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RESEARCH ARTICLE

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Enhancement of physical and hydrological properties of a sandy loam soil via application of different biochar particle sizes during incubation period

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Abstract

In spite of many studies that have been carried out, there is a knowledge-gap as to how different sizes of biochars alter soil properties. Therefore, the main objective of this study was to investigate the effects of different sizes of biochars on soil properties. The biochars were produced at two pyrolysis temperatures (350 and 550 °C) from two feedstocks (rice husk and apple wood chips). Produced biochars were prepared at two diameters (1-2 mm and <1 mm) and mixed with soil at a rate of 2% (w/w). Multiple effects of type, temperature and size of biochars were significant, so as the mixture of soil and finer woodchip biochars produced at 550 °C had significant effects on all soil properties. Soil aggregation and stabilization of macro-aggregates, values of mean weight diameter and water stable aggregates were improved due to increased soil organic matter as binding agents and microbial biomass. In addition, plant available water capacity, air capacity, S-index, meso-pores and water retention content were significantly increased compared to control. But, saturated hydraulic conductivity (Ks) was reduced due to blockage of pores by biochar particles, reduction of pore throat size and available space for flow and also, high field capacity of biochars. So, application of biochar to soil, especially the finest particles of high-tempered woody biochars, can improve physical and hydrological properties of coarse-textured soils and reduce their water drainage by modification of Ks.

Additional key words: aggregate stability; quality indexes; saturated hydraulic conductivity; soil pores; water retention.

Abbreviations used: AC (air capacity); AWC (available water content); BET (Brunauer-Emmett-Teller); CEC (cation exchange capacity); d_{50} (median grain diameter); EC (electrical conductivity); FC (field capacity); Ks (saturated hydraulic conductivity); MWD (mean weight diameter); PAWC (plant available water capacity); S-index (soil physical quality index of Dexter); SOM (soil organic matter); SSA (specific surface area); SWRC (soil water retention curve); WSA (water stable aggregates); ρ_b (bulk density).

Authors' contributions: Performed the experiments and statistical analysis, and wrote the paper: LE. Supervised the work: MS. Advised the research project: MG and SMH. The supervisor and advisors of this research support administrative, technical and material needs.

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Introduction

Biochar is a heterogeneous substance rich in aromatic carbon and minerals. It is produced by pyrolysis of biomass under controlled conditions with clean technology and is used for any purpose that does not involve its rapid mineralization to CO_2 and may eventually become a soil amendment (EBC, 2012). Physicochemical properties of the biochar are controlled by pyrolysis conditions *i.e.* temperature and duration of heating and the original feedstock (Jindo *et al*., 2014). These physicochemical properties can induce changes in the soil physical and hydrological properties. The incorporation of biochar into soil modifies soil physical properties, such as structure, porosity, bulk density, and particle size distribution. This may in turn have consequences for important soil functions *e.g.* soil aeration, water retention, and hydraulic conductivity and finally, plant growth (Atkinson *et al*., 2010). Since soil water retention capacity depends on the pore size distribution, and biochar has high porosity and larger inner surface area, therefore, biochar application to soil can also change the soil hydraulic properties (Brockhoff *et al.*, 2010) by affecting soil aggregation through interactions with soil organic matter (SOM), minerals and microorganisms, bulk density (ρ_b), and porosity.

Many studies have explored the agricultural use of biochar. Peake *et al.* (2014) revealed that biochar amendment decreased the ρ_b and increased the field capacity (FC) and plant available water content (PAWC) of a wide range of soil types. The findings of Barnes *et al.* (2014) revealed that soil properties were improved when biochar was added to sandy and clayey soils, the d_{50} (median grain diameter) of the mixtures increased; while, organic soil d_{50} was reduced. According to their results, the addition of biochar reduced the ρ_b of sand and clay by 17 and 20%, respectively. In contrast, ρ_b of organic soils was increased by 10%. Also, they found that on average, biochar amendment reduced saturated hydraulic conductivity by 92% in sand and 67% in organic soils, but increased by 328% in clay-rich soils.

Different researches showed contrasting results. Some found that biochar had positive effects on soil physical and hydrological properties (Githinji, 2014; Peake *et al.*, 2014) while some reported that biochar application had no effects or negative results on soil physical properties (Busscher *et al.*, 2010; Rogovska *et al.*, 2011; Zhang *et al.*, 2012). These contrasting responses could be as a result of different soil and biochars that had been utilized in previous studies.

Research on biochar application to soil has mostly focused on the effects of different biochars and production conditions on soil properties; but to the best of our knowledge, very few experiments have carefully examined the effects of different sizes of biochar particles on soil physical and hydrological properties. Liu *et al.* (2016) studied the impact of biochar concentration and particle size on hydraulic conductivity and dissolved organic carbon leaching of biochar-sand mixtures and only used one type of mesquite wood biochar prepared at 400 °C. Therefore, the objective of the present study was to investigate more detailed and comprehensively the effect of different charring conditions, feedstocks and sizes of applied biochar on numerous physical and hydrological properties of sandy loam soil. The study was performed under laboratory conditions.

Material and methods

Biochar preparation

The biochars used in this research were obtained from two feedstocks: rice husk (*Oryza sativa.* L.) and apple-wood chips (*Malus pumila*). All materials were first air-dried and then cut into small pieces (less than 4-5 cm). These residues were charred at a heating rate of 10 °C/min and held at 350 and 550 °C for 1 h, respectively. The abbreviated names of biochars are listed in Table 1. After cooling, each biochar was passed through 2 and 1-mm sieves. Therefore we had two particle size diameters of biochars: <1 mm and 1-2 mm.

Table 1. Some physical and chemical characteristics of applied biochars. The values presented in the columns are mean ± standard deviation (n=6).

Treatments[1]	Elemental composition (%)			
	C	H	O	N
WL	74.28 ± 0.15	3.75 ± 2.29	22.31 ± 1.26	0.81 ± 0.09
WH	83.84 ± 1.39	1.31 ± 0.46	14.36 ± 2.83	0.39 ± 0.15
RL	38.91 ± 0.94	1.51 ± 1.33	15.23 ± 1.71	0.65 ± 0.96
RH	41.52 ± 2.10	0.80 ± 0.67	9.41 ± 2.07	0.29 ± 0.81

	pH (1:5)	CEC[2] (cmolc/kg)	Surface area (m^2/g)	Average pore diameter (nm)	Total pore volume (cm^3/g)
WL1	5.68 ± 0.10^{a}	11.13 ± 0.02^{a}	10.21^{a}	8.03^{a}	119^{a}
WL2	5.68 ± 0.11^{a}	10.10 ± 0.01^{a}	10.01^{a}	8.10^{a}	118^{a}
WH1	6.02 ± 0.04^{b}	43.21 ± 0.09^{b}	79.43^{b}	1.91^{b}	248^{b}
WH2	6.02 ± 0.03^{b}	26.54 ± 0.06^{c}	48.69^{c}	2.24^{b}	220^{c}
RL1	6.11 ± 0.01^{c}	10.61 ± 0.11^{a}	5.14^{a}	8.13^{a}	160^{d}
RL2	6.11 ± 0.07^{c}	10.11 ± 0.11^{a}	3.91^{a}	8.27^{a}	151^{d}
RH1	6.33 ± 0.10^{d}	25.7 ± 0.07^{c}	36.57^{c}	2.00^{b}	212^{c}
RH2	6.33 ± 0.13^{d}	19.14 ± 0.14^{d}	23.48^{d}	2.36^{b}	209^{c}

[1] Treatments: WL1, apple wood biochar pyrolysed at 350°C (< 1 mm); WL2, apple wood biochar prepared at 350°C (1-2 mm); WH1, apple wood biochar pyrolysed at 550 °C (< 1 mm); WH2, apple wood biochar prepared at 550°C (1-2 mm); RL1, rice husk biochar pyrolysed at 350°C (< 1 mm); RL2, rice husk biochar pyrolysed at 350°(1-2 mm); RH1, rice husk biochar pyrolysed at 550°C (<1 mm); RH2, rice husk biochar pyrolysed at 550°C (1-2 mm). [2] CEC, cation exchange capacity. Different letters indicate differences among the eight treatments.

Particle size distribution of biochars was determined using a Beckman coulter LS 13 Laser diffraction particle size analyzer. The elemental composition of C, H, and N was determined using the elemental analyzer (vario EL, Elementar, Germany). The specific surface area (SSA), the pore volume, and the average pore size of the biochars were determined using N_2 sorption isotherms, using the Brunauer-Emmett-Teller (BET) method (Belsorp mini Π, BelJapan) (Zhang *et al.*, 2012). Biochar pH was measured using a pH probe with a 1:5 (w/w) suspension of biochar in deionized water (Lei & Zhang, 2013). Cation exchange capacity (CEC) of biochar was determined by the summation of cations adsorbed to the biochar surface by replacing them with ammonium ions (Yuan *et al.*, 2011). Biochar bulk density was measured by helium pycnometry (Brewer *et al.*, 2014). The soil microbial biomass carbon was determined using the fumigation-extraction method (Brookes *et al.*, 1985).

Soil properties and experimental design

Soil samples were collected from 0-20 cm of soil surface layering in the Qazvin plain, Qazvin province, Iran. After air-drying, the soil samples were sieved using a 2-mm sieve and thoroughly homogenized. Total C and N of the soil were measured by an elemental analyzer (Vario EL, Elementar, Germany). Soil pH was measured using a pH probe at a 1:5 (w/w) with deionized water suspension. CEC, $CaCO_3$, electrical conductivity (EC), pH, were measured according to Soil Survey Staff (2014).

The biochars were mixed into the soil at a ratio of 2% (w/w in dry weight basis) to determine its effect on soil aggregation (Ouyang *et al.*, 2013) and the soil without biochar addition as the control, resulting in nine treatments. Abbreviations of treatments are listed in Table 2. The bulk density of the mixtures (ρ_b) of soil and biochars was calculated as follow (Adams, 1973):

$$\rho_b = \frac{100}{\left[\left(\frac{x}{\rho_1}\right) + \frac{(100-x)}{\rho_2}\right]} \qquad [1]$$

where x is the percentage by weight of biochar, ρ_1 is the bulk density of biochar, and ρ_2 is the soil bulk density.

To measure the changes of saturated hydraulic conductivity (K_s) during the incubation period, samples of each treatment were filled into metal cylinders (5 cm height and 5 cm diameter) based on the bulk densities. The bottom of cylinders was packed using 250-mesh gauze. The experimental conditions were similar to incubation period. Six replicates were set up for each treatment on every sampling date. K_s was measured based on falling head (Iranian ATASH setup). Sampling dates were at 5, 15, 30, 50, 80, 120, and 180 days after the beginning of incubation. During these days, changes in soil aggregates were measured using wet sieve

Table 2. Changes of total, macro, meso, and microporosity (cm^3/cm^3) in different mixtures of soil and biochar during incubation period. The values presented in columns are mean ± standard deviation (n=6).

	S	**SWL1**	**SWL2**	**SWH1**	**SWH2**	**SRL1**	**SRL2**	**SRH1**	**SRH2**
Day 5									
Total (cm^3)	30.0 ± 0.12^{aA}	37.0 ± 0.11^{bA}	37.5 ± 0.17^{bA}	40.0 ± 0.18^{bA}	38.0 ± 0.13^{bA}	38.3 ± 0.11^{bA}	37.4 ± 0.14^{bA}	38.6 ± 0.10^{bA}	38.0 ± 0.16^{bA}
Macro (cm^3)	5.80 ± 0.01^{aA}	4.50 ± 0.04^{aA}	5.50 ± 0.09^{aA}	6.10 ± 0.07^{bA}	5.00 ± 0.03^{aA}	5.50 ± 0.01^{aA}	5.60 ± 0.00^{aA}	5.40 ± 0.01^{aA}	5.00 ± 0.001^{aA}
Meso (cm^3)	19.1 ± 0.56^{aA}	26.0 ± 0.17^{bA}	25.4 ± 0.16^{bA}	27.2 ± 0.14^{cA}	26.4 ± 0.10^{bA}	26.2 ± 0.03^{bA}	25.3 ± 0.10^{bA}	26.6 ± 0.03^{bA}	26.5 ± 0.09^{bA}
Micro (cm^3)	5.10 ± 0.02^{aA}	6.50 ± 0.03^{bA}	6.60 ± 0.09^{bA}	6.70 ± 0.06^{bA}	6.60 ± 0.03^{bA}	6.60 ± 0.01^{bA}	6.50 ± 0.00^{bA}	6.60 ± 0.04^{bA}	6.50 ± 0.00^{bA}
Day 30									
Total (cm^3)	31.0 ± 3.10^{aA}	49.0 ± 3.10^{bB}	48.0 ± 1.51^{bB}	61.0 ± 6.51^{cB}	51.0 ± 8.14^{bB}	46.0 ± 5.61^{bB}	45.7 ± 4.31^{bB}	52.0 ± 12.1^{bB}	49.0 ± 1.36^{bB}
Macro (cm^3)	6.10 ± 0.02^{aA}	8.00 ± 1.10^{bB}	8.20 ± 2.13^{bB}	14.0 ± 1.21^{cB}	8.00 ± 0.03^{bB}	6.50 ± 1.01^{bB}	6.70 ± 1.00^{aB}	10.8 ± 0.10^{bB}	9.00 ± 1.21^{bB}
Meso (cm^3)	19.8 ± 1.51^{aA}	32.9 ± 3.41^{bB}	32.3 ± 1.70^{bB}	37.9 ± 3.14^{cB}	34.9 ± 0.14^{bB}	32.0 ± 2.48^{bB}	31.6 ± 2.71^{bB}	33.5 ± 3.41^{bB}	32.3 ± 3.26^{bB}
Micro (cm^3)	5.10 ± 0.03^{aA}	8.10 ± 2.12^{bB}	7.50 ± 0.03^{bB}	9.10 ± 0.00^{bB}	8.10 ± 0.07^{bB}	7.40 ± 0.00^{bB}	7.40 ± 0.12^{bB}	7.70 ± 0.03^{bB}	7.70 ± 0.01^{bB}
Day 180									
Total (cm^3)	30.0 ± 1.96^{aA}	43.0 ± 0.08^{bB}	43.0 ± 0.23^{bB}	51.0 ± 0.16^{cB}	44.0 ± 0.15^{bC}	43.0 ± 0.00^{bB}	43.0 ± 0.21^{bB}	44.0 ± 0.05^{bB}	44.0 ± 2.51^{bB}
Macro (cm^3)	5.20 ± 1.39^{aA}	5.50 ± 0.17^{aA}	6.00 ± 0.17^{aA}	7.00 ± 0.02^{bA}	5.50 ± 0.05^{aA}	7.20 ± 0.02^{bB}	7.20 ± 0.23^{bB}	4.70 ± 0.26^{bB}	7.10 ± 0.08^{bB}
Meso (cm^3)	19.7 ± 1.21^{aA}	30.0 ± 0.15^{bB}	30.0 ± 0.15^{bB}	35.7 ± 0.10^{cB}	30.8 ± 0.09^{bB}	28.6 ± 0.03^{bA}	28.7 ± 0.14^{bA}	31.8 ± 0.14^{bB}	29.9 ± 0.04^{bB}
Micro (cm^3)	5.10 ± 0.69^{aA}	7.50 ± 0.12^{bB}	7.00 ± 0.13^{bB}	8.30 ± 0.08^{bB}	7.90 ± 0.00^{bB}	7.20 ± 0.04^{bB}	7.10 ± 0.30^{bB}	7.50 ± 0.09^{bB}	7.00 ± 0.00^{bB}

S, soil without biochar; SWL1, soil with apple wood biochar pyrolysed at 350 °C (<1 mm); SWL2, soil with apple wood biochar prepared at 350 °C (1-2 mm); SWH1, soil with apple wood biochar pyrolysed at 550 °C (<1 mm); SWH2, soil with apple wood biochar prepared at 550 °C (1-2 mm); SRL1, soil with rice husk biochar pyrolysed at 350 °C (<1 mm); SRL2, soil with rice husk biochar pyrolysed at 350 °(1-2 mm), SRH1, soil with rice husk biochar pyrolysed at 550 °C (<1 mm); SRH2, soil with rice husk biochar pyrolysed at 550 °C (1-2 mm). Different small and capital letters indicate differences among the eight treatments and different days, respectively.

method. The mean weight diameter (MWD) of wet-sieved aggregates was used as an important index for aggregate stability (Besalatpour *et al*., 2013).

Samples were taken at 5, 30, 80, 120 and 180 days after incubation and the measurements of ρ_b, K_s, and soil water retention curve were started. The bulk density of samples was determined by cylinder's method. Soil water retention curves (SWRC) for above treatments were obtained by pressure plates at 0, 0.3, 0.5, 1, 5, 10, and 15 bar suctions.

For determining the changes in the trend of pore size distribution during incubation period, we used Kay's (1990) method which categorized soil porosity into four classes: total porosity (equals to volumetric water content at saturation condition), macropores (<30 µm), micropores (<0.2 µm) and mesopores (0.2-30 µm). Some soil physical quality indicators were derived from the SWRC data, including AC (air capacity) and PAWC, and were calculated as follows (Nellisen *et al*., 2015):

$$AC = \theta_s - \theta_{fc},\ \ PAWC = \theta_{fc} - \theta_{pwp} \qquad [2]$$

where θ_{fc} and θ_{pwp} are the volumetric water contents at -3 m and -150 m, respectively. Soil AC is an indicator of soil aeration and PAWC indicates the capacity of the soil to store and provide available water to plant roots (Nellisen *et al*., 2015). Moreover, the S-index (Dexter, 2004), was used as physical soil quality indicator.

The incubation experiment was conducted at 25 °C in a temperature-controlled room for 180 days. During the incubation period, the moisture of the samples was kept at FC by daily addition of deionized water based on weight loss.

Statistical analysis

Data analyses were performed using the SPSS (SPSS Inc, 2015) and Microsoft Excel (2007) softwares. Significance differences among treatments and sampling dates were examined by the two-way ANOVA in the SPSS software package, in which the post-hoc test of least significant difference (LSD) was used.

Results

Some selected physical and chemical properties of studied soil were as follow: It was a sandy loam soil with 53% sand, 30.8% silt and 16.2% clay. Soil bulk density and SSA were 1.65 g/cm^3 and 16.13 m^2/g. Soil pH was 8.1 and its percentage of SOM and N were 0.7 and 0.01, respectively. Soil CEC and EC were 10.51 cmolc/kg and 8.97 dS/m.

Table 1 lists some physical and chemical properties of biochars. The contents of H, O, and N of biochars were reduced while C content and CEC of biochars increased as pyrolysis temperature increased. The difference between CEC of rice husk and apple wood biochars was significant at different temperatures. Also, CEC difference between WL1 and WL2 as well as RL1 and RL2 was not significant, but it was significant between WH1 and WH2 as well as RH1 and RH2.

Figs. 1a, 1b and 1c reveal the amounts of microaggregates, macroaggregates and MWD, respectively, in different treatments and sampling days. According to Fig. 1a, the biochar amendment did not induce a significant change of the microaggregates at most of the incubation days, and only SWH1 and SRH1 had significant difference with the other treatments at the end of incubation. Also, these two treatments were significantly different between incubation beginning day and 180 days after. Also, the rate of microaggregtaes increased from beginning to end of incubation.

The amount of macroaggregates had the highest value for SWH1 in all of the incubation dates. Macroaggregates increased at the earlier incubation stage and its rate increased and reached a peak at day 15 and then decreased at the later stage, and stabilization stage occurred such that amounts of macroaggregates became almost fixed in all treatments. Specifically, the amount of macroaggregates for SWH1 treatment increased to the maximum (490 g/kg soil) after 15 days of incubation, while the amount of macroaggregates in the control was 219 g/kg soil. Fig. 1b shows that SWH1 was significantly different from the others in all the incubation period.

The MWD values were enhanced significantly (p<0.01) at day 15 for SWH1 and SWH2 as well as SRH1. At the end of the incubation period, SWH1, SWH2, SRH1 and SRH2 were significantly different respect to the others. Throughout the incubation period, the MWD values were remarkably higher forSWH1 treatment than the others (Fig. 1b).

Figs. 2a and 2b illustrate the percentage of stable aggregates >1 mm in water for different woody and herbaceous biochar treatments, respectively, during the incubation period. These aggregates increased gradually to day 5 and after that they show a sudden increase so as their peaks were happened at day 15. Then, their amount was slowly reduced to days 30 and 50. Finally, its rate became fixed until the end of the incubation period. All treatments showed significant differences with the control at all days after the beginning of incubation, but there were no significant differences among them. This trend was similar for woody and herbaceous biochar treatments (Figs. 2a,b).

Table 2 shows changes of total, macro-, meso- and micro-pores of different treatments during incubation period. After 30 days, total pore of all treatments markedly increased and were significantly different respect to control and day 5. Among all treatments, WH1 biochar had the highest effect on increasing of total pore such that SWH1 had the highest total pore. Also, macro-, meso- and micro-pores had the highest volume for the majority of treatments at day 30. SWH1 had the highest volume of macro-, meso- and micro-pores among all treatments and their differences were significant. Little reduction in pores volume occurred after 30 days but its difference until the end of period was not generally significant. It is important to emphasize that biochar application mainly increased total and meso-pores but it had a little effect on macro- and micro-pores.

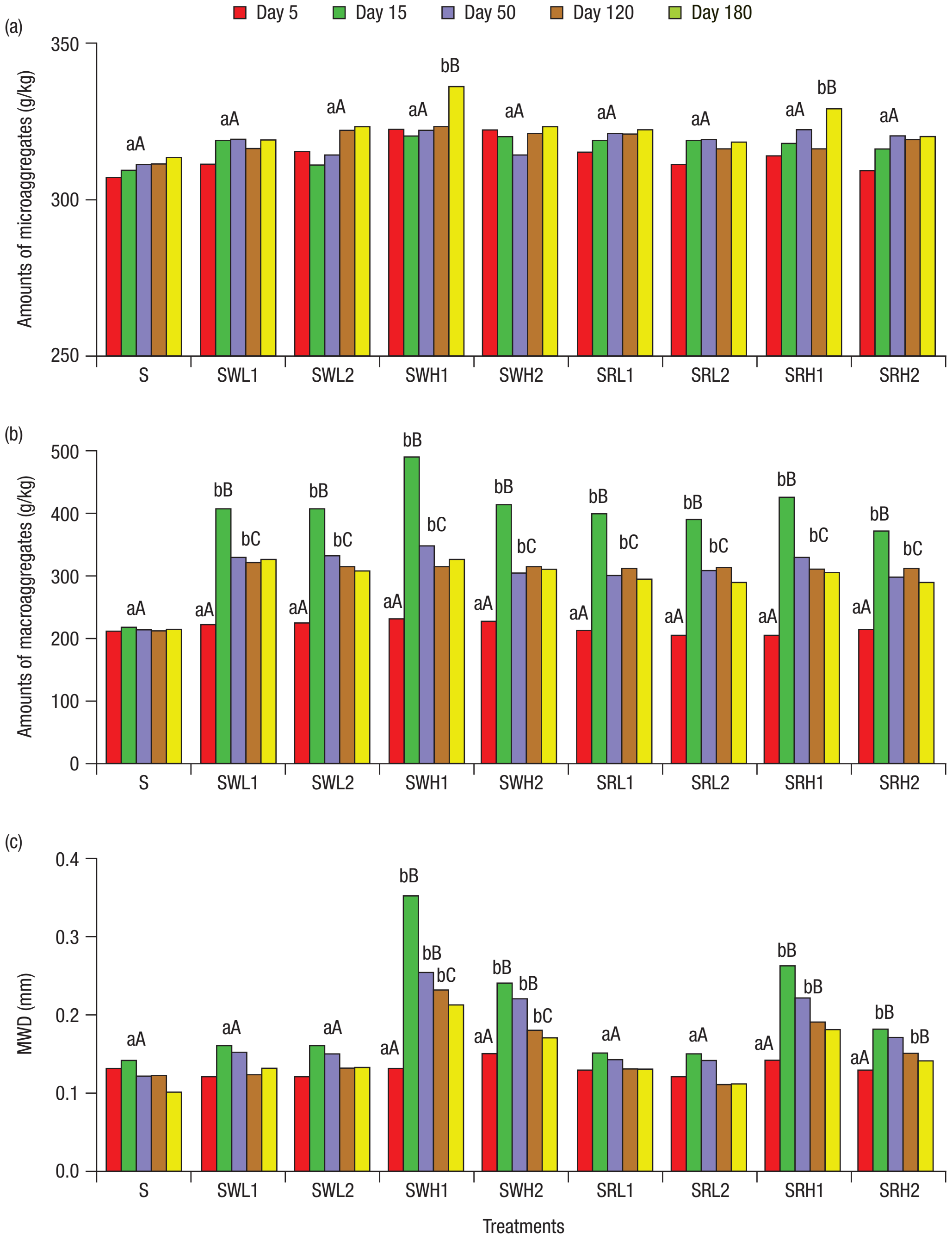

Figure 1. Amounts of microaggregates (a), macroaggregates (b) and mean weight diameter (MWD) (c), for different treatments during incubation period. Different small and capital letters indicate differences among the eight treatments and different days, respectively (see Table 2 for treatments abbreviations).

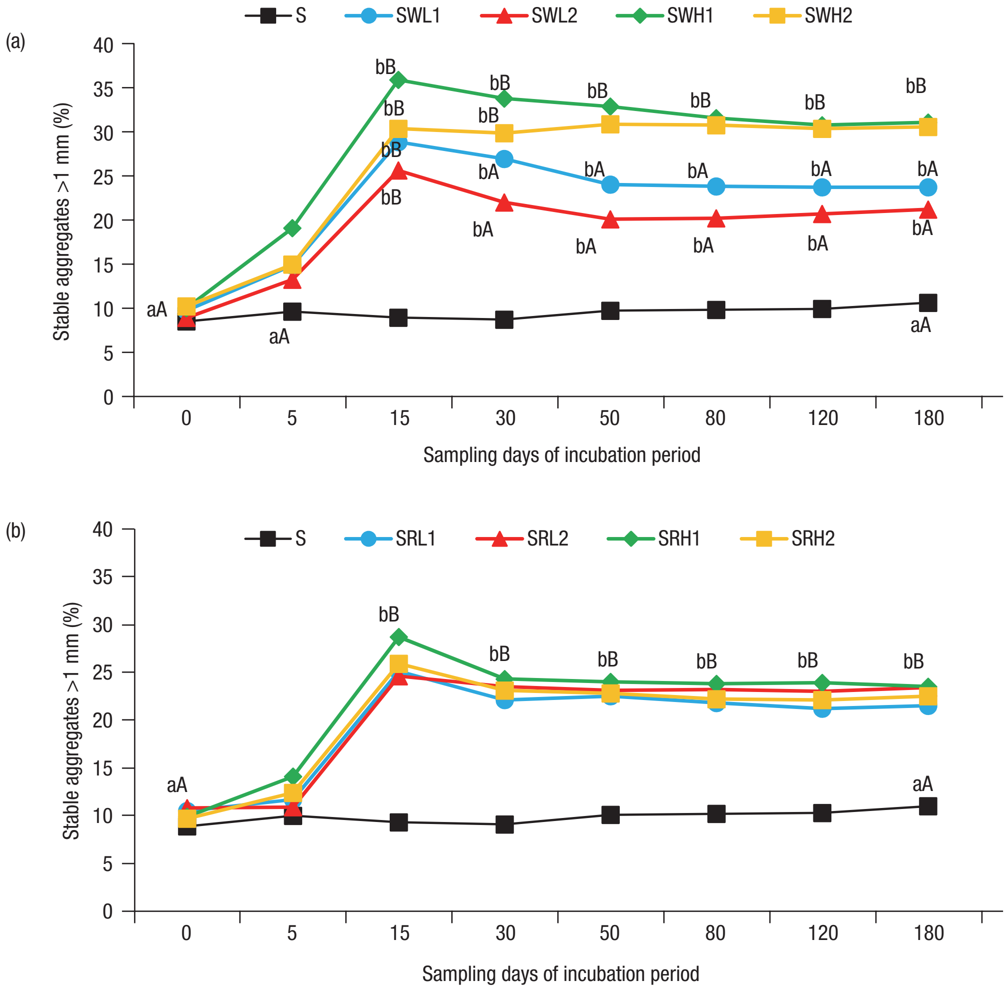

Figure 2. Percentage of stable aggregates >1 mm in different sampling days of incubation period: a) Soil with apple wood biochar treatments, b) Soil with rice husk biochar treatments. Different small and capital letters indicate differences among the eight treatments and different days, respectively (see Table 2 for treatments abbreviations).

The biochar application significantly reduced the bulk density from 1.65 g/cm^3 (control) to 1.55, 1.55, 1.52, 1.54, 1.55, 1.55, 1.45 and 1.47 for SWL1, SWL2, SWH1, SWH2, SRL1, SRL2, SRH1 and SRH2, respectively at day 180 (Figs. 3a,b). SRH1 had the minimum bulk density among the other treatments in above figures. Also, SRH1 and SRH2 were significantly different from the others. Bulk density differences were not significant at different sampling days.

Fig. 4 shows changes of Ks values for different treatments at each sampling date. Compared to the control, the biochar application, especially the treatments containing high-temperature-charred biochars, reduced Ks values at all sampling days. Woodchips biochars resulted in lower Ks values than rice husk biochars. Among all treatments, only SWH1 was significantly different from the other treatments at all sampling dates. In general, the changes of Ks values for other treatments were not significant.

Fig. 5 reveals the changes of AC, PAWC and S-index during the incubation period. AC had no significant differences between treatments and control at day 5. All treatments showed a marked significant difference with control after 30 days, except SRL1 and SRL2 (Figs. 5a,b). SWH1 treatment only revealed a significant difference relative to control and other treatments after 80 days. Changes of AC at days 120 and 180 were also similar to that of day 80. On the other hand, only SWH1 was significantly different respect to control at the end of the incubation period (Fig. 5a).

Regarding PAWC, all treatments showed significant increasing differences with control after 30 days (Figs. 5c,d). Also, SWH1 was significantly different from the other treatments (Fig. 5c). On the other hand, all treatments were significantly different during incubation period at day 5. Besides SWH1, SRH1 had also significant difference with other samples at day 80. This

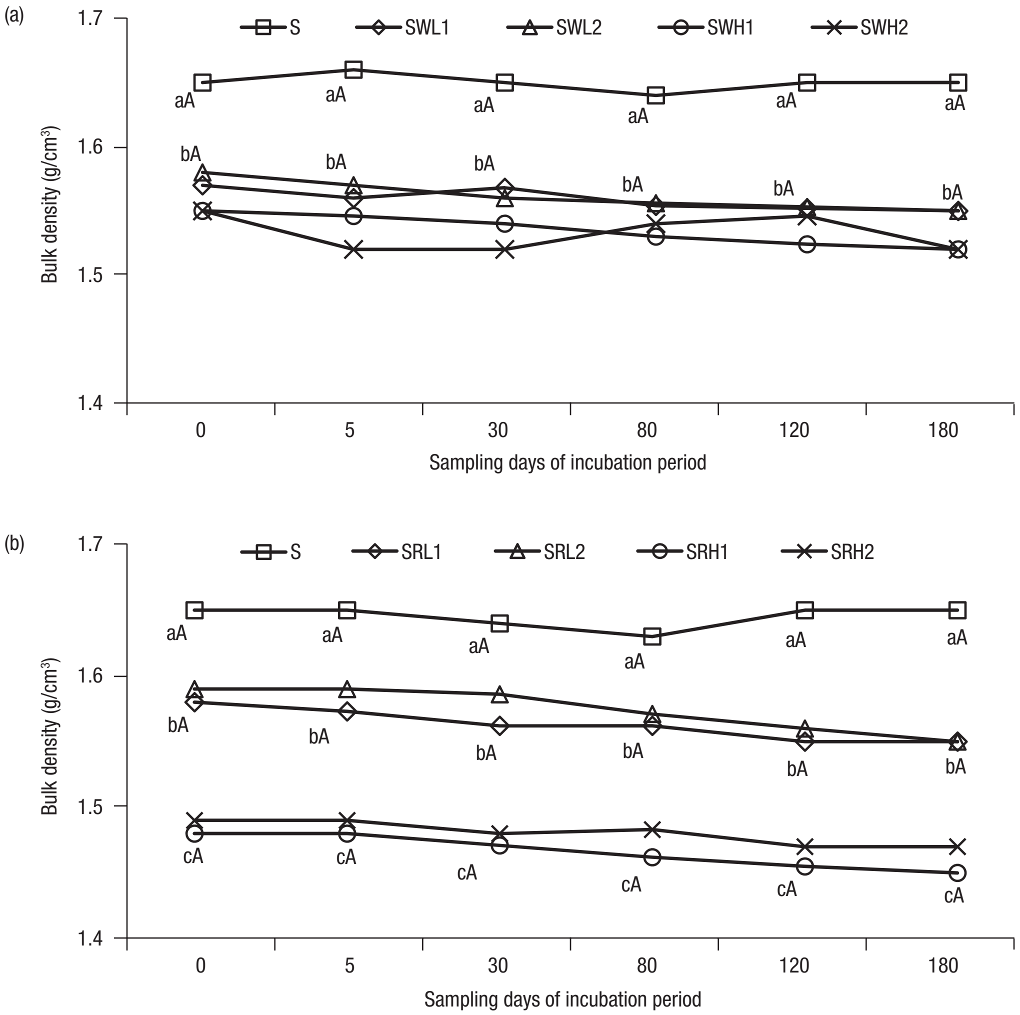

Figure 3. Evolution of bulk densities of different treatments during incubation period: a) Soil with apple wood biochar treatments, b) Soil with rice husk biochar treatments. Different small and capital letters indicate differences among the eight treatments and different days, respectively (see Table 2 for treatments abbreviations).

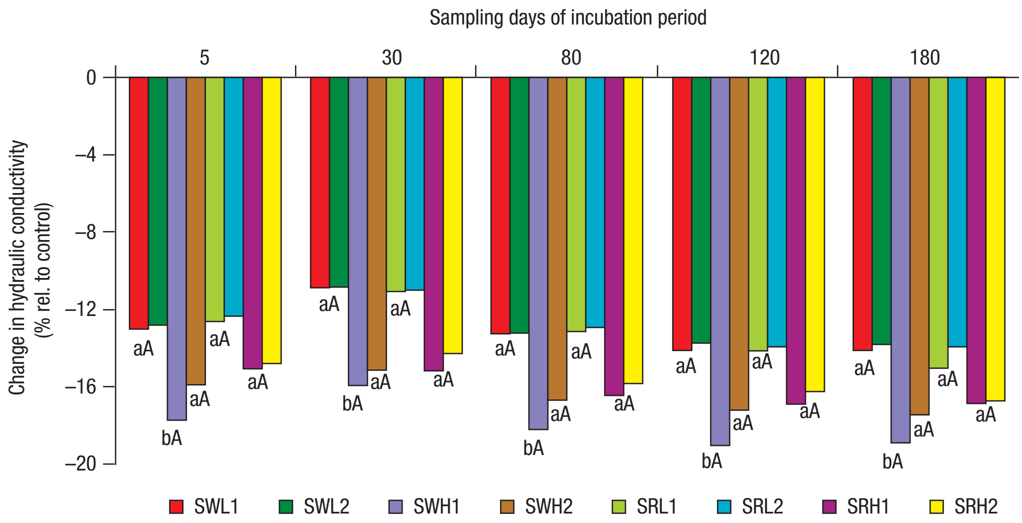

Figure 4. Changes of hydraulic conductivity during incubation period. Different small and capital letters indicate differences among the eight treatments and different days, respectively (see Table 2 for treatments abbreviations).

trend continued to the end of the incubation period. But at day 180, SWH1 only was significantly different from the others (Fig. 5c).

The S-index was significantly affected by biochar amendment in all treatments compared to control. S-index increased at day 30 and was significantly different to the control for all treatments (Figs. 5e,f). SWH1 treatment showed a marked significant difference with the control and other treatments after 30 days. Also differences between S-index at 5 and 30 days were significant. This trend continued until the end of the incubation period. All samples were significantly different from the control. Also, differences between SWH1 and SWH2 and other treatments were significant (Fig. 5e) but differences between SRH1, SRH2, SRL1 and SRL2 were not significant (Fig. 5f).

Fig. 6 shows that after 5 days from incubation, soil moisture at saturation, FC and PWP increased. Two-way ANOVA showed a significant main effect of biochar amendment on retention curve, such that all treatments were significantly different for θ_S, θ_{FC} and θ_{PWP}. Water content increased in all treatments and these changes were more obvious when WH1 and WH2 biochars were applied to sandy loam soil (Figs. 6a,b,c). Also, significant differences were seen between days 5 and 30. Amounts of θ_S, θ_{FC} and θ_{PWP} started to decrease after 80 days from incubation, but their differences with 30 days were not significant except SWH1 treatment. The differences between SWH1 and other treatments were also significant on day 80 for θ_S, θ_{FC} and θ_{PWP}. This trend was stable to days 120 and 180. At these sampling dates, water content at saturation, FC and PWP was unchanged and only SWH1 was significantly different from the others.

In all the treatments, soil microbial biomass C reached the maximum values within the first 5 days and then descended with time (Figs. 7a,b). The biochar application increased microbial biomass throughout the

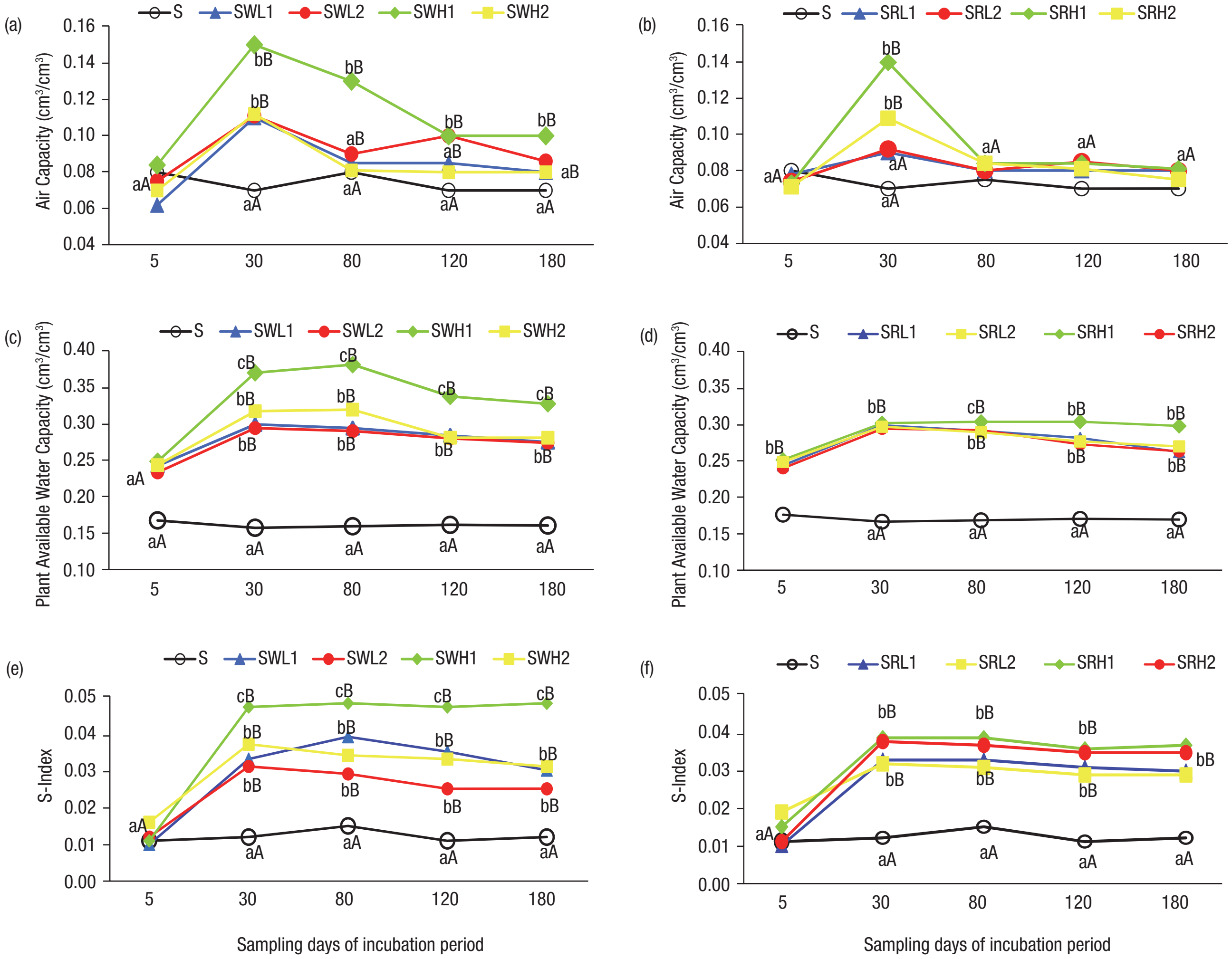

Figure 5. Changes of air capacity (a, b), plant available water capacity (c, d) and S-index (e, f) during the incubation period. Different small and capital letters indicate differences among the eight treatments and different days, respectively (see Table 2 for treatments abbreviations).

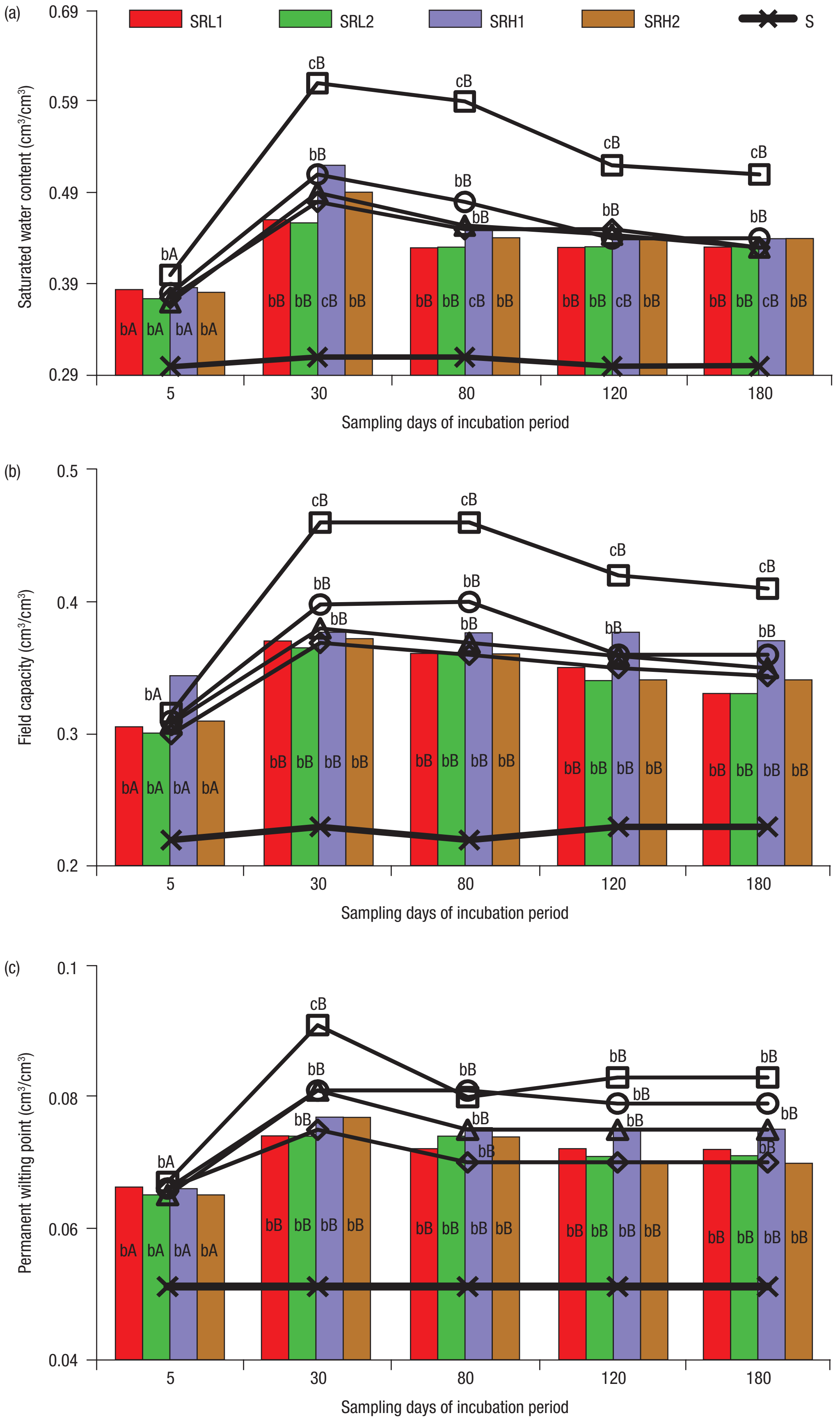

Figure 6. Changes of water content at saturation (a), field capacity (b) and permanent wilting point (c) during the incubation period. Different small and capital letters indicate differences among the eight treatments and different days, respectively (see Table 2 for treatments abbreviations).

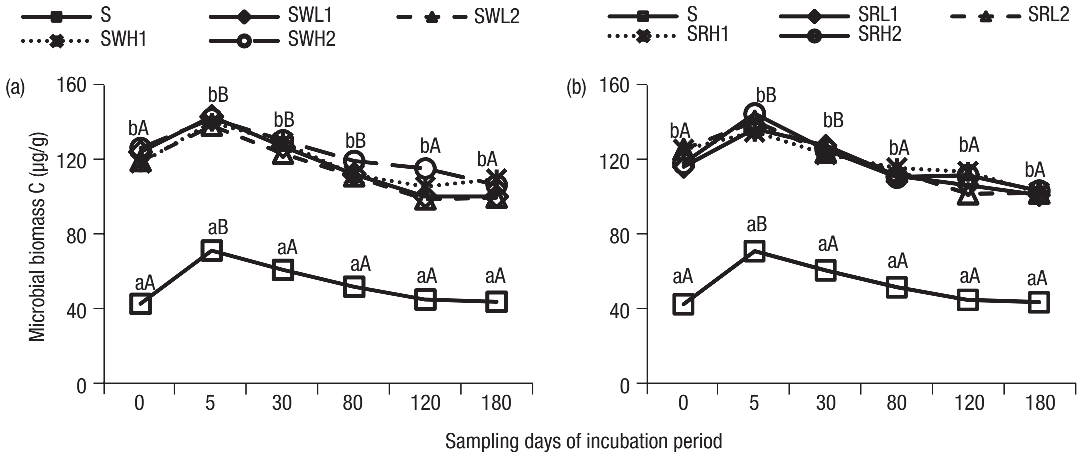

Figure 7. Microbial biomass C (µg/g) for (a) soil and apple wood biochar treatments and (b) soil and rice husk biochar treatments, during the incubation period. Different small and capital letters indicate differences among the eight treatments and different days, respectively (see Table 2 for treatments abbreviations).

incubation period. All treatments showed significant differences with the control. Effects of different temperature and feedstocks were not significant on values of soil microbial biomass C.

Discussion

In this study, it has been demonstrated that biochar amendment generally promoted physical and hydrological properties of sandy loam soil, but finer particles of high-tempered apple wood biochars (WH1) had more effects on soil properties enhancement than the others. This suggested that different feedstocks, charring condition and applied biochar particle sizes can cause different effects on soil physical and hydrological characteristics. According to results, total pore volume, CEC and SSA of WH1 biochar had the highest values and significantly differed from the others. The lowest value of average pore diameter was related to WH1 biochar, too. According to the classification of Downie *et al.* (2009), the porosity of WH1 is considered micro-pore (internal pore diameter <2 nm). So, WH1 microporous structure as well as its finer particle size than WH2 may explain why resulted in significantly higher SSA and CEC than WH2.

Also, biochars from woody biomass tend to exhibit larger surface area and contain higher pore volume compared to biochars produced on herbaceous feedstocks (Atkinson *et al.*, 2010). On the other hand, by increasing the pyrolysis temperature, the volatilization of the plant material increases and leaves a more porous biochar with a larger SSA and CEC.

With regard to results the biochar amendment did not induce a significant change of the microaggregates at the majority of the incubation days. It was not an unexpected result, because the creation of soil aggregates is a function of biological activity and time, and unlikely to occur immediately upon biochar application. Brodowski *et al.* (2006), when studying a long term field experiment site (25-85y), suggested the role of charcoal contributing to the formation of microaggregates. Longer term studies are probably needed to assess the influence of biochar on formation of microaggregates. This result was similar to that of Herath *et al.* (2013). All of them used biochar in this study; especially WH1 improved the formation and stabilization of the soil macroaggregates. Increasing of macroaggregates at early stages of incubation could be related to soil microbial biomass C which showed maximum values at 15 days after incubation, provided binding agents for the formation of soil aggregates. This condition causes more transient and temporary binding agents to improve formation of aggregates. SWH1 had the maximum amount of macroaggregates compared to other treatments at peak value. Because of this, WH1 had relatively higher C/N ratio than the others, which probably lead to a favourable condition for the growth of fungi (Bossuyt *et al.*, 2001), which can play a more important role in the formation of macroaggregates than the bacteria (Ouyang *et al.*, 2013). On the other hand, porous structure and high values of CEC and SSA of WH1 can adsorb different materials such as minerals and organic matters with various molecular sizes and chemical characteristics which serve as binding agents for better arrangement in soil structure (Liang *et al.*, 2006; Ouyang *et al.*, 2013). Macroaggregate amounts of all treatments reduced from their peak to 50 days after incubation which was attributed to the decrease of the binding agents, such as the available organic matter and the microbial biomass with incubation time. Stabilization of macroaggregates started after 50 days in most treatments. It is plausible that aromatic components, which are predicted to be high in biochars, contribute to stabilization of macroaggregates (Brodowski *et al*., 2006). Also, aggregate formation physically protects SOM from biodegradation and, hence, promotes long-term soil structural stability (Six *et al*., 2004). Therefore, it results in less macroaggregate changes after its peak value. These results are in line with Ouyang & Zhang (2013).

All of above-mentioned reasons lead to increase MWD, too. The MWD values had the highest rate at day 15 and WH1 was the best biochar for the increasing MWD. The effect of charring temperature on MWD values was significant at the end of incubation period.

Biochar addition improved water stable aggregates. Similar results were also seen in the research of Ibrahim *et al*. (2013). Observed increases in aggregate stability are attributed to: (1) char acting as a binding agent, (2) char promoting organo-mineral complexes, and (3) biochar hydrophobic surfaces reducing the penetration of water into pores.

Generally, the effect of biochar amendment on total and meso-pores was obvious and macro- and micropores were not significantly affected by the application of biochar. This increase in total pores is a result of two mechanisms: (1) porosity of biochars added to soil and (2) pores that are results of aggregation that increase inter and intra spaces of aggregates. In other words, soil porosity is influenced by biochar application via three mechanisms: (1) direct pore contribution from pores within the biochar, (2) creation of packing or accommodation pores between biochar and the surrounding soil aggregates, and (3) through improved persistence of soil pores due to increased aggregate stability (Major, 2010). Jones *et al*. (2012) concluded that increased meso-porosity was attributed to the biochar partly filling large voids between the soil and particles. Eastman (2011) and Novak *et al*. (2012) reported that short-term changes in pore size distribution following biochar application may result from aggregate settling and thus changes to the accommodation pores. An increase in porosity creates additional capillary soil pores, thus creating additional pathways for water movement and potential water storage while reducing bulk density.

All biochars decreased the bulk density of treatments compared to control. The density of biochars, especially the herbaceous ones, is much lower than mineral soils and so the lowest bulk density is related to SRH1. Incorporation of biochar may therefore increase the soil volume and reduce the bulk density of the soil.

The effect of biochar on the soil Ks has not yet been conclusive (Ouyang & Zhang, 2013). Some reported an increasing effect (Uzoma *et al*., 2011), while others reported no significant changes (Larid *et al*., 2010). These different results might be due to the soils and biochar types used in the studies. In our study, the biochar application reduced Ks values and this effect increased with increasing pyrolysis temperature and decreasing diameter of used biochars, such that SWH1 and SRH1 treatments had the highest effect on decreasing Ks values. Despite the enhancement of soil aggregates and soil porosity as well as decreasing of bulk density, it is expected that Ks values would increase, but unexpectedly, Ks was decreased in all treatments and decreasing rate of Ks in SRH1 and especially SWH1 was remarkable. Similar results in Ks and ρ_b have been reported by Deveraux *et al*. (2012) and Barnes *et al*. (2014).

The decreases observed in Ks are likely due to three mechanisms. The first mechanism could be related to the internal structure of biochars. Our biochars, especially WH1 and RH1, had high porosity of 79.0 and 49.2 cm^3/g, and high specific surface area of 79.4 and 36.6 m^2/g, respectively. On the other hand, average pore diameter of WH1 and RH1 was 1.91 and 2 nm, respectively. Thus, these biochars had a greater porosity and surface area than control. This highly porous structure of biochars creates two theoretical flow pathways, one by connecting the pores within the biochar-soil matrix and a second by connecting the pores within the biochars (Barnes *et al*., 2014). According to BET measurements, all used biochars include many pores larger than the diameter of a water molecule (0.28 nm). However, this second pathway likely has greater tortuosity and smaller median pore throat size due to the size of the smallest pores as well as their lack of complete connectivity (Brewer *et al*., 2014). While these pores contribute to the bulk density and total porosity of the matrix, they may not contribute to the effective porosity (Barnes *et al*., 2014). Moreover, the biochar particles, probably, create torturous interstitial space between the soil and biochar grains and cause to further decreasing Ks.

The second mechanism that causes decrease in Ks is the blockage of pathways by biochar particles. According to laser diffraction for determination of particle size distribution of biochars, about 67% of WH1 biochar particles were <0.2 nm, while only 42% of RH1 particles had the mentioned size. These fine particles can block pores and decrease Ks. Liu *et al*. (2016) found that Ks decreased significantly (by 67%, $p<0.01$) when biochar particles (<0.251 mm) are smaller than sand particles (0.251-0.853 mm) and decreased by 15% ($p<0.01$) when biochar particles (0.853-2.00 mm) are bigger than sand particles. When biochar and sand particles sizes are comparable, no significant changes in hydraulic conductivity were observed. They proposed that the decrease of Ks by adding smaller biochar is driven by the combination of several mechanisms, including partial saturation, smaller particle size and grain shape of biochar, which will reduce the available space for flow, reduce pore throat size and increase tortuosity. As earlier mentioned, in our study all treatments showed reduction in Ks. The decrease of Ks by adding larger biochars such as WL2, WH2, RL2 and RH2 is caused by non-uniform particle size distribution yielding a net decrease in pore throat size.

The other mechanism that causes decrease in Ks is related to the high field capacity of biochar, *i.e.* water sorbs to biochar particles, contributing to the apparent decrease in Ks (Barnes *et al.*, 2014). Uzoma *et al.* (2011) concluded that reduction of Ks in sandy soil after application of biochar was a result of increasing water retention capacity. These results together confirm that biochar amendment does influence hydraulic conductivity and the mechanisms that control it are largely physical, including the relative size of biochar and soil particles and their proportions (Liu *et al.*, 2016) and swelling and grain segregation, leading to the clogging of pores, decrease in pore radii, and possibly a variation in bulk density and sample heterogeneity over the experiment (Barnes *et al.*, 2014).

Our result was consistent with that of Githinji (2014) that revealed a decrease in Ks of a sandy loam soil with application of biochar because of hydrophobicity of biochar. Ouyang *et al.* (2013) reported that Ks values of both silty clay and sandy loam soils increased with biochar amendment but were not significantly different.

Biochar application had direct and indirect effects on water retention capacity, that its direct effect is related to the large inner surface area of biochar and the indirect effect is linked to the soil aggregation or structure improved by biochar. Water retention at lower suctions depends on the content of larger pores, which is strongly affected by the soil structure, while water retention at high suctions is influenced more by soil texture and surface area (Kutilek *et al.*, 2006). In our study, the biochar application reduced the soil bulk density and improved the soil aggregate structure, thus increasing the total soil porosity and mesopores, which resulted in the increase of water content at low suctions. Furthermore, since SOM content and composition affect both soil structure and adsorption properties, soil water retention may also be affected by changes in SOM (Rawls *et al.*, 2003). The biochar treatments remarkably promoted the SOM content, which might increase the water retention capacity (Rawls *et al.*, 2003). The incorporation of woodchip biochars with finer particles resulted in high water retention capacity than the rice husk biochars. This is due to higher SSA of finer particles than coarse ones as well as more porous structure of woody biochar relative to herbaceous one. The water retention presented an increasing trend as the pyrolysis temperature of biochar increased, which was similar to Novak *et al.*´s (2012) results. With increasing charring temperature, ash content of biochars increased, too. Verheijen *et al.* (2009) reported that the ash fraction could change the electrical charge on clay particles, causing the soil particles to move closer and increasing secondary macroporosity and consequently increase the water content at low sections. According to Gaskin *et al.* (2008), biochar will not only modify the soil water retention capacity of the bulk soil but also the physical location of the water location within the soil matrix, since smallest pores are filled up first and empty progressively after the larger pores.

Since AC is a function of macro-pores, when macropores increase, AC increases, too. But this trend was not stable during the incubation of all samples, because some treatments increased in either saturated water content or field capacity, therefore AC did not change.

The highest PAWC after SWH1 was related to SWH2 and SRH1, respectively. Thus it can be concluded that if a remarkable increases of PAWC is expected, woody fine-sized biochars produced at high temperature must be applied to soils. As earlier mentioned, these enhancements could be attributed to the high porosity and surface area associated with biochar. This is because the numerous surface area and pores of biochar have to be first filled up before gravitational drainage down the soil thereby reducing water permeability and increasing water retention in the treated soil (Uzoma *et al.*, 2011). The implication is that biochar addition to a coarse-textured soil can provide more residence time for percolating soil moisture within the root zone, thereby making soil moisture more available to plants growing on the soil. Biochar had more influence on PAWC than any other predictor. It is generally admitted that the abilities of biochar addition to reduce bulk density and to increase the ability of the soil to store and release water (as reflected in changes to FC and PAWC) are both underpinned by the physical properties of the biochars, in particular by its porosity (Novak *et al.*, 2012). These results suggest that biochar amendment can alter soil physical properties in ways favourable to agricultural productivity. Traditionally, such soil characteristics have been sustained or enhanced by maintaining or raising SOM levels. Biochar significantly increased PAWC of all treated sandy loam soils compared to control. The highest available water capacity (~130% higher than the control) was found in the SWH1 treatment.

According to Dexter (2004), physical quality indexes of SWH1 and SWH2 were only higher than 0.05 and therefore they were considered of very good quality. These two treatments were also significantly different. Physical quality indexes of SRH1 and SRH2 were 0.035≤ S≤ 0.050 and therefore had good quality indexes. Other treatments were categorized as poor physical properties. This result revealed the role of charring temperature and size of biochar particles. Biochars produced at high temperature with fine particles can improve soil physical quality index. In addition, woody biochar could have more effect than herbaceous feedstocks.

In summary, the effects of different feedstocks, charring condition and applied biochar particle sizes on physical and hydrological properties of sandy loam soils were remarkably significant. All biochars used, especially WH1, improved the formation and stabilization of the soil macroaggregates, MWD and WSA. Because porous structure and high CEC and SSA of WH1 can adsorb different minerals and organic matters, they serve as binding agents for better arrangement in soil structure. The effect of biochar amendment on total and meso-pores was obvious and macro- and micropores were not significantly affected by the application of biochars. The biochar application reduced Ks values and this effect increased with increasing pyrolysis temperature and decreasing diameter of the biochars used. Biochars produced at high temperature with fine particles can improve physical quality index of sandy loam soil. In addition, woody biochar could have more effect than herbaceous feedstocks.

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