Effects of Compaction Stress, Biochar Application Rate, Irrigation Water Quality, and Their Interactions on Selected Physical Properties of Gypsiferous Soil

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Abstract

This study was conducted in the laboratories of the Department of Soil Sciences and Water Resources, College of Agriculture, Tikrit University during the growing season 2024 to investigate the effect of compaction stress represented by bulk densities (1.2, 1.3, 1.4, 1.5, 1.6, and 1.7 Mg m-3), biochar application rates (0, 0.5, and 1% w/w), irrigation water quality (River water (EC = 0.680 dS m-1), well water (EC = 2.740 dS m-1), and drainage water (EC = 6.320 dS m-1) and their interaction on selected physical properties of a gypsiferous soil. The results showed that increasing bulk density significantly affected all measured soil physical properties. Total porosity decreased to 0.343, and saturated hydraulic conductivity declined to 0.04 cm min^{-1}, whereas shear strength increased to 2.28 kg cm^{-2} and soil penetration resistance increased to 52.55 kPa cm^{-2}. Soil water content at field capacity, permanent wilting point and available water also decreased with increasing compaction. When the application rate of biochar was increased to 1%, the physical properties of the soil were significantly improved. The mean total porosity was increased to 0.458, the saturated hydraulic conductivity was 0.33cm min-1 and the soil penetration resistance was decreased to 31.28kPa cm-2. Moreover, biochar improved the water holding capacity of the soil and increased the moisture content of the soil. Also, the quality of irrigation water had a significant effect on all studied properties.

Significant two-way and three-way interactions were observed among compaction stress, biochar application, and irrigation water quality. The best overall soil physical properties were obtained with 1% biochar application, River water irrigation, and the lowest bulk density, whereas the poorest results were recorded under no biochar application, drainage water irrigation, and the highest bulk density.

Keywords: Gypsiferous soil; Compaction stress; Biochar; Irrigation water quality; Total porosity; Saturated hydraulic conductivity; Soil penetration resistance; Shear strength; Soil water retention curve.

1. Introduction

Gypsiferous soils are present in dry and semi dry zones particularly in Iraq where they occupy large areas of agricultural land. These soils have high contents of gypsum ($CaSO_4 \cdot 2H_2O$), which gives them specific physical and chemical properties that directly affect plant growth and productivity. Among the major problems associated with these soils are weak structural development, low aggregate stability, and high susceptibility to compaction, resulting in deterioration of their physical properties, reduced water

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and nutrient use efficiency, and consequently decreased agricultural productivity (1). Soil compaction stress is considered one of the most important factors affecting soil physical properties. It occurs due to the movement of heavy agricultural machinery, soil disturbance under unsuitable moisture conditions, or continuous pressure on the soil surface. Compaction increases bulk density, decreases total porosity, reduces infiltration rate and saturated hydraulic conductivity, and increases soil penetration resistance. These impacts limit root growth, reduce plant uptake of water and nutrients, and adversely influence biological activity in the soil (2). In recent years many studies have been conducted to investigate the effectiveness of biochar as organic soil amendment. Biochar is made by heating plant or animal residues in an oxygen-free environment. It is featured by high porosity, large surface area and long-term chemical stability. Biochar improves soil structure, bulk density, porosity, water retention, microbial activity and nutrient use efficiency. It is therefore a promising technology for the reclamation of degraded soils, particularly gypsiferous soils (3). However, the quality of irrigation water has become a critical component of managing agricultural soils, especially with the increasing demand for water and the reduction of freshwater resources due to climate change and population growth. Saline or poor quality irrigation water leads to salt accumulation in the root zone and affects soil structure, water and air movement and increases soil resistance to water movement thus reducing plant water uptake efficiency. These effects become more pronounced in gypsiferous soils, which possess sensitive physical characteristics that respond strongly to changes in irrigation water quality (4). The importance of studying the interaction among soil compaction stress, biochar levels, and irrigation water quality arises because the effect of each factor is not independent, but their interactions may lead to improvement or deterioration of soil physical properties. Biochar may alleviate the adverse effects of compaction by increasing porosity, reducing bulk density, and improving water conductivity, whereas irrigation water quality may influence biochar efficiency and soil response to mechanical stresses. These effects consequently affect water use efficiency, plant growth, and productivity. Recent studies indicate that integrated management of these factors represents a major approach for achieving sustainable agriculture in dryland regions (5). Therefore, this study was conducted to evaluate the individual and interactive effects of soil compaction stresses, biochar levels, and irrigation water quality on some physical properties of gypsiferous soil.

2. Materials and Methods

Soil Collection Site and Preparation

The soil samples were gathered from the Research Station of the College of Agriculture / University of Tikrit on 15/10/2024. The site is located on 250 m above sea level, 38°23′34″ E longitude and 34°48′40″ N latitude. Samples of soil were collected from the surface layer (depth 0–15 cm). The soil was air-dried in the laboratory, gently pounded with a wooden hammer, and plant residues and gravel were removed. The soil was then passed through a 2-mm sieve and stored in tightly sealed plastic containers until use (Table 1).

Experimental Treatments

The experiment included the following treatments:

1. Soil compaction stresses: Six levels of bulk density were applied :1.20, 1.30, 1.40, 1.50, 1.60, and 1.70 Mg m^{-3}.

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2. Biochar: Three levels were applied: 0, 0.5 and 1% (w/w) of soil.

3. Irrigation water quality: Three types of irrigation water were used, fresh water, moderate saline well water and highly saline drainage water as presented in Table (2).

Biochar was mixed well with soil, and the treated soils were placed in non-perforated plastic pots of 1 kg capacity. The prepared soil samples were irrigated with the designated irrigation water until 80% of field capacity. The samples were maintained under these conditions for two months, then air-dried, crushed using a wooden hammer, and passed through a 2-mm sieve. Soil compaction was performed at the previously mentioned bulk densities using a Proctor reference density apparatus (locally manufactured) inside metal rings with a diameter of 6.1 cm and a height of 2 cm. Compaction was achieved by applying 25 blows using a 2-kg hammer dropped from a height of 50 cm (6).

Studied Soil Properties

1. Soil Water Retention Curve

The soil water content was determined for soil samples compacted at bulk densities of 1.2, 1.4, 1.6 and 1.8 Mg m-3. A sufficient amount of soil was wetted to a water content corresponding to 100 kPa, as this level of moisture facilitates the compaction of soil without being too dry or too wet, thereby avoiding the breakdown of aggregates during compaction (7).

The soil samples were wetted and kept in sealed polythene bags for 2 days for uniform moisture distribution. The mass of soil needed to fill the metal rings (6.1 cm diameter and 2 cm height) was calculated using Equation (1):

$$\textbf{Soil mass(dry)} = \textbf{bulk density} \times \textbf{volume}\ \left[\left(\frac{\textbf{diameter}}{\textbf{2}}\right)^{\textbf{2}} \boldsymbol{\pi} \times \textbf{height}\right] \quad ...(1)$$

The compacted soil samples were saturated by capillary action for a period ranging from 2 to 8 days depending on bulk density to achieve complete saturation.

The water content of compacted soils was measured at matric suctions of 15, 33, 100, 500, 700, 1000, and 1500 kPa according to the method proposed by (8). Soil water content at 0 and 5 kPa suction was determined by applying a water column pressure using ceramic glass funnels (centered glass funnels) with porous plates having pore diameters of 20 μm. The soil water retention curve was then constructed to describe the relationship between gravimetric water content and soil water suction in compacted gypsiferous soils.

2. Total Porosity (%)

Total porosity was calculated based on bulk density and particle density values according to the following equation:

$$\textbf{TP} = (\textbf{1} - \boldsymbol{\rho}\textbf{b})/\boldsymbol{\rho}\textbf{s X 100} \ldots\ldots (\textbf{2})$$

Where:

TP = Total porosity (%).

ρs = Particle density (Mg m^{-3}).

ρb = Bulk density(Mg m^{-3}).

3. Shear Strength

The soil shear strength was measured using a laboratory motorized shear vane apparatus. The soil samples were first wetted to a water content corresponding to a suction of 33 kPa and then compacted to the desired bulk density levels. The shear failure torque was measured and the shear strength has been calculated by the following equation:

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$$S = \frac{T}{\pi D^2\left(\frac{H}{2}+\frac{D}{6}\right)} \dots\dots\dots (3)$$

Where:

S = Shear strength (kg cm^{-2} or kPa).
T = Torque (kg cm).
D = Shear vane diameter (cm).
H = Vane height within the soil sample (cm).

4. Soil Penetration Resistance

Soil penetration resistance was measured after moistening soil samples to 33 kPa suction and compacting them at bulk densities of 1.30, 1.40, 1.50, 1.60, and 1.70 Mg m^{-3} using a Static Digital Mini Cone Penetrometer.

5. Saturated Hydraulic Conductivity

Saturated hydraulic conductivity was determined at the above bulk densities using the constant-head method inside metal cores with a diameter of 5 cm and a height of 5 cm. The cores were saturated from the bottom, followed by applying a constant water head of 4 cm. The volume of water passing through the soil column over time was measured, and saturated hydraulic conductivity was calculated according to Darcy's law (9):

$$K_s = \frac{V \times L}{A \times t \times H} \dots\dots\dots (4)$$

Where:
Ks = Saturated hydraulic conductivity (cm min^{-1}).
V = Volume of water passing through the sample (cm^3).
L = Length of soil column (cm).
A= Cross-sectional area of the sample (cm^2).
t = Flow time (min).
H = Hydraulic head difference (cm).

Statistical Analysis

The data were statistically analyzed using the Statistical Analysis System (SAS) software. Analysis of variance (ANOVA) was performed according to a Completely Randomized Design (CRD). Differences among means were tested at a 5% significance level using Duncan's Multiple Range Test (10).

Table (1). Some physical and chemical properties of the studied soil

Property	Unit	Value	Analytical method used
Sand	g kg^{-1}	521	Determined by the pipette method (11)
Clay		223	
Silt		256	
Soil texture	—	Sand clay loam	
Bulk density	Mg m^{-3}	1.42	Determined using the core method according to the procedure proposed by (12)
Cation exchange capacity (CEC)	cmolc kg^{-1}	19.02	Determined using ammonium acetate extraction method (11)
pH (1:1 soil:water suspension)	—	7.48	Measured using a pH meter (13)
Electrical conductivity (EC)	dS m^{-1}	2.51	Measured using an electrical conductivity meter (13)
Calcium sulfate ($CaSO_4$)	g kg^{-1}	80.24	Determined by dilution method (14)

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Calcium carbonate ($CaCO_3$)	g kg^{-1}	190.11	Determined by the gravimetric method (13)
Organic matter (O.M.)	g kg^{-1}	7.11	Determined by wet digestion method (11)
Available nitrogen	mg kg^{-1}	19.35	Determined using the micro-Kjeldahl method (11)
Available phosphorus	mg kg^{-1}	7.02	Extracted with 0.5 M sodium bicarbonate solution ($NaHCO_3$) at pH 8.5 according to the method of (15)
Available potassium	mg kg^{-1}	119.95	Extracted with ammonium acetate according to the method described in (11) and measured using a flame photometer
Volumetric water content at 33 kPa	%	18.14	According to the method of (16)
Volumetric water content at 1500 kPa	%	8.01	According to the method of (16)

Table (2). Some chemical characteristics of the irrigation water used in the study

Property	**Unit**	**River water (W_1)**	**Well water (W_2)**	**Drainage water (W_3)**
Electrical conductivity (EC)	dS m^{-1}	0.68	2.74	6.32
pH	—	7.48	7.76	8.05
Sodium (Na^+)	mmolc L^{-1}	2.31	8.42	25.64
Potassium (K^+)		0.15	0.38	0.61
Calcium (Ca^{2+})		3.82	8.96	15.84
Magnesium (Mg^{2+})		2.56	8.10	19.25
Chloride (Cl^-)		2.18	9.14	28.37
Carbonate (CO_3^{2-})		0.00	0.00	0.14
Bicarbonate (HCO_3^-)		2.63	3.88	4.56
Sulfate (SO_4^{2-})		4.03	11.84	27.63

3- Results and Discussion

- **Soil Water Retention Curve**

The soil water retention curve reflects the relationship between soil water tension and gravimetric water content. It is considered one of the most important physical functions used for estimating plant-available water, irrigation scheduling, and evaluating the physical quality of soils.

The results presented in Figure (1) showed that the gravimetric water content increased gradually and consistently with increasing biochar application rate. The treatment receiving 1% biochar surpassed both the 0.5% biochar treatment and the untreated control across all investigated soil water tensions, bulk density levels, and irrigation water qualities. At a bulk density of 1.2 Mg m^{-3} under fresh water irrigation, the water content at 0.1 kPa tension increased from 41.98% in the control treatment to 44.19% with 0.5% biochar application and further increased to 46.39% with 1% biochar application, representing an overall increase of approximately 10.5% between the highest and lowest biochar levels. Meanwhile, at 1500 kPa tension, which is close to the permanent wilting point, the values increased from 12.05% to 13.67% and then to 15.48%, representing a greater overall increase of about 28.5%. A similar trend

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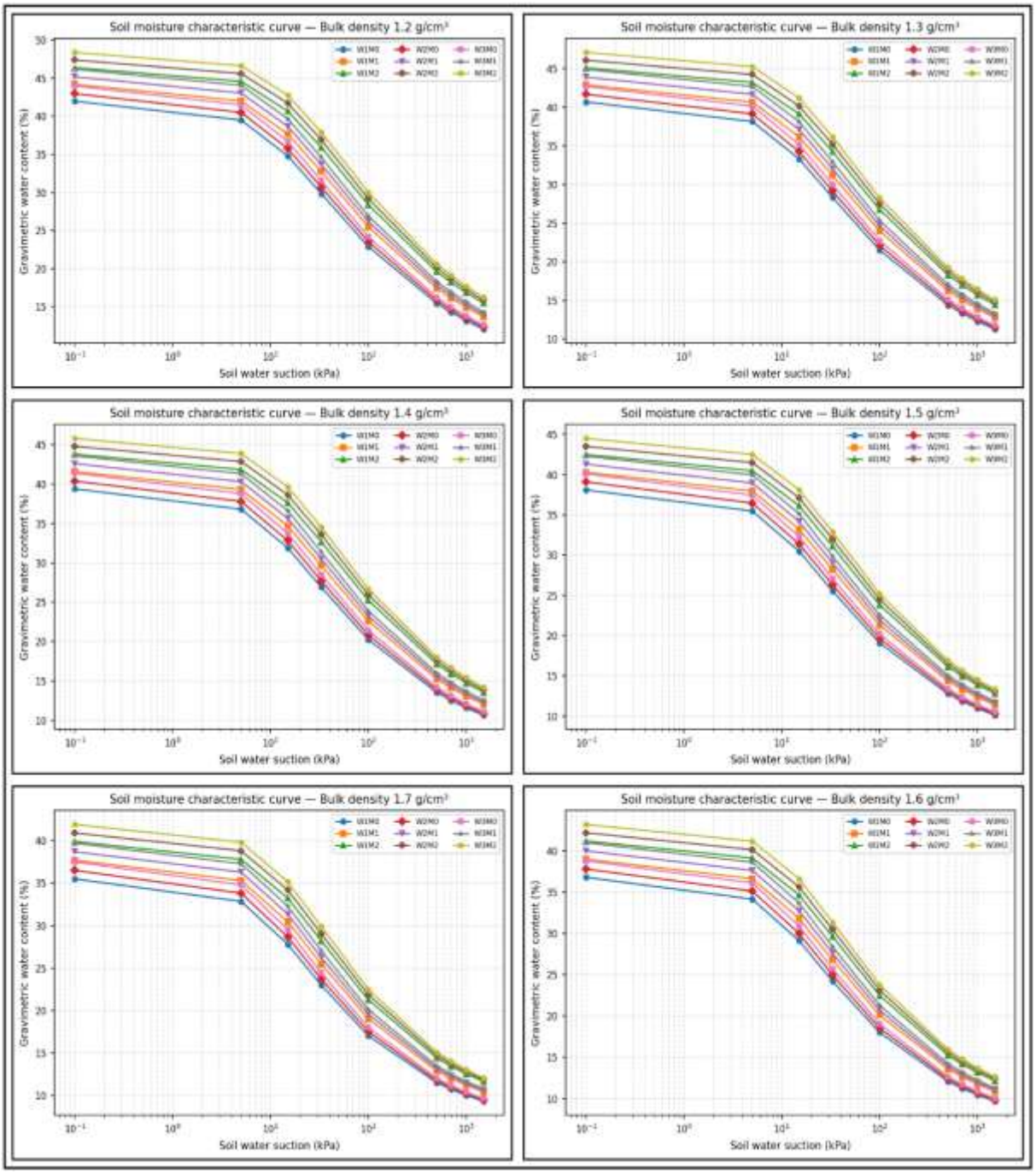
was observed under the highest compaction level, where increasing bulk density to 1.7 Mg m^{-3} increased the water content at 0.1 kPa tension from 35.49% to 39.89%, with an increase of approximately 12.4%, while at 1500 kPa tension it increased from 9.34% to 11.67%, representing an increase of about 24.9%. These comparisons indicate that the effect of biochar on increasing soil water retention was not restricted to a specific compaction level but remained relatively consistent even under the highest compaction intensity. Moreover, this effect was more pronounced at higher soil water tensions than at low tensions close to saturation.

The increase in water content with increasing biochar application rate can be attributed to the highly porous nature of biochar and its large specific surface area which contributes to increase the volume of fine and medium sized pores within the soil. These pores are mainly responsible for water retention under high tension conditions. In addition, biochar enhances soil organic matter content and increases its capacity to adsorb water within its internal porous structure (17). Recently, meta-analyses of large numbers of studies have shown that the application of biochar increases the field capacity and plant-available water by approximately 15–27%, depending on the soil texture and biochar type, with greater effects observed in coarse-textured soils than in medium and fine textured soils (18). In addition, (19) reported that biochar alters the soil microstructure and pore size distribution, resulting in better hydraulic functions related to soil water retention at high tension levels. This is totally consistent with the trend observed in the present study.

It was also observed from Figure (1) that soil water content at all investigated tensions increased according to the following order: fresh water irrigation < well water irrigation < drainage water irrigation, although the differences among irrigation water qualities were less pronounced than those resulting from biochar addition. At a bulk density of 1.2 Mg m^{-3} and without biochar application, the water content at saturation increased from 41.98% under fresh water irrigation to 42.98% under well water irrigation and then to 43.98% under drainage water irrigation, representing an overall increase of approximately 4.8%. A similar increase was observed at 1500 kPa tension, where the water content increased from 12.05% to 12.33% and then to 12.61%, with an increase of about 4.6%. The same pattern was repeated at a bulk density of 1.7 Mg m^{-3}, where the saturated water content increased from 35.49% under fresh water irrigation to 37.49% under drainage water irrigation, representing an increase of approximately 5.6%.

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Figure 1. Effect of compaction stresses, biochar level, and water Quality on soil moisture characteristic curves.



This response may be related to the effect of salt concentration and exchangeable sodium percentage of irrigation water on aggregate stability and soil structure. This process is called rapid aggregate slaking. Higher salinity or sodicity levels such as those associated with well water and drainage water in comparison to fresh water may lead to partial disintegration of

soil aggregates. This process leads to the release and migration of fine soil particles which can partially clog larger and medium sized pores. This leads to a decrease in the proportion of large pores and an increase in the proportion of small pores which hold water at different soil water tensions (20).

From 1.2 to 1.7 Mg m^{-3} soil bulk density, the gravimetric water content decreased with increasing bulk density consistently at all soil water tension levels, regardless of biochar addition and irrigation water quality as shown in the same figure. In the treatment irrigated with fresh water without biochar addition, the water content at saturation decreased from 41.98 % at bulk density of 1.2 Mg m-3 to 35.49 % at bulk density of 1.7 Mg m-3, which was about 15.5 % reduction. Meanwhile, the reduction at tension 1500 kPa was about 22.5% and the value decreased from 12.05% to 9.34%. This indicates that the negative effect of soil compaction became more pronounced as soil water tension increased, where the differences among the curves representing different bulk densities gradually widened towards the permanent wilting point. This behavior differs from what is occasionally observed in some highly gypsiferous soils, where curves of different bulk densities may converge or even intersect at high tensions due to variations in pore size distribution associated with gypsum content (21). The reasons for the further decrease are connected with the compaction of the soil that reduces the total porosity, compressing large and medium pores and bringing the soil particles closer to each other. Consequently, the volume of stored water decreases across all water tension levels, rather than only at saturation.

Regarding the interaction among the three studied factors, it is evident that the positive effect of biochar addition in increasing soil water retention remained consistent under all investigated compaction levels, without eliminating the adverse effect of compaction. This suggests that both factors operate in a relatively independent manner in shaping the soil moisture characteristic curve. When comparing the treatment with the highest water retention capacity, namely irrigation with drainage water combined with 1% biochar addition, with the treatment exhibiting the lowest water retention, namely fresh water irrigation without biochar addition, at a bulk density of 1.2 Mg m^{-3}, the saturated water content increased from 41.98% to 48.39%, representing an increase of approximately 15.3%. At 1500 kPa tension, the water content increased from 12.05% to 16.22%, corresponding to an increase of about 34.6%.

A similar trend was observed even at the highest compaction level studied, where the increase between the same two treatments at a bulk density of 1.7 Mg m^{-3} reached approximately 18.0% at saturation and 29.4% at 1500 kPa tension. These results suggest that the combined application of higher biochar rates and proper irrigation water quality management can offset a large part of the negative impact of soil compaction on water retention capacity, although it cannot completely remove its adverse effects.

• Total Porosity

The results in Table (3) show that total soil porosity was significantly affected by bulk density, biochar level, and irrigation water quality.

Bulk density exerted the greatest effect on total porosity, as the mean overall porosity decreased gradually from 0.542 at a bulk density of 1.2 Mg m^{-3} to 0.343 at a bulk density of 1.7 Mg m^{-3}. The decrease is because as the bulk density increases, the

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soil particles pack closer together and the pore volume, especially the macropores, decreases thus decreasing the total pore space and increasing the soil compaction. Moreover, compaction increases particle contact and restricts the formation of stable granular structure, which is evidenced by a distinct reduction in the total porosity. This result is in accordance with well-known principles of soil physics which postulate a strong inverse relationship between bulk density and total porosity (22).

Total porosity was significantly increased with biochar application. The overall mean went up from 0.426 at 0% biochar addition to 0.442 at 0.5% application level and reached 0.458 at the highest biochar addition rate (1%). This is due to the low density, high porosity and large surface area of the biochar. Biochar increases the space between soil particles and hence improves the structure of the soil. It also contributes to the formation of stable soil aggregates through interactions with organic matter and clay minerals. Biochar increases the distribution of macro- and mesopores and, therefore, the total porosity and the movement of air and water in the soil, reducing the negative effects of compaction (23).

The results also showed a significant effect of irrigation water quality on total porosity. Irrigation with fresh water recorded the highest mean value (0.447), followed by well water with a mean of 0.442, whereas drainage water recorded the lowest mean value (0.436). This can be attributed to the fact that increasing irrigation water salinity enhances the accumulation of dissolved salts within soil pores, increases osmotic stress, and may cause precipitation of certain salts within fine pores. These processes limit the development of soil structure and reduce the volume of effective pores. Furthermore, irrigation water with high sodium content can lead to clay dispersion and breakdown of soil aggregates, which may block macropores and reduce total porosity with continuous irrigation (20).

The results of the three-way interaction showed that the highest total porosity value (0.561) was observed in the treatment of fresh water irrigation with 1% biochar application at bulk density of 1.2 Mg m^{-3}. In contrast, the lowest value (0.317) was observed under drainage water irrigation without biochar addition at a bulk density of 1.7 Mg m^{-3}.

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Table 3. Effect of compaction stresses, biochar levels, irrigation water quality, and their interactions on total porosity values.

Irrigation water quality	Biochar %	Bulk density (Mg m⁻³)						Biochar × water quality
		1.2	1.3	1.4	1.5	1.6	1.7	
River water	0	0.532^{a}	0.491^{fg}	0.451^{kl}	0.411^{pφ}	0.372^{uv}	0.334^{z}	0.432^{c}
	0.5	0.545^{a}	0.505^{ef}	0.467^{ij}	0.428^{mn}	0.390st	0.349^{xy}	0.447^{b}
	1	0.561^{a}	0.522^{cd}	0.482^{gh}	0.444^{lm}	0.405^{φr}	0.366^{vw}	0.463^{a}
Well water	0	0.529^{ab}	0.488^{fg}	0.447^{kl}	0.404^{φr}	0.364^{wx}	0.323^{A}	0.426^{d}
	0.5	0.542^{a}	0.501^{ef}	0.462^{jk}	0.422^{op}	0.384^{tu}	0.344^{xy}	0.443^{bc}
	1	0.558^{a}	0.519^{cd}	0.477^{hi}	0.439^{mn}	0.399^{rs}	0.360^{vw}	0.459^{a}
Drainage water	0	0.523^{bc}	0.482^{gh}	0.441^{lm}	0.399^{rs}	0.358^{xy}	0.317^{A}	0.420^{e}
	0.5	0.537^{ab}	0.496^{fg}	0.456^{kl}	0.416^{pφ}	0.376^{uv}	0.336^{yz}	0.436^{cd}
	1	0.551^{ab}	0.512^{de}	0.472^{ij}	0.433^{no}	0.394st	0.354^{wx}	0.453^{ab}
Bulk density average		0.542^{a}	0.502^{b}	0.462^{c}	0.422^{d}	0.382^{e}	0.343^{f}	
								Biochar
Biochar × Bulk density	0	0.528^{b}	0.487^{f}	0.446^{i}	0.405^{l}	0.365^{n}	0.325^{p}	0.426^{c}
	0.5	0.541^{ab}	0.501^{e}	0.462^{h}	0.422^{k}	0.383^{m}	0.343^{o}	0.442^{b}
	1	0.557^{a}	0.518^{d}	0.477^{g}	0.439^{j}	0.399^{l}	0.360^{n}	0.458^{a}
								water quality
Bulk density × water quality	Fresh water	0.546^{a}	0.506^{c}	0.467^{d}	0.428^{g}	0.389^{j}	0.350^{l}	0.447^{a}
	Well water	0.543^{ab}	0.503^{c}	0.462^{e}	0.422^{h}	0.382^{k}	0.342^{lm}	0.442^{b}
	Drainage water	0.537^{b}	0.497^{d}	0.456^{f}	0.416^{i}	0.376^{k}	0.336^{m}	0.436^{c}

Shear stress (kg cm⁻²)

Table (4) shows that bulk density, irrigation water quality, biochar level and their binary interactions had a significant effect on soil shear stress. The results showed a definite trend of increasing shear stress with increasing bulk density from 1.2 to 1.7 Mg m⁻³, with the mean increasing from 0.77 to 2.28 kg cm⁻² overall. This increase is due to the higher bulk density which decreases the volume of large pores and increases the number of contact points among soil particles, thereby increasing the frictional forces and the internal cohesion that the larger stress must overcome to successfully overcome soil resistance to shear. This finding is in accordance with the mechanical principles of soil behavior that confirm the positive correlation of shear strength with the degree of compaction and bulk density since compaction increases soil resistance against deformation and failure. These results are in agreement with the results reported by (22) who indicated that increasing bulk density increases soil shear

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resistance due to increased particles contact and reduced porosity.

The results also showed a significant effect of the quality of irrigation water on the shear stress of soil. The highest mean value was obtained under drainage water irrigation (1.56 kg cm-2) followed by well water irrigation (1.48 kg cm-2). The lowest mean value was recorded under fresh water irrigation (1.42 kg cm-2). This response is due to higher concentrations of salts and divalent cations (especially calcium and magnesium) in well and drainage waters which cause flocculation of soil particles and decrease the thickness of the diffuse double layer around soil colloids. Thus the interparticle cohesive forces increase and the shear strength of soil increases. However, low salinity fresh water will have weaker effect and relatively low shear resistance of soil.

The results also showed that biochar application significantly increased soil shear stress, the mean value increased from 1.39 kg cm^{-2} without application of biochar to 1.58 kg cm^{-2} with addition of 1% biochar. The increase may be attributed to the ability of biochar to improve the binding between soil particles and the stability of the soil structure . Moreover, biochar favors the formation of stable aggregates due to the high surface area and many functional groups allowing the attachment of mineral particles with organic components, increasing the cohesion and shear strength of the soil. These results agree with (23) who reported that biochar application improves soil structural stability and resistance to mechanical stresses due to improved aggregate bonding and decreased soil susceptibility to deformation.

The results of the triple interaction of irrigation water quality, biochar level, and bulk density, showed a significant effect on soil shear stress, and the soil responses were different depending on the combined effects of these factors. The maximum value of shear stress (2.52 kg cm^{-2}) was recorded with irrigation with drainage water with addition of 1% biochar at bulk density 1.7 Mg m^{-3} and minimum value (0.67 kg cm^{-2}) was recorded with irrigation with fresh water without biochar application at bulk density 1.2 Mg m^{-3}.

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Table 4. Effect of compaction stresses, biochar levels, irrigation water quality, and their interactions on soil shear stress values (kg cm^{-2}).

Irrigation water quality	Biochar %	Bulk density (Mg m^{-3})						Biochar × water quality
		1.2	1.3	1.4	1.5	1.6	1.7	
River water	0	0.67^{s}	0.89^{r}	1.13^{p}	1.46^{m}	1.74^{j}	2.08^{f}	1.33^{f}
	0.5	0.72^{rs}	0.97^{q}	1.20^{o}	1.55^{l}	1.87^{h}	2.18^{d}	1.42^{e}
	1	0.78^{r}	1.03^{p}	1.31^{n}	1.66^{j}	1.96^{g}	2.31^{c}	1.51^{d}
Well water	0	0.70^{rs}	0.94^{q}	1.19^{o}	1.52^{l}	1.83^{i}	2.15^{e}	1.39^{e}
	0.5	0.76^{r}	1.01^{p}	1.28^{n}	1.62^{k}	1.93^{g}	2.29^{c}	1.48^{d}
	1	0.82^{q}	1.08^{o}	1.37^{m}	1.73^{i}	2.03^{f}	2.39^{b}	1.57^{b}
Drainage water	0	0.75^{r}	0.99^{p}	1.25^{n}	1.60^{k}	1.91^{gh}	2.25^{cd}	1.46^{d}
	0.5	0.81^{q}	1.07^{o}	1.35^{m}	1.71^{i}	2.01^{f}	2.37^{b}	1.55^{c}
	1	0.88^{p}	1.16^{n}	1.46^{l}	1.83^{h}	2.15^{e}	2.52^{a}	1.67^{a}
Bulk density average		0.77^{f}	1.02^{e}	1.28^{d}	1.63^{c}	1.94^{b}	2.28^{a}	
								Biochar
Biochar × Bulk density	0	0.71^{r}	0.94^{o}	1.19^{l}	1.53^{i}	1.83^{f}	2.16^{c}	1.39^{c}
	0.5	0.76^{q}	1.02^{n}	1.28^{k}	1.63^{h}	1.94^{e}	2.28^{b}	1.49^{b}
	1	0.83^{p}	1.09^{m}	1.38^{j}	1.74^{g}	2.05^{d}	2.41^{a}	1.58^{a}
								water quality
Bulk density × water quality	Fresh water	0.72^{r}	0.96^{o}	1.21^{l}	1.56^{i}	1.86^{f}	2.19^{c}	1.42^{c}
	Well water	0.76^{q}	1.01^{n}	1.28^{k}	1.62^{h}	1.93^{e}	2.28^{b}	1.48^{b}
	Drainage water	0.81^{p}	1.07^{m}	1.35^{j}	1.71^{g}	2.02^{d}	2.38^{a}	1.56^{a}

Soil Penetration Resistance (kPa cm^{-2})

Table (5) showed that soil penetration resistance was significantly affected by bulk density, rate of biochar application and quality of irrigation water. Bulk density was the most influential variable in determining penetration resistance, with the overall mean increasing from 14.70 kPa cm^{-2} at a bulk density of 1.2 Mg m^{-3} to 52.55 kPa cm^{-2} at 1.7 Mg m^{-3}, an increase of approximately 257%. This increase is caused by a tighter packing of soil particles and a decrease in the pore volume, especially the macropores, which leads to an increase in particle cohesion and frictional resistance and thus an increase in the force required for soil penetration (24). Application of biochar significantly decreased the soil penetration resistance. The control treatment (0% biochar) showed the highest mean value of 34.30 kPa cm^{-2} which was decreased to 32.79 kPa cm^{-2} when 0.5% biochar was applied and further decreased to 31.28 kPa cm^{-2} at the highest application rate (1% biochar). These results demonstrate the

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positive effect of biochar in improving the physical condition of the soil. The decrease in penetration resistance can be explained by the high porosity and low bulk density of biochar, which improve the soil structural stability, reduce the bulk density, improve pore-size distribution, and therefore reduce particle cohesion and soil mechanical resistance. These findings agree with those described by (25).

Table 5. Effect of compaction stress, biochar level, irrigation water quality, and their interactions on soil penetration resistance (kPa cm^{-2}).

Irrigation water quality	**Biochar %**	**Bulk density (Mg m^{-3})**						**Biochar × water quality**
		1.2	1.3	1.4	1.5	1.6	1.7	
River water	0	15.10^{j}	21.77^{i}	28.93^{h}	36.60^{g}	44.76^{ef}	53.42^{ab}	33.43^{bc}
	0.5	14.00^{jk}	20.50^{i}	27.50^{h}	35.00^{gh}	43.00^{f}	51.50^{bc}	31.92^{cd}
	1	12.90^{k}	19.23^{i}	26.07^{hi}	33.40^{h}	41.24^{fg}	49.58^{cd}	30.40^{de}
Well water	0	15.80^{j}	22.54^{i}	29.77^{gh}	37.50^{fg}	45.74^{de}	54.48^{a}	34.30^{ab}
	0.5	14.70^{j}	21.27^{i}	28.34^{h}	35.91^{g}	43.98^{ef}	52.55^{ab}	32.79^{c}
	1	13.60^{jk}	20.01^{i}	26.91^{h}	34.32^{gh}	42.22^{f}	50.63^{bc}	31.28^{cd}
Drainage water	0	16.50^{j}	23.30^{i}	30.61^{g}	38.41^{f}	46.72^{d}	55.52^{a}	35.18^{a}
	0.5	15.40^{j}	22.04^{i}	29.18^{gh}	36.82^{fg}	44.96^{de}	53.60^{ab}	33.67^{b}
	1	14.30^{j}	20.78^{i}	27.75^{h}	35.23^{g}	43.20^{ef}	51.68^{bc}	32.16^{c}
Bulk density average		14.70^{f}	21.27^{e}	28.34^{d}	35.91^{c}	43.98^{b}	52.55^{a}	
								Biochar
Biochar × Bulk density	0	15.80^{p}	22.54^{mn}	29.77^{jk}	37.50^{fg}	45.74^{cd}	54.47^{a}	34.30^{a}
	0.5	14.70^{9}	21.27^{n}	28.34^{k}	35.91^{gh}	43.98^{de}	52.55^{b}	32.79^{b}
	1	13.60^{r}	20.01^{o}	26.91^{l}	34.32^{hi}	42.22^{ef}	50.63^{c}	31.28^{c}
								water quality
Bulk density × water quality	Fresh water	14.00^{l}	20.50^{k}	27.50^{j}	35.00^{hi}	43.00^{ef}	51.50^{bc}	31.92^{c}
	Well water	14.70^{l}	21.27^{k}	28.34^{j}	35.91^{gh}	43.98^{de}	52.55^{b}	32.79^{b}
	Drainage water	15.40^{l}	22.04^{k}	29.18^{j}	36.82^{g}	44.96^{cd}	53.60^{a}	33.67^{a}

Irrigation water quality also had a significant effect on penetration resistance. The lowest mean value (31.92 kPa cm^{-2}) was obtained under freshwater irrigation, followed by well water (32.79 kPa cm^{-2}), whereas drainage water produced the highest mean (33.67 kPa cm^{-2}). This response can be explained by the higher salinity of irrigation water, which promotes salt accumulation within soil pores, increases particle cohesion, reduces effective porosity, and consequently

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increases the mechanical resistance of the soil, particularly in compacted gypsiferous soils (26).

The three-way interaction of irrigation water quality, biochar level and bulk density showed that the maximum penetration resistance (55.52 kPa cm^{-2}) was recorded under the treatment of drainage water × 0% biochar × 1.7 Mg m^{-3} bulk density, while the minimum value (12.90 kPa cm^{-2}) was recorded under fresh water × 1% biochar × 1.2 Mg m^{-3} bulk density. The negative effects of salinity and soil compaction are more pronounced in absence of soil amendments. However, biochar is effective in alleviating the effects of salinity and compaction even under high bulk density conditions by improving soil structure, increasing pore space and reducing the cohesive forces between soil particles.

• Saturated Hydraulic Conductivity (cm min^{-1})

Table (6) revealed that saturated hydraulic conductivity (Ksat) was significantly affected by compaction stress, biochar application level, irrigation water quality and their two-ways and three-ways interactions. Saturated hydraulic conductivity decreased gradually with increasing compaction stress up to bulk density of 1.7 Mg m-3. The overall mean values decreased from 0.56, 0.45, 0.34, 0.23, 0.11 and 0.04 cm min-1 at bulk densities of 1.2, 1.3, 1.4, 1.5, 1.6 and 1.7 Mg m-3, respectively. The macropores and the ratio of micropores are decreased and increased, respectively, on compaction due to the reorganization of soil particles during compaction . Consequently, the hydraulic connectivity between pores is broken, the tortuosity of water flow paths is increased and the ability of the soil to transmit water under saturated conditions is greatly reduced. Compaction increases the number of contact points between particles and decreases the overall porosity, especially air-filled porosity, thus reducing the efficiency of water movement under a hydraulic gradient.

The effects are more severe in gypsiferous soils, where compaction increases the partial collapse of soil structure and compression of soil aggregates and the closure of macropores which are the main pathways for water flow. Furthermore, the reduction of interconnected pores reduces the permeability of the soil, increasing resistance to water flow, and thus leading to much lower rates of water transmission than in less compacted soils (27).

Results have also shown that the saturated hydraulic conductivity was significantly improved with the increase of biochar application rate. The overall mean was increased from 0.25cmmin-1 at the 0% biochar level to 0.29cmmin-1 at the 0.5% level and to 0.33cmmin-1 at the 1% application level. The improvement is attributed to the high porosity and large specific surface area of biochar that enhance the soil structural stability and aggregate formation and promote the development of a more continuous network of interconnected macropores that are responsible for water transmission under saturated conditions. Biochar also reduces the bulk density of the soil, increases total and effective porosity and improves particle aggregation, which in turn decreases hydraulic resistance and allows water to move more easily through the soil profile. Biochar also reduces the negative effects of compaction in gypsiferous soils by protecting pore continuity and structural stability and improving the saturated hydraulic conductivity. These results are in agreement with those reported by (25).

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Table 6. Effect of Compaction Stress, Biochar Level, Irrigation Water Quality, and Their Interactions on Saturated Hydraulic Conductivity (cm min^{-1}).

Irrigation water quality	Biochar %	Bulk density (Mg m^{-3})						Biochar × water quality
		1.2	1.3	1.4	1.5	1.6	1.7	
River water	0	0.55^{b}	0.43^{f}	0.32^{j}	0.20^{n}	0.09^{r}	0.02^{u}	0.27^{d}
	0.5	0.58^{a}	0.47^{de}	0.36^{h}	0.25^{m}	0.14^{p}	0.05^{t}	0.31^{b}
	1	0.61^{a}	0.50^{cd}	0.40^{g}	0.30^{jkl}	0.19^{no}	0.11^{q}	0.35^{a}
Well water	0	0.54^{b}	0.41^{fg}	0.30^{jk}	0.18^{o}	0.07^{s}	0.02^{u}	0.25^{e}
	0.5	0.57^{ab}	0.45^{e}	0.34^{i}	0.23^{mn}	0.11^{q}	0.02^{u}	0.29^{c}
	1	0.59^{a}	0.48^{d}	0.38^{h}	0.27^{l}	0.16^{p}	0.07^{s}	0.33^{b}
Drainage water	0	0.52^{c}	0.40^{g}	0.28^{k}	0.16^{p}	0.04^{t}	0.02^{u}	0.24^{e}
	0.5	0.54^{b}	0.43^{f}	0.31^{j}	0.20^{n}	0.09^{r}	0.02^{u}	0.27^{d}
	1	0.57^{ab}	0.47^{de}	0.35^{i}	0.25^{m}	0.14^{p}	0.05^{t}	0.30^{c}
Bulk density average		0.56^{a}	0.45^{b}	0.34^{c}	0.23^{d}	0.11^{e}	0.04^{f}	
								Biochar
Biochar × Bulk density	0	0.54^{b}	0.41^{f}	0.30^{j}	0.18^{n}	0.07^{r}	0.02^{t}	0.25^{c}
	0.5	0.56^{ab}	0.45^{e}	0.34^{i}	0.23^{m}	0.11^{q}	0.03^{t}	0.29^{b}
	1	0.59^{a}	0.48^{d}	0.38^{h}	0.27^{l}	0.16^{p}	0.08^{r}	0.33^{a}
								water quality
Bulk density × water quality	Fresh water	0.58^{a}	0.47^{c}	0.36^{f}	0.25^{h}	0.14^{j}	0.06^{l}	0.31^{a}
	Well water	0.57^{a}	0.45^{d}	0.34^{g}	0.23^{i}	0.11^{k}	0.04^{m}	0.29^{b}
	Drainage water	0.54^{b}	0.43^{e}	0.31^{fg}	0.20$^{i\ j}$	0.09^{k}	0.03^{m}	0.27^{c}

Saturated hydraulic conductivity was also significantly affected by the irrigation water quality. The maximum mean value (0.31cm min-1) was recorded under freshwater irrigation followed by well water (0.29cm min-1) whereas the minimum mean value (0.27cm min-1) was recorded under drainage water irrigation. This reduction is mainly attributed to the degradation of the quality of irrigation water and the increasing salinity, particularly the increased sodium concentrations as reflected by the increased sodium adsorption ratio (SAR). High SAR disperses clay, weakening the binding forces between soil particles and breaking down soil aggregates, resulting in the clogging of macropores and their conversion to smaller pores with lower water-conducting capacity. Also, repeated irrigation results in accumulation of soluble salts in the root zone, which decreases the pore continuity, increases the

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hydraulic resistance, and thus reduces the saturated hydraulic conductivity. The effects are more pronounced in soils of relatively high clay content or when the irrigation water has high SAR values. The degradation of soil pore structure is a gradual process. These findings agree with those reported by (28).

The three-way interaction among compaction stress, biochar application, and irrigation water quality was also statistically significant. The highest saturated hydraulic conductivity (0.61 cm min^{-1}) was obtained under freshwater irrigation combined with 1% biochar at a bulk density of 1.2 Mg m^{-3}. In contrast, the lowest value (0.02 cm min^{-1}) was observed in several treatments at the highest bulk density (1.7 Mg m^{-3}) without biochar application under either well water or drainage water irrigation.

4. Conclusions and Recommendations

Conclusions

1. An increase in compaction stress (bulk density) negatively affected the physical properties of the gypsiferous soil. Soil penetration resistance and shear strength increased while total porosity, saturated hydraulic conductivity and soil water content decreased.
2. Application of biochar, especially at the 1% level, resulted in substantial improvement in the physical properties of the soil, with increase in total porosity, saturated hydraulic conductivity and water retention and reduction in soil penetration resistance.
3. Irrigation water quality had a significant effect on all studied physical properties. Fresh water irrigation gave the best soil physical characteristics and the use of highly saline drainage water caused a marked deterioration of these properties.
4. Results showed significant two-way and three-way interaction effects of compaction stress, biochar level and irrigation water quality. The best soil physical properties were obtained with the lowest bulk density (1.2 Mg m-3) coupled with 1% biochar application and fresh-water irrigation. The worst results, however, were obtained at the highest bulk density (1.7 Mg m^{-3}) and without biochar application and irrigation with saline drainage water.

5. Recommendations

1. It is recommended to apply 1% biochar to improve the physical properties of gypsiferous soils and to mitigate the negative effects of soil compaction.
2. Wherever possible low salinity water should be used for irrigation and continuous use of highly saline drainage water should be avoided especially on gypsiferous soils.
3. Long-term field experiments are recommended to evaluate the effects of biochar with various qualities of irrigation water and determine its effect on crop productivity in gypsiferous soils.

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