of biochar is also an effective approach to mitigate climate change as it decreases the CO_2 emission from soil to atmosphere (Joseph et al. 2007).

Aggregation of soil is the assimilation of individual soil particles that influence many soil physical, chemical, and biological processes, such as soil aeration, soil water infiltration, and soil microbial activities (Zhang et al. 2017). Soil aggregate sizes and stability play a vital role in soil conservation by minimizing the damage caused due to the erodibility agents of wind, water, and anthropogenic activities (Ghosh et al. 2016). Aggregates smaller than 0.84 mm in diameter are well thought out as erodible by wind and their proportion in the upper 25.4 mm of soil surface considered the wind erodible fraction (Colazo and Buschiazzo 2010).

Extensive research has been underway in recent years on effects of biochar on soil processes such as enzymatic activity, enrichment of nutrients for plants (Al-Wabel et al. 2017), and carbon sequestration (Feng and Zhu 2017; Abbas et al. 2018a, b). However, the potential of biochar for improvement of soil aggregation has rarely been assessed, particularly, in arid conditions where excessive plowing in the fallow-based cropping system is deteriorating soil aggregation and overall health of soil and plants. In this study, mung bean is selected as a test crop because it is an important short-term legume crop in Pakistan and recommended for different cropping sequences to improve soil fertility status due to its nodulation capacity. Moreover, the production of biochar from paper mulberry leaves will also help in converting waste material into a useful soil amendment. Therefore, it is hypothesized that biochar combination with poultry manure, sugarcane bagasse, and wheat crop residues acts as an additive for the carbon fractions, soil moisture retention, and polysaccharides associated with aggregate stability and sizes. The objective of this study was to evaluate the potential of biochar with or without different organic plant materials in the soil for enhancement of soil organic carbon fractions, soil moisture retention, and the relationship of polysaccharides contents with respect to different soil aggregates.

Materials and methods

Soil sampling

A greenhouse pot experiment was conducted at the PMAS-Arid Agriculture University Rawalpindi, Pakistan. The bulk soil was collected from arid agriculture land and ground with soil diaglomerator and passed through 2-mm sieve. The soil used in this study was categorized as sandy clay loam having pH 7.78, ECe 0.27 dSm^{-1}, nitrate-nitrogen 3.83 mg kg^{-1}, available phosphorous 6.50 mg kg^{-1}, and TOC 3.37 g kg^{-1} (Table 1).

Experimental setup

Pots with 20 cm width and 30 cm height were filled with 2.50-kg grounded soil. After incorporating all organic materials such as biochar, poultry litter, sugarcane bagasse, and wheat crop residues (on 01% TOC equivalent basis) into the soil, pots were incubated at room temperature (25~30 °C) with plastic bags for 15 days. The recommended dose of fertilizer (25 kg N, 35 kg P_2O_5, and 0 kg K_2O ha^{-1}) in the form of urea and single superphosphate was applied before sowing of seeds. Four seeds of mung bean (*Vigna radiata* L.), variety Chakwal Mung-2006, were sown in each pot and placed in a greenhouse under controlled conditions. After a week of germination, four plants were thinned to two uniform seedlings per pot. Irrigation requirements were fulfilled by tap water fit for irrigation. Treatments were replicated three times using a completely randomized design (CRD). The crop was harvested at maturity and soil samples were taken and analyzed for carbon fractions, moisture content, polysaccharide content, and aggregate size distribution.

Biochar production

Biochar was prepared from paper mulberry (*Broussonetia papyrifera*) leaves in the laboratory. For this, dry leaves after oven drying were ground with plant grinder and kept in a muffle furnace at 350 °C for 3 h.

Organic material properties

The biochar had 1.5% N and 9.5 pH while the poultry litter contained 1.71% N and 7.8 pH. The sugarcane bagasse and wheat crop residues contained 0.72% N and 0.52% N, respectively.

Table 1 Physicochemical properties of experimental soil

Characteristics	Values
Clay (%)	26
Sand (%)	50
Silt (%)	24
Soil texture	Sandy clay loam
pH	7.78
ECe (dSm^{-1})	0.27
Available P (mg kg^{-1})	5.75
Total organic carbon (g kg^{-1})	3.37
Nitrate-nitrogen (mg kg^{-1})	3.83

Organic carbon fraction measurements

Total organic carbon was measured by titrating the samples with 0.5 N ferrous ammonium sulfate solution until the color changed from blue to dark green (Walkley and Black 1934). Particulate organic carbon was measured by dispersing particles with sodium hexametaphosphate. Then, the material passed through 50-μm sieve and then rinsed with water to remove silt and clay. The POC and sand retained on a sieve and then was dried at 100 °C, ground and passed through 18-μm screen (Cambardella and Elliott 1992) and analyzed for carbon (Nelson and Sommers 2005). Microbial biomass carbon of soil was determined through the fumigation-extraction method. The CO_2 evolved during incubation of soil in the closed jar was measured by trapping CO_2 in 25 mL of NaOH solution and then titrated against standard HCl solution using phenolphthalein as an indicator (Nannipieri et al. 1978) (Table 2).

Dry soil aggregate size distribution analysis

The dry soil aggregate size distribution was measured by taking the 750 g of soil sample and then passed through the sieves of > 8, 4–8, 2.5–4, 1.25–2.5, 0.63–1.25, 0.25–0.63, 0.05–0.25, and < 0.05 mm in rotary sieve machine (Robertson et al. 1984). At the start of the experiment, first three sieves > 8, 4–8, and 2.5–4 mm had no soil while the remaining sieves 1.25–2.5, 0.63–1.25, 0.25–0.63, 0.05–0.25, and < 0.05 had the weight of soil aggregates 0.8, 7.12, 27.45, 40.34, and 24.2%, respectively.

Polysaccharide determinations

Hot water extractable polysaccharides were measured from a 1-g ground sample of each soil aggregate fraction by adding 40 mL of distilled water at 80 °C for 24 h. The solution was collected after centrifuged and 2 mL of the aliquot was added with 1 mL of phenol solution (5% w/v) followed by immediate addition of 5 mL of concentrated sulfuric acid. Then, samples were measured on a spectrophotometer at 485 nm (DuBois et al. 1956).

Table 2 Total organic carbon content of amendments

Organic amendment	Total organic carbon (%)	Weight applied per pot 2 kg soil (g)
Biochar	66	30.3
Poultry litter	16	125
Sugarcane bagasse	51	38
Crop residue	42	47.6

Water content measurements

Water contents at field capacity and permanent wilting point were measured using pressure membrane apparatus. The soil samples were applied with pressures of 0.33, 1, 5, and 15 bars. The RETC-Fit software was used to simulate the moisture characteristic curves (Reeve and Carter 1991).

Statistical analysis

Data was analyzed using SPSS (Version 19.0) for analysis of variance (ANOVA). Least significance difference (LSD) test was used for comparison of treatment means (Gokmen et al. 2001).

Results and discussion

Carbon stock and its fractions

Treatments effect on total TOC, POC, MBC, and CO_2-C were statistically significant (Table 3). Biochar and combination of biochar with organic materials gave significantly higher stocks of TOC than control. Organic amendment application is reported to ameliorate the degraded soils by increasing soil organic carbon in the semi-arid area (Masciandaro et al. 2013). The decomposition of organic materials and their stability in soil generally depends on the material C/N ratio and their physical and biological protection in the soil and climatic conditions (Hernandez et al. 2017). Moreover, the organic matter plays a critical role in aggregate stability by providing the binding agents in the soil system (Tejada et al. 2009). The treatment biochar (11.42 g kg^{-1}) and crop residue (11.04 g kg^{-1}) had the highest TOC values that were higher than all other treatments. The lowest TOC content was measured in control (5.57 g kg^{-1}). Increase in TOC contents was observed when biochar applied with the combination of poultry litter and sugarcane bagasse.

Particulate organic carbon data clearly indicate that the effect of organic amendments was statistically higher in case of biochar and also in biochar along with crop residue application. Quantities of POC ranged from 2.01 to 3.8 g kg^{-1}. The lowest value was recorded for control treatment (2.01 g kg^{-1}). Poultry litter decreased the POC contents (2.19 g kg^{-1}). The results regarding microbial biomass carbon revealed that higher amount of MBC was observed in the treatment biochar with the numerical value of 0.25 g kg^{-1} soil, while the minimum amount of microbial biomass C was observed in control treatment (0.16 g kg^{-1}). The treatments B + PL (0.24 g kg^{-1}) and biochar plus crop residue (0.229 g kg^{-1}) produced higher MBC than all other treatments that were statistically similar to each other. Microbial biomass C was observed to increase when biochar applied in combination with poultry litter and

Table 3 Soil organic carbon and its fractions as affected by biochar and other organic inputs

Treatments	TOC (g kg^{-1})	POC (g kg^{-1})	MBC (g kg^{-1})	CO_2-C (μg g^{-1}soil day^{-1})
Control	5.57e	2.02c	0.16b	33.2e
Biochar (B)	11.42a	3.80a	0.25a	49.0a
Poultry litter (PL)	8.49d	2.19c	0.21ab	37.0d
Sugarcane bagasse (SB)	9.77c	2.97b	0.20ab	43.8b
Crop residue (CR)	11.04ab	3.80a	0.22ab	39.3c
B + PL	10.19bc	2.55bc	0.24a	39.2c
B + SB	10.09bc	2.61bc	0.21ab	44.5b
B + CR	9.29cd	3.24ab	0.23a	41.0c

Least significance least (LSD) of test at $P < 0.05$ used for comparison of mean. B + PL, biochar + poultry litter; B + SB, biochar + sugarcane bagasse; B + CR, biochar + crop residues

crop residue (0.240 and 0.229 g kg^{-1}) than when both applied individually (207 and 218 g kg^{-1}, respectively).

The data pertaining to mineralizable carbon ranged from 33.25 to 48.99 μg CO_2-C g^{-1} soil day^{-1}. Soil samples treated with biochar and sugarcane bagasse produced relatively maximum mineralizable carbon (CO_2-C). Overall, no statistical difference was observed among the treatments when biochar applied with crop residue or poultry litter. It was also observed that the interaction of biochar and sugarcane bagasse was not synergistic. Moreover, the highest emission CO_2-C was observed in biochar with the numerical values of 48.99 μg CO_2-C g^{-1} soil day^{-1} while the minimum emission of CO_2-C was observed in control treatment. The results were in line with the findings of Luo et al. (2011) and Jones et al. (2010); they also found that maximum CO_2-C was recorded in soil samples amended with biochar.

Biochar applied in this experiment contains 66% total organic carbon, so it ultimately increases the contents of particulate organic carbon and total organic carbon of soil. Microbial biomass carbon and mineralizable carbon were statistically non-significant. Biochar and its combinations with other organic plant materials can improve the soil organic carbon which is important for multiple properties of soil. Due to the recalcitrance of biochar, it remains in soil up to years in the form of POC fraction and sometimes up to decades and centuries to store carbon, especially in arid soils (Liang et al. 2010).

Dry soil aggregate size distribution

Data pertaining to soil aggregate size distribution are given in Fig. 1. A significant improvement in all soil aggregation was observed. About 11.36% large macroaggregates were formed in soil fraction > 8-mm size. Improvement in soil aggregates (< 0.05) was recorded as its value was lower in the experimental soil as compared with control. The ratio of soil aggregates (0.25–0.63 mm) was almost equal in control and experimental soil. In soil aggregate < 0.05-mm size, the highest value was recorded in control (22.03%) and lowest was in treatment B + PL (16.09%). So, a lower value indicates that more soil aggregates were formed as compared with control treatment. Similarly, in 0.05–0.25-mm size, lower value was obtained in poultry litter treatment (18.67%) while higher value was recorded in control (31.89%). So, poultry litter performs better in the transformation of microaggregates into the macroaggregates.

Microaggregates reduced with the carbon sources addition. Among microaggregates, poultry litter gives better results as compared with control. In soil aggregate 0.05–0.25-mm size, all treatments gave clear differences as compared with control treatment. All treatment showed the same results in soil aggregates of 0.63–1.25-mm size. Sugarcane bagasse improved soil aggregation between 1.25–4-mm sizes while in macroaggregates, poultry litter enhanced the soil aggregation. Actually, sugarcane bagasse has maximum carbohydrates contents, which act as binding agents in soil aggregation. Frey (2005) also depicted in a similar type of experiment that large aggregates were passed through the sieve of 2.5 mm and soil was amended with organic material was incubated at 25 °C. Rapid changes were observed in soil aggregates. Biochar and organic amendments such as wheat crop residues and poultry litter have been suggested to recover degraded soil of arid soil. Biochar-amended soil have more condense

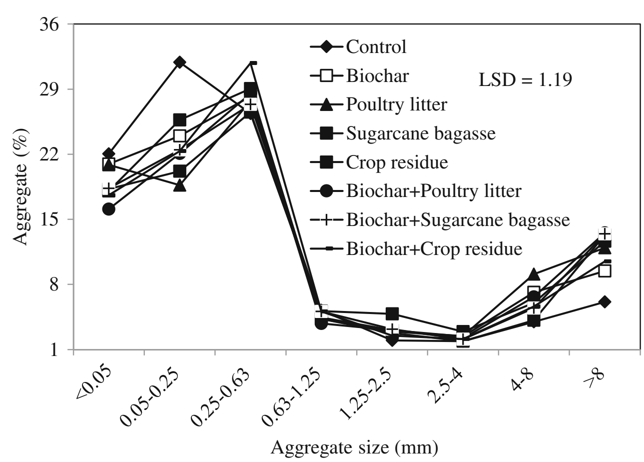

Fig. 1 Aggregate distribution (%) as affected by biochar and its combination with different organic materials

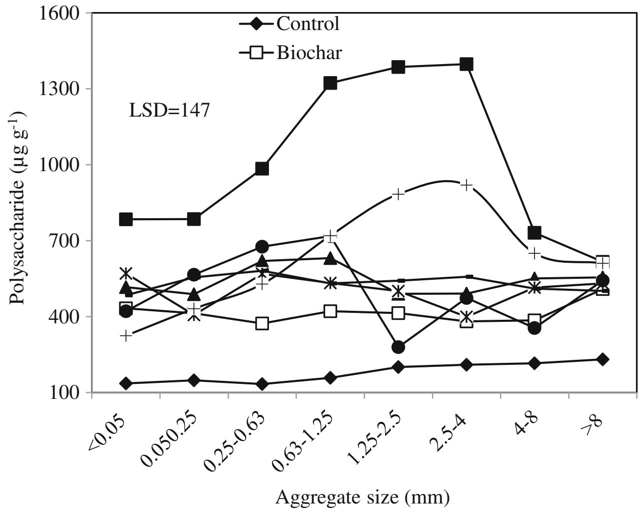

Fig. 2 Polysaccharide content in different soil aggregate size as affected by biochar in combination organic amendments indicating maximum polysaccharide content in the size of 0.63 to 4 mm with sugarcane bagasse.

aromatic hydrogen- and carbon-bonded group which are resistant to soil degradation and help in aggregates formation along with protection of carbon pools (Hansen et al. 2016).

Polysaccharide contents

The dynamics of soil polysaccharides contents with respect to different organic materials amendment soil is given in Fig. 2. Data clearly showed that sugarcane bagasse treatment produces the highest contents of polysaccharides (1001.18 μg g^{-1}) while the lowest amount of polysaccharides contents was measured in control treatment (179.29 μg g^{-1}). The highest amount of polysaccharides was measured (629.61 μg g^{-1}) in soil aggregates of 0.63–1.25-mm size and minimum amount (459.12 μg g^{-1}) was measured in soil aggregates of < 0.05-mm size. It was observed that polysaccharides contents decreased from soil aggregates of 0.63–1.25-mm size up to soil aggregates < 0.05-mm size. The results were in line with the findings of Bongiovanni and Lobartini (2006); they also observed the decrease in the polysaccharides (0.24, 0.33, 0.29, and 0.19 g kg^{-1}) with the decrease in the soil aggregate sizes (2800–2000, 2000–250, 250–53 and < 53 μm), respectively.

Sugarcane bagasse contains 48.6% cellulose, 31.1% hemicelluloses, and 19.1% lignin (Sanjuan et al. 2001). The samples with the smallest amounts of lignin did not produce the largest amounts of total polysaccharides (Masarin et al. 2011). Also, it was observed that sugarcane bagasse is not easily decomposable material, so the clear result in soil aggregation had not been given as compared with other carbon sources.

Water characteristic curves

The RETC-Fit software was used to simulate the water contents at field capacity, permanent wilting point, and plant available water. The data regarding soil moisture characteristic curve influenced by the application of biochar and other organic inputs is given in Table 4 and Fig. 3. Available water contents (θ_{AWC}) were obtained by the difference of water contents at field capacity (θ_{FC}) and at the permanent wilting point (θ_{PWP}). The higher available water contents were measured in soil samples treated with sugarcane bagasse and biochar + sugarcane bagasse (14.3 and 14.75%, respectively). Biochar retained more water (13.69%) as compared with poultry litter (12.51%) and crop residue application (12.96%). Results showed that biochar in combination with sugarcane bagasse (B + SB, 28.96%), and sugarcane bagasse (27.86%) and biochar (27.67%) alone, retained higher water contents at field capacity. Biochar retained more water as compared with other carbon sources possibly because of its porous structure and extremely high surface area. This structure changes the physical properties of the soil, creating a reef-like structure. Results were in line with the findings of Herath et al. (2013).

Crop yield and yield components

Mung bean plant shoot length, biomass, and pods per plant are effective in biochar and sugarcane bagasse also in combination with Table 5. The plant biomass data was ranged from 41 to

Table 4 Field capacity, permanent wilting point, and plant available water content as influenced by biochar in combination with other organic amendments

Treatments	Treatments	θ_{FC} (%)	θ_{PWP} (%)	θ_{AMC} (%)
Control	Control	26.12	16.94	9.18
Biochar (B)	Biochar	27.67	13.98	13.69
Poultry litter (PL)	Poultry litter	27.45	14.94	12.51
Sugarcane bagasse (SB)	Sugarcane bagasse	27.86	13.56	14.3
Crop residue (CR)	Crop residue	26.35	13.39	12.96
B + PL	Biochar + PL	26.96	14.12	12.84
B + SB	Biochar + SB	28.96	14.21	14.75
B + CR	Biochar + CR	26.98	14.76	12.22

Least significance least (LSD) of test at $P < 0.05$ used for comparison of mean. B + PL, biochar + poultry litter; B + SB, biochar + sugarcane bagasse; B + CR, biochar + crop residues

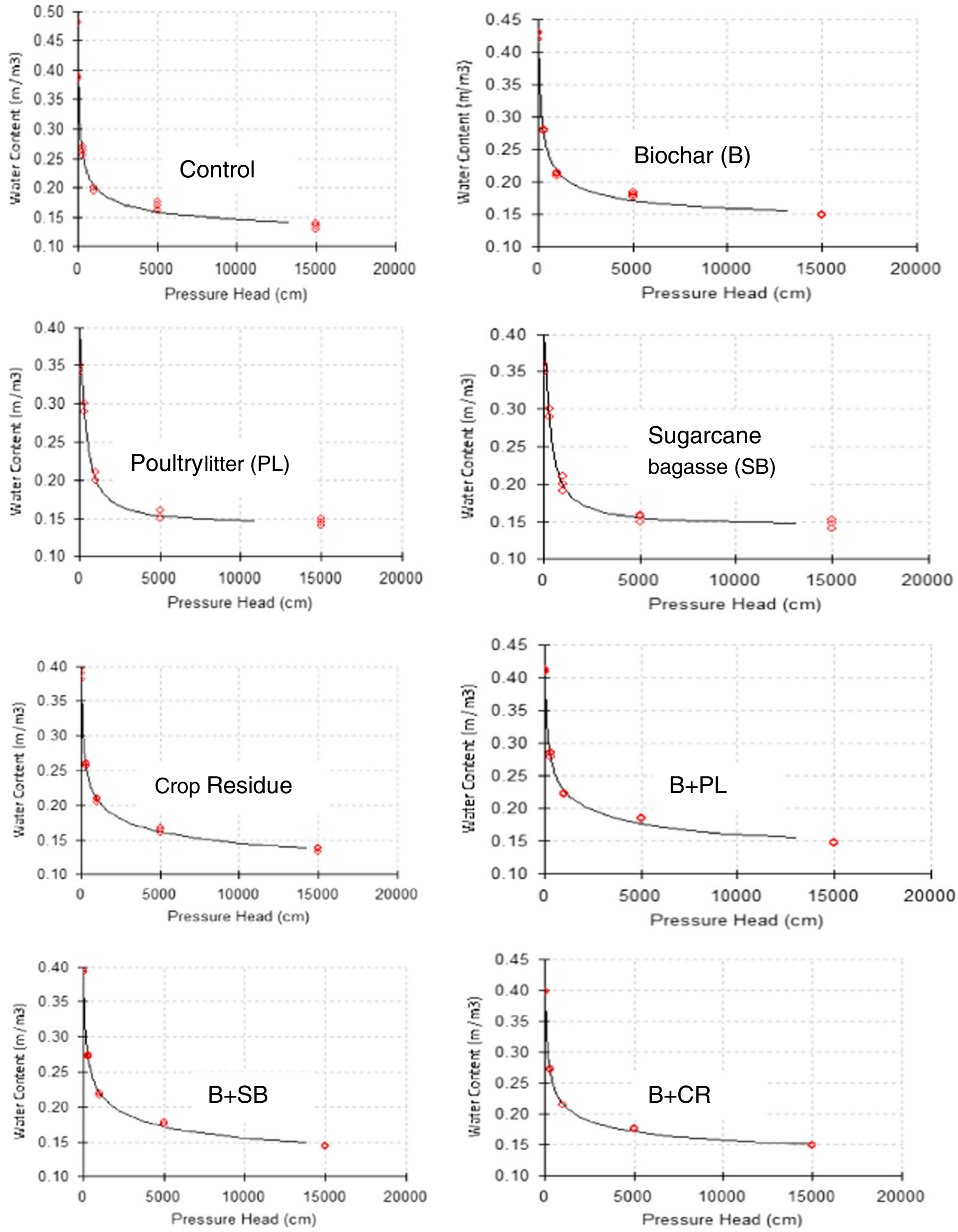

Fig. 3 RETC-Fit predicted soil moisture characteristic curves under biochar and its combination with different organic amendments

Table 5 Crop data as influenced by biochar in combination with other organic amendments

Treatments	Shoot length (cm)	Biomass per plant (g)	Pods plant^{-1}
Control	31c	41f	11.3d
Biochar(B)	37a	56.3b	16b
Poultry litter(PL)	31c	44.7e	13.7c
Sugarcane bagasse(SB)	34.7ab	56.3b	19a
Crop residue(CR)	34.3abc	48.7d	15.3bc
B + PL	33bc	49d	15.3bc
B + SB	37.7a	61.3a	19a
B + CR	35.7ab	52c	16.3b

Least significance least (LSD) of test at $P < 0.05$ used for comparison of mean. B + PL, biochar + poultry litter; B + SB, biochar + sugarcane bagasse; B + CR, biochar + crop residues

61.33 g. The result of B + PL litter was highly statistically significant among all other treatments with the numerical value 61.33 g. Biochar and sugarcane bagasse results were statistically non-significant. The plant height was in ranged of 31 to 37.67 cm. The maximum plant height (37.67 cm) was recorded in B + PL and the lowest height (31 cm) was recorded in control, which could be due to soil compaction and less root penetration. The result of biochar application with and without sugarcane bagasse and wheat crop residues was also statistically non-significant. It was observed that the short-term stay of biochar amendments did not improve crop yield but effectively improves soil carbon pools (Zhang et al. 2012).

Conclusion

Result depicted that various organic amendments improve different characteristics of the soil. The biochar in combination with sugarcane bagasse and wheat crop residues significantly improves water holding capacity and particulate organic carbon as well as total organic carbon. Sugarcane bagasse can considerably improve the polysaccharide content of all sized aggregates. The aggregation was promoted by all the organic amendments; however, the addition of poultry litter promoted relatively more macroaggregation.

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