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Short-Term Impacts of Biochar Applications on Physico-Mechanic and Chemical Properties af Two Contrasting Textured Soils

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ABSTRACT

The effect of biochar applications on soil properties varies significantly depending on soil textures. Therefore, a pot experiment was carried out to investigate the effects of biochar (BC) amendment on some soil physico-mechanic and chemical properties, such as bulk density (BD), particle density (PD), mean weight diameter (MWD), aggregate stability (AS), Attarberg limits, soil pH, electric conductivity (EC), organic carbon (OC), total nitrogen (TN), and C:N ratio of two different textured calcareous soils (Clay and Sandy Loam). Biochar produced from sunflower residues were mixed with soils at the rate of 0, 1, 2 and 4%. All pots were watered to field capacity and incubated for 30 days. The results showed that biochar improved soil structural properties for both studied soils. Although mean weight diameter (MWD) was increased in clay soil, it was decreased in sandy loam soil. The liquid limit was increased by an increment of BC application rates in both soils, and the plastic limit was increased in single clay soil. BC affected selected soil chemical properties by decreasing soil pH, and increasing the soil EC, OC, TN, and C: N ratio, but no effect was detected on $CaCO_3$ content in both soils. Organic carbon mineralization ratio increased in the clay soil amended with BC, however, decreased in the sandy loam soil compared with the control sample. As a conclusion, the biochar amendment improved soil physico-mechanic properties of the studied soils. However, the effect on chemical properties was inconsistent

1. Introduction

Biochar is a charcoal produced by pyrolysis of biomass in a closed container at relatively low temperatures (<700° C) with restricted oxygen conditions (Lehmann and Joseph, 2009). Biochar amendment can mitigate the impact of climate change and is regarded as a promising strategy for soil carbon (C) sequestration (Lehmann 2007; Woolf et al. 2010). Due to its stability and low degradation rate in soil compare with other common organic matter resources, its effect on soil physical, chemical and biological properties may continue for a long time period (Atkinson et al. 2010).

The high porosity and a high surface area exceeding 400 m^2 g^{-1} of biochar were reported by (Brown et al. 2006), and thereby increasing the holding capacity of water and nutrient in soil (Ippolito et al. 2011). The results of many researchers showed that biochar amendment reduced soil bulk density by increase soil porosity and aeration (Tammeorg et al. 2014; Omondi et al. 2016). It helped to improve soil structure by producing more stable soil aggregate through the promotion of macroaggregate formation (Herath et al. 2013; Ouyang et al. 2013). Soil structure stability is affected by different factors, such as clay content, and amount and type of soil organic matter (Six et al. 2004). The stability of soil aggregate can protect soil organic matter by reducing the decomposition (Six et al. 2002).

Increasing of organic matter content by the addition of biochar can significantly enhance soil microbial activity, which plays the main role for stabilization and formation of soil macroaggregates (Lehmann and Joseph 2009). The increase in aggregate stability by addition of biochar was associated with an increase in physically protected C incorporated in macroaggregates at fine textured silt loam soil; however, at coarse-textured sandy loam soil biochar had no effect on aggregation (Wang et al. 2017). Pituello et al. (2018), found that promoting of aggregate stability by addition of biochar improve the physical fertility of the soil, especially with coarse-textured and low organic carbon contented soils. Soil conditions and feedstocks of tested biochars were effective in improving soil properties (Omondi et al. 2016).

Due to the role of biochar in increasing soil water holding capacity by increasing soil porosity, it has a

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certain effect in the limits of Atterberg (liquid and plastic limits), however, no more studies had explained biochar amendment effect on these limits adequately. About the effect of biochar on soil chemical properties, there is high variability of the result depends on the biomass used, the temperature during pyrolysis and residence time (Teβin, 2016). Biochar usually has alkaline (pH>7) activity (Lehmann and Joseph 2009), high ash contents, and high surface areas and could result in increased soil pH as reported by Novak et al. (2009). Thus, a lot of studies investigated about the effect of biochar amendment on acidic soil showed that soil pH was increased, e.g., (Tasneem and Zahir 2017). High content of ash in biochar can increase soil pH, due to the presence of readily soluble oxides of CaO, MgO, Fe_2O_3 in biochar (Koukouzas et al. 2007). However, oxidation of biochar could decrease the pH of the soil around the vicinity of biochar particles (Cheng et al. 2006). Soil EC increased significantly with biochar amendment in most of the research. This increase was attributed to the release of weakly bound nutrients of biochar in the soil solution (Chintala et al. 2013).

The C: N ratios of biochar vary widely and ranged between 7- 400, with a high mean of 61, and it is considered as a high N depleted (Lehmann and Joseph 2009). Since, C: N ratios increase immobilization of N occurs, biochar amendment to the soil add a supplemental amount to the both C and N stock (Clough et al. 2013). The mineralization of organic matter in the soil during the incubation period is an important indicator of soil microorganism activity. The objective of this study was to determine the short-term effects of biochar applications doses on improving the physico-mechanic and chemical properties of two different contrasting textured soils having poor aggregation properties.

2. Materials and Methods

Site description and soil sampling

Agricultural soil located at Central of Anatolia region, Konya plain (1016 m H), where clay soil from Sarıcalar Research and Application Farm (38°05'48.0"N, 32°26'23.0"E), and sandy loam from a soil plot at Çumra basin (37°33'38.3"N, 32°40'00.0"E) under cultivation were collected from the surface (0-20 cm) and used in this study (Table 1). Both textured soil samples used in the study were weak aggregated properties and low exchangeable-extractable sodium contents and with alkali reaction and no salinity problems (Bal et al. 2011; Şeker et al. 2016). Soil samples were sieved in situ by 4 mm sieve, and then after air-drying part of samples passed through a 2 mm sieve and experiment establishment at the laboratory in April 2018.

Preparation of biochar

Biochar produced from sunflower residues, and before the pyrolysis process dried in an oven at 70° C for 24 hours to remove moisture, thereafter, wrapped with aluminum foil to prevent the entrance of oxygen and then pyrolyzed in a muffle furnace at a temperature of 450° C for one hour. After cooling, the biochar was passed through 2 mm sieve and stored in a plastic container until the starting of the experiment. Biochar was a very high alkaline reaction (pH: 10.2) and EC value and C/N:25,9 (Table 1)

Table 1
Properties of soil and used material.

Soil parameters	Clay soil	Sandy loam soil	Biochar
Clay (%)	50.70	8.60	-
Silt (%)	36.00	14.00	-
Sand (%)	13.30	77.40	-
pH*, **	8.0	8.2	10.2
EC*, ** (dS m^{-1})	0.6	0.3	15.0
$CaCO_3$ (%)	13.2	11.9	10.6
OC (%)	2.3	0.9	62.1
N (%)	0.2	0.1	2.4
C/N	13.9	8.7	25.9
Field cap. (g g^{-1})	0.37	0.20	-

*(1:2.5) Dilution rate for soils, **(1:20) dilution rate for biochar

Incubation experiment setup

Soil samples of 3 kg based on a dry weight basis were completely mixed with biochar (BC) at a rate of 0%(control), 1, 2 and 4% for both soil texture, the mixtures were placed in the pots, then watered at field capacity and subsequently incubated for 30 days at 23±2°C. During the incubation period, after every 3 days, water losses were compensated by adding deionized water up to field capacity.

Statistical Analyses

The study was a pot experiment with four replications in accordance with a completely randomized plot design, and all data (means ± standard deviation) were analyzed by one-way ANOVA, and differences in means were compared by the least significant difference test at $P < 0.05$. All statistical analysis was carried out by (Minitab, 2013).

Soil Analyses

Soil texture was determined by Bouyoucos hydrometer method (Gee and Bauder, 1986). Soil bulk density (BD) was measured through the protocol developed by Jacobs et al. (1964), particle density (PD) was measured by pycnometer method (Blake and Hartge, 1986), and then soil total porosity was calculated by the relation between BD and PD (Danielson and Sutherland, 1986). Soil aggregation status was studied by a wet sieving method adapted by (Kemper and Rosenau, 1986). At the end of the incubation period, dry soil samples passed through a sieve of 4 mm, then put on the top of (2, 1, 0.5 and 0.25 mm) sieves, then transported to the Yoder machine and sieved for 10 minutes. Mean weight diameter (MWD), an index of soil aggregate stability was calculated according to the following equation (van Bavel, 1950):

$$MWD = \sum_{i=1}^{n} Xi * Wi$$

Where: Xi is the average diameter (mm) for particles in its fraction and Wi is the weight percentage of the fraction in the whole soil.

Aggregate stability values were determined by artificial rainfall simulator according to Gugino et al. (2009). The liquid limit was measured by penetrometer method after passing soil samples from 0.42 mm mesh sieve according to (TSE 1987). Plastic limit (PL), Liquid limit (LL) and Plasticity index (PI) was determined through an established method by (ASTM, 2010). Soil pH and electric conductivity (EC) (1:2.5) were measured in the laboratory after the end of incubation (Mclean 1982; Rhoades 1982). Calcium carbonate ($CaCO_3$) was determined by reaction with dilute hydrochloric acid in Scheibler calcium, by measuring the volume of emitted CO_2 from carbonates (Nelson 1982). Soil organic carbon (OC) was measured by a wet combustion method proposed by Smith and Weldon (1941). Total Nitrogen (TN) was determined by using the LECO CN-2000 device with Dumas dry burning method (Wright and Bailey, 2001). The mineralization rate of OC was detected in control treatments by calculating the rate between the inherent soil OC before incubation and the OC after one month of incubation, and for the BC doses by adding the contributing amount came from BC before and after the incubation period.

3. Results and Discussion

Physico-mechanic properties

The effect of biochar amendment at rates of 1, 2 and 4% on soil physico-mechanic properties of clay and sandy loam soils, such as bulk density, particle density, soil porosity, mean weight diameter, aggregate stability, liquid limit, plastic limit, and plastic index, which are presented in (Table 2). Soil bulk density was significantly decreased (P< 0.001) with increasing of biochar rates for both soils texture compared with the control treatments (Table 2). There are no significant differences between application rates of biochar in clay soil; however, BC 4% decreased bulk density by 5.8% in sandy loam soil. Particle density was decreased significantly (P<0.001) in clay soil only at BC 4% and no significant effect on sandy loam soil. The results of total porosity obtained from the relation between bulk and particle density significantly (P<0.001) increased in both soil texture, but no significant effect between rates of BC in clay soil. In the sandy loam, total porosity was increased with increasing of BC amendments and the rate of 4% had the highest value.

The results of mean MWD in clay soil significantly (P<0.01) increased with increasing of BC rates and the highest MWD was found at 4% by being increased nearly 33%, however, no significant effect between BC rates. Contrarily, in sandy loam soil, increasing of BC amendments affected negatively and significantly (P<0.001) decreased the MWD, and the lowest value was at 4% by being decreased by 33%.

Table 2
Effect of biochar on soil physical properties in clay and sandy loam soil

Properties	Clay soil				P Value
	Control	1%	2%	4%	
Bulk density (g cm^{-3})	0.95±0.00 a	0.91±0.00 b	0.91±0.00 b	0.91±0.00 b	***
Particle density (g cm^{-3})	2.56±0.00 a	2.58±0.01 a	2.56±0.01 a	2.49±0.02 b	***
Total porosity (%)	0.62±0.00 b	0.65±0.00 a	0.65±0.00 a	0.64±0.00 a	***
MWD (mm)	0.22±0.02 b	0.29±0.04 a	0.31±0.04 a	0.33±0.03 a	**
Aggregate stability (%)	7.88±1.32 c	15.44±0.97 b	17.82±1.26 a	13.65±0.79 b	***
	Sandy loam soil				
Bulk density (g cm^{-3})	1.20±0.01 a	1.21±0.00 a	1.19±0.00 a	1.13±0.01 b	***
Particle density (g cm^{-3})	2.50±0.03	2.54±0.01	2.53±0.01	2.51±0.02	NS
Total porosity (%)	0.52±0.00 b	0.52±0.00 b	0.53±0.00 b	0.55±0.00a	***
MWD (mm)	0.33±0.00 a	0.27±0.01 b	0.23±0.04 bc	0.22±0.01 c	***
Aggregate stability (%)	6.06±0.88 b	8.40±0.53 a	6.67±1.26 ab	6.29±0.43 b	**

Significant at ***P* <0.01, ****P* <0.001; NS: Not significant

The results of AS obtained from rainfall simulator experiment showed significantly (P<0.001) increased with increasing of BC rates in clay soil, and highest AS was at 2% by being increased 126%. Whereas in the sandy loam soil, AS significantly (P<0.01) increased 36.6% when only 1 % of BC was applied, but no significant effect at 2% and 4% application rates. Figure 1 shows the effect of biochar doses on Atterberg limits in clay soil. The liquid limit results showed a significant increase (R^2: 0.97, P<0.001) with an increase of BC rates, and the highest increase was 11% for clay soil when 4% rate was applied. The results of plastic limit were significantly increased (R^2: 0.99, P<0.01) with an increase of BC doses and plastic limit increased by 14% at 4% of BC. The plasticity index showed no significant increase (R^2: 0.57) with increasing of BC doses, however, the degree of plasticity was found in plastic class according to Leonards (1962).

Chemical properties

The results of the effect of applied biochar at rates of 1, 2 and 4% on soil chemical properties, such as soil pH, electric conductivity, calcium carbonate, total nitrogen, organic carbon, and C/N ratio are presented in (Table 2). Soil pH was significantly (P<0.001) decreased by increasing of BC doses, and the highest increase were at 4% rate of BC with 2.1% and 2.4% in both clay and sandy loam soils, respectively.

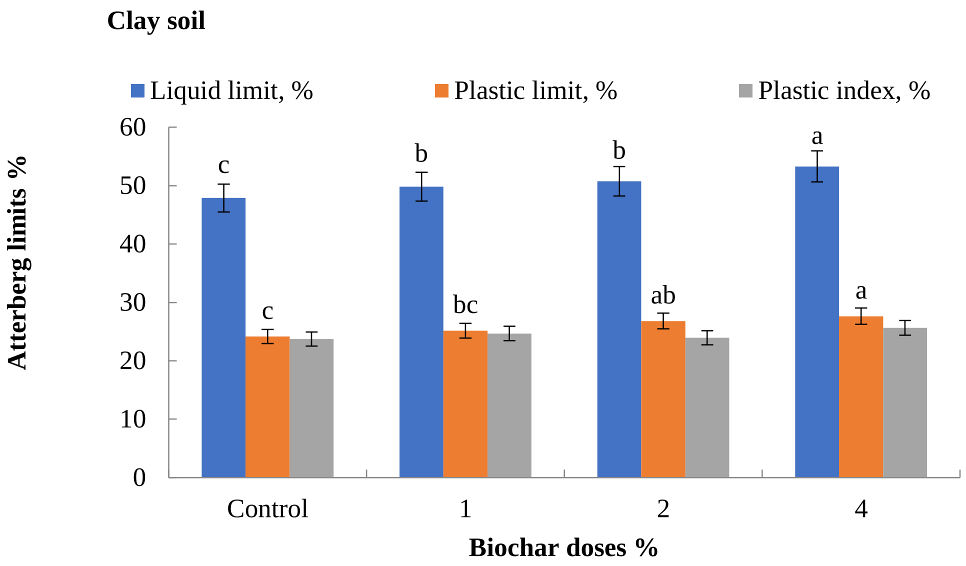

Figure 1
Illustration of liquid limit, plastic limit and plastic index of clay soil.

Table 3
Effect of biochar on soil chemical properties in clay and sandy loam soil

Properties	Clay soil				P Value
	Control	1%	2%	4%	
pH (1:2.5 H_2O)	8.02±0.00 a	7.89±0.02 b	7.88±0.00 b	7.85±0.00 c	***
EC (1:2.5 H_2O dS m^{-1})	0.57±0.03 d	1.04±0.019 c	1.33±0.006 b	2.07±0.078 a	***
OC (%)	2.41±0.01 d	2.95±0.03 c	3.34±0.08 b	4.16±0.12 a	***
$CaCO_3$ (%)	13.23±0.56	12.95±0.51	13.26±0.63	13.54±0.07	NS
Total nitrogen (%)	0.17±0.02 c	0.19±0.00 bc	0.21±0.01 ab	0.23±0.02 a	***
C/N	10.15±1.91 b	11.05±0.37 b	12.23±1.11 ab	14.92±1.34 a	*
	Sandy loam soil				
pH (1:2.5 H_2O)	8.20±0.01 a	8.07±0.01 b	8.04±0.00 c	8.00±0.01 d	***
EC (1:2.5 H_2O ds.m^{-1})	0.25±0.01 d	0.62±0.02 c	1.03±0.01 b	1.76±0.09 a	***
OC (%)	0.92±0.01 d	1.38±0.01 c	1.65±0.02 b	2.58±0.02 a	***
$CaCO_3$ (%)	11.90±0.40	11.66±0.27	12.33±0.28	12.31±0.40	NS
Total nitrogen (%)	0.12±0.00 c	0.16±0.00 b	0.17±0.00 b	0.18±0.00 a	***
C/N	4.95±0.27 d	6.73±0.32 c	11.38±0.93 b	14.13±0.91 a	***

Significant at *P <0.05, ***P <0.001; NS: Not significant.

The EC values were significantly (P<0.001) increased with increasing of BC rates in both soils of the study, and the rate of 4% had the highest EC value, which was increased by 263% and 604% in clay and sandy loam soils, respectively. CaCO3 content was not affected by the addition of BC in both soils. TN was increased significantly (P<0.001) by increasing BC rates in both soils, and the highest increase of TN was at 4% of BC in both soils, by a rate of 35.3% and 50% in clay and sandy loam soils, respectively. OC takes the same trend of nitrogen by significant increasing (P<0.001) with an increase of BC, and the highest values were at a rate of 4% by increasing rate of 72.6% and 180% in clay and sandy loam soils, respectively. The relationship between carbon and nitrogen which is expressed as C/N ratio showed a significant (P<0.05 and P<0.001) increase in clay soil and sandy loam soil with increasing of BC. It was found that the highest applied dose showed a higher value of C/N and C/N increased respectively by 47 and 185.4% in sandy loam and clay soil when biochar was applied at a rate of 4%. The mineralization rate of OC at the end of the short-term incubation period (one month) as illustrated in figure 3 and 4 was 11.5% at the clay soil, and 43% at sandy loam soil in control treatments, whereas at the BC amendments of 1, 2, and 4%, the mineralized OC was significantly increased (P<0.001) by the means of 23.9, 21.1, and 23.3% in a clay soil, and significantly decreased (P<0.001) by the means of 34.6, 15.8, and 23.6% in a sandy loam soil, respectively.

Discussion and conclusion

In both soils, the short-term amendment effects of biochar applications on the physico-mechanical properties were limited even if they were found significant statistically. The bulk density was decreased with concurrently increasing of BC doses and soil porosity in fine and coarse-textured soils, and these results are compatible with other studies (Lehmann and Joseph, 2009; Glab et al. 2016; Ningning et al. 2016). Due to the low density of biochar around 1.5 to 1.7 g cm^{-3} (Oberlin 2002) and 1.47 g cm^{-3} such as biochar made from pine wood collected from fire site (Brown et al. 2006), the particle density of our soils with 4% of BC amendment was significantly decreased. One of the mechanisms of soil aggregation is made by forming cation bridges between clay particles and soil organic matter (Juriga and Šimanský, 2018). In addition, biochar has high basic cation content (Rajkovich et al. 2012), therefore, its application to the soil can join clay and organic particles together by cation bridges (Bronick and Lal, 2005). In this study, the aggregation index of MWD was significantly increased with increasing of biochar doses only in clay soil. In contrast to the results of sandy loam soil, it was shown that MWD decreased with increasing of BC doses because of the weak bond between sand particle, although both soils have low exchangeable-extractable sodium contents (Bal et al. 2011; Şeker et al. 2016), which made a weak soil aggregate that cannot resist the wet sieving. Our results about the effect of biochar on MWD in sandy loam soil are in agreement with Fungo et al. (2017), who found that biochar did not affect on MWD alone, but when a combined application with green manure or urea showed a significant increase in MWD. Similarly, Herath et al. (2015) and Peng et al. (2016) founds that no effect of biochar amendment on soil micro-aggregates. However, the results of soil aggregate stability by rainfall simulator showed a significant increase in values of both soils compare with control, meaning that biochar amendment promoted the formation of more stable soil aggregate, which is resistant to degradation by rainfall drops. But when biochar doses were increased up to 4% in clay soil, as well as up to 2 and 4% in sandy, soil aggregate decreased compare with 1%, this was probably attributed to the effect of raindrops to reduce the particle size of biochar from certain types of biomass (Graetz and Skjemstad 2003). The liquid limit was significantly increased with increasing of BC doses in both soils. No more studies about the direct effect of BC on Atterberg limits have been carried out, however, it was reported that biochar can improve soil physical and hydraulic properties, such as soil porosity and soil water holding capacity (Şeker and Manirakiza 2020). Likewise, the result of the plastic limit in clay soil showed a significant increase for the same reason. Plasticity index results showed that there was no significant effect of BC amendment on soil plasticity; however, it was classified as plastic soils according to (Leonards 1962) classification. According to (Mitchell 1976) and depending on the results of Atterberg limits, the estimate clay mineral of our studied clay soil is kaolinite.

The pH of biochar considerably depends on the type of used feedstock and pyrolysis temperature, and it has been well documented that biochar amendment can significantly alter the pH of the soil (Lehmann and Joseph 2009). Although our results showed that pH of BC that used in this experiment was up to 10.2, soil pH was significantly decreased with increasing of BC doses as compared with the control in both soils. Cheng et al. (2006) reported that pH of biochar can be decreased to a value of 2.5 after incubation at 70° C in a short time period of four months and attributed that to the effect of incubation on increasing of oxidization process, thereby decreasing soil pH around biochar particle. About the effect of BC amendment on soil EC, our results showed a remarkable increase in soil EC with increasing of BC doses, and these results are agreement with numbers of studies such as (Lehmann and Joseph 2009; Tasneem and Zahir 2017) this increase in soil EC could be attributed to the release of weakly bound nutrients of biochar in the soil solution (Chintala et al. 2013).

The OC was significantly increased with BC amendment in both soil, this was expected because of the high sequestration of C in biochar. The increasing rate was more in sandy loam soil than clay soil, because of the inherent low content of OC in sandy soil. The TN content was increased significantly in both soils, but the increasing rate was higher in sandy soil than clay soil. Our results of TN and OC are in agreement with Laird et al. (2010), who found that biochar amendment significantly increased TN and OC. The C/N ratio was significantly increased in both soils under cultivation with increasing of BC, due to its high C content in biochar.

The results of mineralized OC illustrated in figures 3 and 4 have shown that the mineralization rate of control treatments in sandy loam soil was approximately fourfold more than that at a clay soil. This supposed to be because of the effect of clay by making colloidal complexes led to reducing the mineralization rate in clay soil (Six et al. 1998; Sparks 2003). Whereas at the BC amendments, our results have shown an increase in the mineralization rate of clay soil in comparison with control, however, it was relatively still at a stable rate with increase of BC doses, may be because of the high activity and number of microorganisms in clay soils still sufficient even in with increasing of OC in soil (Lehmann et al. 2011). While the opposite occurred in a sandy loam soil the BC amendments had an effect by decreasing the rate of mineralization in significantly compared with control, due to higher mineralization ratio of the control sample non-amended with BC at sandy loam soil. Although the organic carbon content of the sandy loam soil is lower than the clay soil, the mineralization rate in the control sample in sandy loam soil was found higher than the clay soil. The reason for this is considered to be due to bonding of clay colloids and humus complexes (Sollins et al. 1996; Six et al. 1998).

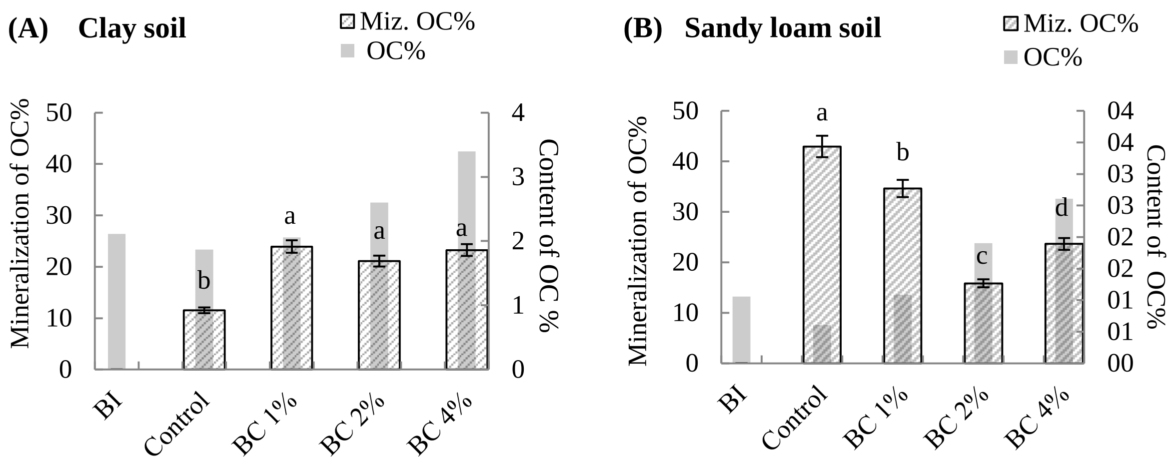

Figure 3
Illustration the effect of incubation period on mineralization of organic carbon in clay and sandy loam soils; BI (Before incubation)

This study was carried out under laboratory condition to investigate the effect of biochar amendment in a short-term period on some soil physico-mechanic and chemical properties. The results obtained showed that BC amendment had a positive effect on soil structural properties, by enhancing soil porosity, reducing BD, and increasing soil aggregation in both soils of study. However, MWD was significantly increased only in clay soil and decreased in sandy loam soil, due to the weak bind between BC and sand particles. Our results of soil LL test had shown a significant increase with increasing of BC doses in both studied soils. Which could be attributed to the benefits of BC to promote the soil aggregates and increase the soil porosity, thereby, increasing the soil water storage capacity and raise the liquid limit of soil. The results of PL detected at a clay soil showed the same trend with a significant increase by increase of BC doses. Whereas the results of plastic limits did not show a significant effect because of increase both LL and PL. The chemical properties showed that the benefit of biochar to decrease soil pH in the study soils, which had relatively high lime content. The BC additions were increased C sequestration capacity by significantly increasing of soil OC. The rate of OC mineralization was more at sandy loam soil than clay soil, due to the effect of clay to reducing OC that process, and the mineralization rate still relatively stable even with an increase of BC doses. Whereas in sandy loam soil BC doses were significantly decrease the mineralization rate by increase the sequestration of OC. Although that BC amendment had a negative effect on soil EC and C:N ratio by raising their values significantly, but generally it improves soil physico-mechanic and chemical properties in both soils. Overall, biochar effect was more pronounced on the sandy loam soil than clay soil.

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