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Study the Effect of Soil Compaction and Biochar on Some Soil Physical Parameters

Ali Kadhim Ahmed[1]*, Ibrahim Ahmad Hadres[1], Ahmed Albajary[2], Solarov Oleksandr[3]

[1]Department of Soil Science and Water Resources, College of Agriculture, University of Diyala, Diyala, Iraq.
[2]Department of Plant Production, Technical Institute, Northern Technical University, Hawija, Iraq.
[3]Department of Tractors, Agricultural Machines and Transport Technologies, Engineering-Technological Faculty, Sumy National Agrarian University, Sumy, Ukraine.
*Corresponding author: alikadhim@uodiyala.edu.iq

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Abstract

An experiment was conducted to evaluate the effect of soil compaction levels and biochar addition on some soil physical parameters, namely; bulk density, particle density, soil porosity, hydraulic conductivity and infiltration. It included two factors: soil compaction with two levels of 0 and 2 kg and biochar addition with two levels of 0 and 2 %. The results showed that the soil compaction of 2 kg significantly affected in the bulk density, soil porosity, and hydraulic conductivity comparing with the soil compaction 0 kg, with no significant effect on particle density and infiltration. Meanwhile, 2 % biochar addition significantly affected in the bulk density, soil porosity, and hydraulic conductivity compared with 0 % biochar addition, with no significant effect on particle density and infiltration. Moreover, the results showed that the interaction between soil compaction and biochar addition led to a significant effect giving lowest bulk density 0.99 Mg m^{-3}, particle density 2.42 Mg m^{-3}, hydraulic conductivity 1.46 cm h^{-1}, and highest soil porosity 59.20 %, with 0 kg soil compaction and 2 % biochar, but lowest infiltration 8.10 cm h^{-1} with 2 kg soil compaction and 2 % biochar.

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Introduction

Agricultural soil compaction is soil structure degradation and an increase in bulk density or a decrease in soil porosity due to loads applied externally or internally (Alakukku, 2012). Compaction can adversely affect almost all physical, chemical and biological properties and functions of the soil. Along with soil erosion, it is seen as the most serious environmental problem caused by conventional agriculture (Whalley *et al.,* 1995). Soil compaction is a complex problem in which soil, crops, weather and machinery interact. External stress caused by the use of heavy machinery and improper soil management can lead to subsoil compaction, which can lead to the formation of impermeable layers inside the soil that restrict water and nutrient cycles.

This process can also cause on-site effects such as reduced crop growth, yield and quality as well as off-site effects such as increased surface water runoff and soil erosion (Batey, 2009).

It results in unusual conditions that are reflected in the flow of soil, and chemical reactions in the soil, including the dissolution of elements Nutrients in the soil solution and their movement to the plant, in such conditions, there is a decrease in the movement and exchange of gases, including oxygen, causing reductive conditions to prevail at the expense of oxidative conditions (Patrick and Henderson, 1981). And it occurs by reducing the air volume in the voids without reducing its water content. It should not be confused with the compaction process, which means the release of water from among the soil particles under the influence of a constant and continuous weight. Air voids cannot be completely removed by the compaction process, but they can be reduced with an appropriate control method to the greatest extent possible (Baqir, 2013).

The mechanical properties of soil are crucial to achieve distinguished agricultural production. Physical fertility is prioritised over nutritional fertility because the germination of seeds and emergence of seedlings constitute the first stage of plant life and are directly related to soil hardness. This topic is of particular importance in gypsum soils, which are characterised by high hardness. Soil hardens when it dries, and conducting agricultural operations and facilitating the growth and penetration of roots are difficult unless it is rehydrated. In addition to changes in the structure of soil, compaction reduces the area of soil pores and enhances soil strength while impeding root growth, leading to a reduction in the absorption of water and nutrients by crops (Nawaz *et al.,* 2013; Keller *et al.,* 2019). The concept of soil hardening that arises in the absence of external influences is different from that of soil compaction that occurs as a result of an external influence, specifically, mechanical force. Soil hardening hinders the emergence of seedlings and growth and penetration of roots, therefore leading to the deterioration of agricultural production on hardened soil. The natural compaction of soil, which is measured by micromorphological parameters, tensile strength, soil resistance to penetration and bulk density, is the main factor that directly or indirectly affects the physical and micromorphological properties that are analysed and is responsible for the noticeable difference between hardened and nonhardened soil horizons (Fabiola *et al.,* 2003; Zheng *et al.,* 2022). The infiltration rate decreases with the number of passages of a mechanical unit over time due to the decreased bulk density and increased porosity of soil (Souli *et al.,* 2024). Studies have suggested that no-till agricultural systems and not using heavy equipment can considerably reduce bulk density (Jasim *et al.,* 2024).

Biochar is a porous organic carbon compound that is produced through pyrolytic conversion at 300–1000℃ under the conditions of oxygen deficiency. As a contemporary soil amendment, biochar serves as a naturally occurring substance that integrates harmoniously with soil constituents and lacks adverse effects upon its incorporation. Consequently, it is regarded as an ecologically benign enhancer. This material functions to diminish the extent of water leaching beyond the root zone, thereby facilitating the retention of moisture within the confines of the root area, and thus plays a pivotal role in augmenting the efficacy of irrigation water infiltration and combating desertification (Jeffery *et al.,* 2011).

Many studies have substantiated that adding biochar to soil enhances various soil physical properties, such as soil water conductivity, total porosity and bulk density (Al-Moosa *et al.,* 2021). Adding biochar improves soil properties and increases water retention in soil and water availability to plants, (Huang *et al.,* 2021; Yang and Lu, 2021). Conversely, alternative research indicates that the application of biochar does not exert a remarkable influence on the physical or hydraulic characteristics of soil (Fungo *et al.,* 2017). Although the effects of biochar are not invariably beneficial, no negative effects have been reported (Hardie *et al.,* 2014; Aller *et al.,* 2017; Mukherjee and Lal, 2013). Biochar is regarded as an important amendment that has attracted considerable scholarly interest in recent years. A substantial portion of the extant literature has identified biochar as a promising technology for enhancing soil properties while simultaneously ameliorating physical and hydraulic parameters, including soil structure, water retention and soil physical quality (He *et al.,* 2020; Knoblauch *et al.,* 2021; Amoah-Antwi *et al.,* 2020). Moreover, biochar is characterised by its high porosity and specific surface area. Therefore, its incorporation into soil can enhance the overall pore structure (Yu and Lu, 2020). The prolonged utilisation of biochar on the field surface exerts advantageous effects on the physical and hydraulic attributes of soil. The application of biochar results in a reduction in soil bulk density and a decrease in the degree of soil compaction. The introduction of biochar also modifies the distribution of soil pore sizes, leading to an increase in total porosity, and has been shown to enhance soil health metrics and the soil physical quality index (Li *et al.,* 2023; Zhang *et al.,* 2023). The present study aims to assess the effect of soil compaction and biochar addition on some soil physical properties.

Materials and Methods

An experiment was conducted at the soil physics laboratory of the Department of Soil Sciences and Water Resources, College of Agriculture, University of Diyala, in January 2023. The soil had a sandy loam texture (Table 1) and was collected from the beach of the Diyala River at a surface horizon of 0-30 cm. After collection, it was air-dried, ground with a wooden hammer and passed through a sieve with a hole diameter of 2 mm. The hydrometer method was used for particle size analysis (Black *et al.,* 1965).

Soil preparation

An apparatus was engineered with an iron base to support plastic pipes vertically. Each base held 12 tubes, each truncated to a diameter of 0.1016 m and length of 0.3 m and utilising a concave cover. A central hole was drilled with an auger with a diameter of 10 mm. A thick layer of gravel (0.02 m) was placed at the base of the tube, which was lined with glass wool. The periphery of the tube was treated with a viscous substance to mitigate the ingress of water through the tube walls, thereby ensuring that the assessment of hydraulic conductivity and infiltration remained unaltered. Biochar was sieved by using a mesh with an aperture of 2 mm and incorporated at ratios of 0 and 2% based on the dry weight of soil, which was consistently maintained at the limits of field capacity (Hillel, 2003).

Experiment design and statistical analysis

The experiment was designed in accordance with a complete randomised design (CRD) with three replicates. Duncan's test was used to compare treatment means at the 0.01 level by using a statistical programme (SAS, 2013). The treatment included the following parameters:
A) Soil compaction at two levels:

1. Without soil compaction (0 kg).
2. With soil compaction. Compaction was performed with 20 knocks by using a weight of 2 kg. The weight was dropped from a fixed vertical height (50 cm) for regular and stable hammering.

B) Biochar addition to soil at two levels:

1. Without biochar addition (0%).
2. Biochar was added to soil at a level of 2% of the weight of soil (2%). It was produced from corn straw waste by using an oven (Germany Nabentherm, Max Temperature 1300°C, 400 V, IS. OA, 50160 Hz) at 500°C and isolated from the air for 2 h.

Studied characteristics

Soil Bulk Density

Bulk density was estimated in accordance with the cylinder method (core method). The cylinder diameter and height were 4.9 and 5.1 cm, respectively. Part of the surface layer was removed. Subsequently, the cylinder was embedded in soil, and a piece of wood was placed on the cylinder with light tapping until it was filled with soil. The excess soil was cut with a sharp knife. The samples were dried in an oven maintained at 105°C for 24 h. Subsequently, bulk density was determined as the ratio of the dry soil mass to the volumetric capacity of the cylinder (Al-Tamimi and Mahdi, 2017), by using Equation 1:

$$\rho_b = Ms/Vt \text{ .... } (1)$$

Where ρ_b is the soil bulk density (g cm^{-3}), Ms is the mass of the kiln-dried soil sample (g) and Vt is the total volume of soil with its natural structure (cm^3).

Particle density

Density was estimated by applying a pycnometer density bottle in accordance with a previously described method (Black *et al.,* 1965).

Porosity

Porosity was estimated from bulk and particle density values (Hillel, 2012), by using Equation 2:

$$f = \left[1 - \frac{\rho_b}{\rho_s}\right] \times 100 \text{ .... } (2)$$

Where f is the soil porosity (%), and ρs is the particle density (mg m^{-3}).

Hydraulic conductivity

The columns were saturated with water to determine hydrological characteristics and allowed to rest for one day. The hydraulic conductivity of the saturated soil within the columns was evaluated by employing a burette holder in conjunction with a 250 ml volumetric flask. A consistent 1 cm water column was applied to the soil surface. The volume of water descending through the column over time was methodically recorded and analysed by using Darcy's equation (Hillel, 2003), according to Equation 3:

$$\mathrm{Ks} = \mathrm{VL}/(\mathrm{At}(\mathrm{h}+\mathrm{L})) \ \ldots\ldots\ldots\ldots\ldots\ldots.(3)$$

Where Ks represents the saturated hydraulic conductivity of the soil (cm m^{-1}), V denotes the volume of water descending from the column (cm^3), A indicates the cross-sectional area of the soil column (cm^2), t symbolises the time interval (min), L refers to the length of the soil column (cm) and h signifies the height of the water column (cm).

Infiltration

Soil water infiltration was assessed by using a mini disk infiltrometer by following the methodology outlined by Zhang (1997). Readings were recorded at 30 s intervals for sandy loam soil. The resultant values were calculated by using a Microsoft Excel spreadsheet. Figure 1 illustrates the components of the mini disk infiltrometer according to Equation 4:

$$\mathrm{I} = \mathrm{C1T} + \mathrm{C2}\sqrt{T} \ \ldots\ldots\ldots.(4)$$

Where I is the infiltration, C1 is the constant related to the saturated water conductivity, C2 is the soil absorbency and T is the time.
Soil water conductivity (K) is calculated with Equation 5.

$$\mathrm{K} = \frac{C1}{A} \ \ldots\ldots\ldots\ldots..(5)$$

Where A is an experimental constant and is calculated from Equations 6 and 7:

$$A = \frac{11.65(n^{0.1}-1)\ exp\ exp\ [2.92(n\ -1.9)\alpha h0\ ]}{(\alpha\ r0\ )^{0.91}} \quad n\ \geq 1.9 \quad \ldots\ldots\ldots\ldots\ldots(6)$$

$$A = \frac{11.65(n^{0.1}-1)\ exp\ exp\ [7.5(n\ -1.9)\alpha h0\ ]}{(\alpha\ r0\ )^{0.91}} \quad n < 1.9 \ \ldots\ldots\ldots..(7)$$

Where h is the tension, r is the radius of the porous disk (2.25 cm) and (n and α) are the constants of the van Genuchen equation measured from moisture tension curve data using the RETC programme.

Figure 1. Components of the mini disk infiltrometer

Table 1. Physicochemical characteristics of the study soil

Character	Value	Unit
Bulk density	1.33	Mg m^{-3}
Particle density	2.61	Mg m^{-3}
Soil porosity	49.12	%
Hydraulic Conductivity	2.09	cm h^{-1}
Sand	280	
Silt	420	gm kg^{-1}
Clay	300	
Texture class	Silt loam	………
Electric Conductivity (EC) (1:1)	2.32	ds m^{-1}
ph (1:1)	7.56	……..
Infiltration	10.30	cm h^{-1}
Organic matter (om)	1.53	
Calcium carbonate	198	gm kg^{-1}
Available Nitrogen	31.47	
Available Phosphorus	10.32	mg kg^{-1}

Results and Discussion

Soil bulk density (Mg m^{-3})

Table 2 show the effect of soil compaction and biochar addition on soil bulk density. As the level of soil compaction increased from 0 to 2 kg, the soil bulk density significantly increased from 1.16 to 1.27 Mg m^{-3}, due to a decrease in soil porosity. The loads applied to soil led to an increase in soil density and reduced porosity. This result corresponds with the findings of Abdulkareem *et al.* (2023); Amoah-Antwi *et al.* (2020).

Table 2 also illustrates that increasing the biochar addition from 0 to 2% significantly decreased the bulk density from 1.33 to 1.09 Mg m^{-3} given that biochar is characterised by its high porosity and specific surface area, its incorporation into soil can enhance the overall pore structure. This result corresponds to the findings of Yu and Lu (2020); Goyal and Kahlon (2023).

Table 2. Effect of soil compaction and Biochar on soil bulk density (Mg m^{-3})

Soil compaction (kg)	Biochar (%)		Mean effect of soil compaction
	0	2	
0	1.33 a	0.99 c	1.16 b
2	1.34 a	1.20 b	1.27 a
Mean effect of biochar	1.33 a	1.09 b	

*Different letters indicator for a significant difference among treatments at the probability level of (P<0.01).
*Similar letters indicate no significant differences among treatments at the probability level of (P<0.01).

Table 2 also presents that the interaction of soil compaction and biochar had a significant effect on bulk density. The lowest bulk density of 0.99 Mg m^{-3} was found under the soil compaction of 0 kg and biochar addition of 2 %, whereas the highest bulk density of 1.34 Mg m^{-3} was found under the soil compaction of 2 kg and biochar addition of 0 %.

Particle density (Mg m^{-3})

Table 3 show the effect of soil compaction and biochar on particle density. As soil compaction increased from 0 to 2 kg, the particle density decreased insignificantly from 2.51 to 2.49 Mg m^{-3}.

Table 3 also shows that increasing the biochar addition from 0 to 2 % led to an insignificant effect in particle density from 2.58 to 2.43 Mg m^{-3}.

Table 3 presents that the interaction of soil compaction and biochar had a significant effect on particle density. The lowest particle density of 2.42 Mg m^{-3} was found under the soil compaction of 0 kg and biochar addition of 2 %, whereas the highest particle density of 2.61 Mg m^{-3} was found under the soil compaction of 0 kg and biochar addition of 0 %.

Table 3. Effect of compaction levels and Biochar on particle density (Mg m^{-3})

Soil compaction (kg)	Biochar (%)		Mean effect of soil compaction
	0	2	
0	2.61 a	2.42 b	2.51 a
2	2.55 a	2.44 b	2.49 a
Mean effect of biochar	2.58 a	2.43 a	

Soil porosity (%)

Table 4 shows the effect of soil compaction and biochar addition on soil porosity. Increasing the level of soil compaction from 0 kg to 2 kg significantly decreased soil porosity from 54.16 to 49.67 % because the loads applied on soil increased bulk density and reduced porosity. This result corresponds to the finding of Abdulkareem *et al.* (2023).

Table 4 also shows that increasing the biochar addition from 0 to 2 % significantly increased soil porosity from 48.81 to 55.01 %, due to the decrease in the particle density and increase in the porosity of biochar. This finding is commensurate with the results of Islam *et al.* (2021); Jang *et al.* (2023). Given that biochar is characterised by its high porosity and specific surface area, its incorporation into soil can enhance the overall pore structure. This result corresponds to the finding of Yu and Lu (2020).

Table 4. Effect of soil compaction and Biochar on soil porosity (%)

Soil compaction (kg)	Biochar (%)		Mean effect of soil compaction
	0	2	
0	49.12 bc	59.20 a	54.16 a
2	48.51 c	50.83 b	49.67 b
Mean effect of biochar	48.81 b	55.01 a	

Table 4 and also presents that the interaction of soil compaction and biochar addition had a significant effect on soil porosity. The lowest soil porosity of 48.51 % was found under a soil compaction of 2 kg and biochar addition of 0 %, whereas the highest soil porosity of 59.20 % was found under a soil compaction of 0 kg and biochar addition of 2 %.

Hydraulic conductivity (cm h^{-1})

Table 5 illustrates the effect of soil compaction and biochar on hydraulic conductivity. As the level of soil compaction increased from 0 to 2 kg, hydraulic conductivity decreased significantly from 1.77 to 1.60 cm h^{-1}, due to the increase in the bulk density and decreased porosity of soil. This result corresponds to the finding of Shaheb *et al.* (2021).

Table 5 also shows that increasing the biochar addition from 0 to 2 % significantly decreased of hydraulic conductivity from 1.92 to 1.46 cm h^{-1}, due to the low bulk density and high micropore content of sandy loam. This result is consistent with the finding of Al-Moosa *et al.* (2021).

Table 5. Effect of soil compaction and biochar in soil hydraulic conductivity (cm h^{-1})

Soil compaction (kg)	Biochar (%)		Mean effect of soil compaction
	0	2	
0	2.09 a	1.46 b	1.77 a
2	1.75 b	1.46 b	1.60 b
Mean effect of biochar	1.92 a	1.46 b	

Table 5 also shows that the interaction between soil compaction and biochar addition had a significant effect on hydraulic conductivity. The lowest hydraulic conductivity of 1.46 cm h^{-1} was obtained under the soil compaction level of 0 and 2 kg with biochar addition of 2 %, whereas the highest hydraulic conductivity of 2.09 cm h^{-1} was obtained under the soil compaction level of 0 kg and biochar addition of 0 %.

Infiltration (cm h^{-1})

Table 6 shows effect of soil compaction and biochar on infiltration. With increasing the soil compaction from 0 to 2 kg the infiltration decreased non significantly from 9.61 to 8.13 cm h^{-1}.

Also, it is clear from Table 6 that the biochar addition from 0 to 2 %, led to a non-significant decrease in the infiltration from 9.23 to 8.51 cm h^{-1}.

Table 6. Effect of soil compaction and Biochar in infiltration (cm h^{-1})

Soil compaction (kg)	Biochar (%)		Mean effect of soil compaction
	0	2	
0	10.30 a	8.93 ab	9.61 a
2	8.16 a	8.10 a	8.13 a
Mean effect of biochar	9.23 a	8.51 a	

As presented in Table 6, the interaction of soil compaction and biochar had a significant effect on infiltration. The lowest infiltration was 8.10 cm h^{-1} under the soil compaction of 2 kg and biochar addition of 2 %, whereas the highest infiltration was 10.30 cm h^{-1} under the soil compaction of 0 kg and biochar addition of 0 %.

Conclusions

The results showed that the soil compaction of 2 kg significantly affected in the bulk density, soil porosity, and hydraulic conductivity comparing with the soil compaction 0 kg, with no significant effect on particle density and infiltration. Meanwhile, 2 % biochar addition significantly affected in the bulk density, soil porosity, and hydraulic conductivity compared with 0 % biochar addition, with no significant effect on particle density and infiltration. Moreover, the results showed that the interaction between soil compaction and biochar addition led to a significant effect giving lowest bulk density 0.99 Mg m^{-3}, particle density 2.42 Mg m^{-3}, hydraulic conductivity 1.46 cm h^{-1}, and highest soil porosity 59.20 %, with 0 kg soil compaction and 2 % biochar, but lowest infiltration 8.10 cm h^{-1} with 2 kg soil compaction and 2 % biochar. Soil compaction adversely affected soil physical properties, whereas biochar addition improved soil physical properties. A comprehensive approach controlling the unit weight of agricultural machinery to reduce the pressure on soil and using biochar addition on the basis of soil physical properties must be adopted to improve the risk of the soil compaction of agricultural land. These strategies aim to restore soil vitality and support sustainable farming practices.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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