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Response of Saline and Sandy Soils to Different Soil Amendments: Compost, Biochar, Zeolite and Agricultural Gypsum

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EGYPT faces a significant food production gap due to land degradation. To bridge this gap, workers in the agricultural sector should maximize the utilization of degraded soils. The reclamation of saline and sandy soils has become a national priority. So, this study was carried out following a completely randomized design (CRD) aiming to evaluate the effectiveness of different soil amendments (compost, biochar, zeolite and agricultural gypsum) in improving the properties of two soil types (saline and sandy). Specifically, the study focused on the impact of the soil amendments on the physical and chemical properties, water retention, leachate characteristics and nutrient dynamics. To achieve this, 60 soil columns were used, as each column was filled with 1000 g of air-dried and sieved soil (≤2 mm), representing one of the two studied soil types (30 for saline and 30 for sandy). Each amendment was mixed with the abovementioned soil additives at a rate of 10% by weight, then each column was irrigated with tap water to achieve saturation. Soil and leachate samples were collected at two key time points (after 20 and 40 days from the beginning of the experiment). All amendments had significant effects on most of the studied characteristics of both soils, and this was also reflected in the leachate characteristics. For example, all the amendments were successful in reducing EC over time except biochar and zeolite amendments. The amendment that had the most pronounced effect was agricultural gypsum, bringing EC down to 7.25 dSm^{-1} after 40 days in saline soil. Compost and biochar significantly improved organic matter content compared to other treatments, as zeolite and gypsum had no significant impacts. Biochar and zeolite also improved water retention, achieving final values of 15.3% and 14.8%, respectively in sandy soil. Generally, integrating these amendments into soil management practices can boost agricultural productivity in Egypt's degraded soils.

Keywords: Compost, Biochar, Zeolite and Agricultural gypsum.

Introduction

Raising global demand for food, in conjunction with rapid population growth, has increased the challenges of food security, especially in countries with limited arable lands **(Gomiero, 2016).** Egypt is among the countries, which faces a pronounced food production gap, and this problem is exacerbated mainly due to soil degradation, including high salinity and desertification **(Mohamed *et al.* 2019).** To bridge this gap, maximizing the utilization of these degraded soils (*e.g.*, saline, sandy) has become a national priority. However, these soils suffer from many problems, such as low fertility, poor structure, and inefficient water retention that severely limit their agricultural productivity **(Kopittke *et al.* 2019).** The application of soil conditioners plays a crucial role in improving the degraded soil properties in terms of increasing its fertility and water retention capacity **(Osman, 2018).**

Organic amendments are such as compost and biochar, each have its own distinct mechanisms, in soil rehabilitation and improving general plant performance. Compost is an organic amendment, which increases organic matter content in soil, improves soil structure, enhances microbial activity and this consequently increases soil fertility. In sandy soils, it leads to increase the water-holding capacity as well as reducing rapid drainage and nutrient leaching. While, under saline soil circumstances, it helps in mitigating the harmful impact of salinity *via* reducing Na^+ accumulation (**Dai *et al.* 2024; Gioacchini *et al.* 2024**). Biochar amendment (a substance derived from biomass pyrolysis rich in carbon) is widely utilized for improving the degraded soil properties due to its porous structure, which improves the soil aeration as well as enhances the water retention and microbial colonization. Additionally, it has a high surface area and strong adsorption capacity; thus, its characteristics help retain essential nutrients and prevent their leaching, especially under sandy soil conditions **(Lu *et al*. 2024; Qi *et al.* 2024; Sharma, 2024).**

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Inorganic amendments are such as zeolite and agricultural gypsum, as each of them has distinct mechanisms, which contribute to the soil rehabilitation and general plant performance. Zeolite, a crystalline aluminosilicate mineral, has a high CEC, making it an effective in nutrient retention and water management. Additionally, it leads to reduce nutrient loss through leaching. Under sandy soil conditions, it improves moisture retention. While under saline soil conditions, it leads to reduce Na^+ toxicity *via* facilitating sodium exchange with Ca^{++} and K^+ (**Manjaiah *et al*. 2019; Nakachew *et al.* 2025; Oguz & Arslan, 2025**). Agricultural gypsum ($CaSO_4 \cdot 2H_2O$) improves the degraded soil structure such as saline soil *via* displacing Na^+ with Ca^{++}, reducing dispersion of the soil as well as increasing its permeability. Moreover, it supplies essential calcium and sulfur, which are vital nutrients for higher plant growth. (**Amer *et al.* 2023; Singh *et al.* 2023; Rashmi *et al*. 2024).**

Most previous studies have examined the effect of one or more substances under direct field conditions on the properties of only one type of degraded soil. Consequently, there is a lack of studies that compare the effect of more than one substance on more than one type of degraded soil under the same condition. Therefore, it is essential to conduct research experiments that evaluate the effectiveness of soil conditioners on different degraded soils under the same conditions to ensure the accuracy and consistency of application recommendations.

This study aims to evaluate the effectiveness of compost, biochar, zeolite, and agricultural gypsum in improving the physicochemical properties and water management of saline and sandy soils in Egypt.

2. Materials and Methods

The primary objective of this research work was to evaluate the response of various degraded soil types spread throughout Egypt to certain organic and mineral materials under same climatic and atmospheric conditions. Given that degraded soils in Egypt are naturally distributed across geographically dispersed locations, it is practically impossible to collect and study all types simultaneously under the same conditions except in a laboratory experiment. Therefore, a columns experiment was implemented, as it provides a uniform distribution of treatments and controls the amount of added materials and irrigation rates, reducing interference or loss of accuracy. The first phase of the experiment began by studying two types of degraded soils in Egypt (saline and sandy). The work will be completed in the near future to include other types of degraded soils, such as calcareous and heavy clay soils, to provide a more comprehensive and in-depth picture.

A columns experiment was implemented in the laboratory of postgraduate research at the Faculty of Agriculture, Mansoura Univ., Egypt, from February of 2024 to March of 2025 to assess how soil amendments could mitigate salt stress and improve soil structure of saline soils. Also, sandy soil was selected because of its insufficient water retention and low fertility, which makes it particularly susceptible to nutrient leaching. The saline soil was obtained from El Serw City located at the Northern Nile Delta (El-Zarqa District, Damietta Governorate, Egypt. The sandy soil was collected from Qalapshoo Village located at Belqas District, Dakahlia Governorate, Egypt. The physical and chemical properties of both studied soils are shown in Table1, as the soil analysis was done following the standard methods described by **Black (1965), Hesse (1971), Gee and Baudet (1986) and Tandon (2005).** SAR (sodium adsorption ratio) was calculated according to the equation of **Richards (1954),** while ESP (Exchangeable sodium percentage) was calculated depending on the equation of **Rashidi and Seisepour, (2008).**

$$\text{S.A.R.} = \frac{Na^+}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}}$$

ESP= 1.95+1.03 SAR.

The characteristics of the studied soil conditioners are presented in Table 2. All studied substances were analyzed according to **Tandon (2005).** Compost was produced from well decomposed maize residues, left in air to dry, then sieved to pass through a 2 mm mesh before being applied in the experimental farm of Mansoura University. Additionally, the biochar amendment was produced from maize residues through slow pyrolysis at 500°C in a muffle, in absence of oxygen, then sieved to ensure uniformity. Meanwile, zeolite (Clinoptilolite-type) was purchased from the commercial Egyptian market, then crushed and sieved to the desired particle size. Agricultural gypsum was also obtained from the Egyptian market in finely ground from, and used in its natural form. The research work was implemented following a completely randomized design (CRD) with six replicates for each treatment to evaluate the impact of different natural soil conditioners (compost, biochar, zeolite and agricultural gypsum in addition to untreated soil as control on various degraded soil types (saline and sandy).

Table 1. Physical and chemical properties of the soil studied.

Properties		Physical properties	
		Saline soil	**Sandy soil**
Particles size distribution, %	**Sand**	20.00	90.50
	Silt	30.00	4.70
	Clay	50.00	4.80
Texture class		Clay	Sand
Bulk density, g cm^{-3}		1.240	1.700
Total porosity%		52.30	39.30
Water holding capacity, %		43.05	11.22
Properties		**Chemical properties**	
		Saline soil	**Sandy soil**
EC_w, dS m^{-1}		8.10	1.20
pH (1:2.5 soil suspension)		7.90	7.90
$CaCO_3$, %		1.90	1.00
OM (organic matter),%		1.80	0.40
CEC cmol kg^{-1}		54.00	8.00
Available macro-nutrients (mg Kg soil^{-1})	**Nitrogen**	50.00	20.0
	Phosphorus	12.00	5.00
	Potassium	180.0	80.0
ESP		10.76	5.28
SAR		8.55	3.23

Table 2. Characteristics of the studied soil conditioners.

Property (Unit)	Compost	Biochar	Zeolite	Agricultural Gypsum
pH (1:10)	7.10	8.92	7.82	7.3
EC (dSm^{-1}, 1:10)	3.24	4.92	5.01	2.52
CEC (cmolc kg^{-1})	65.0	75.9	160.0	5.05
K_2O (%)	1.20	-	5.00	-
CaO (%)	4.50	-	9.00	32.00
P_2O_5 (%)	0.90	-	1.30	-
SiO_2 (%)	-	-	64.00	-
Na_2O (%)	-	-	1.00	-
Organic Matter (%)	37.8	-	-	-
Nitrogen (N, %)	1.88	0.53	-	-
Carbon (C, %)	22.0	79.02	-	-
Calcium Sulfate ($CaSO_4 \cdot 2H_2O$, %)	-	-	-	92.05

The experiment utilized 60 soil columns, each made from polyvinyl chloride (PVC) and measuring 11 cm in diameter and 31 cm in height (Fig. 1). These columns were designed to replicate controlled soil conditions and were placed in a climate-regulated growth chamber with a constant temperature of 25 °C (± 2) and relative humidity of 60–65% throughout the period of experiment to maintain consistent experimental conditions. To ensure proper drainage without soil loss, a nylon mesh was firmly positioned at the base of each column. On top of this mesh, a 2.5 cm layer of acid-washed sand (treated with 1M HCl) was laid down, acting as a filtration layer that retained soil particles while allowing leachate collection. Each column was filled with 1000 g of air-dried and sieved soil (≤2 mm), representing either saline (30 columns) or sandy soil (30 columns).

Each conditioner (compost, biochar, zeolite, and agricultural gypsum) was mixed thoroughly at a rate of 10% by weight before the soil was packed into the columns, with a control treatment (no amendment) serving as a reference for comparison. Each amendment was mixed with the soil outside the column to avoid the soil structural disturbance, which could result from compaction or pressure within the column. After mixing, the soil and amendment mixture were gently transferred to the columns without mechanical compaction. Natural settlement by gravity and irrigation with tap water to reach the saturation and achieve the proper position within the column. On the other hand, the columns were set up on a rack fitted with funnels to channel drainage into bottles placed beneath each column to gather leachate.

This configuration facilitated the systematic observation of water movement and nutrient leaching, allowing for an accurate assessment of how effective soil amendments were in improving degraded soil conditions. Irrigation was kept at saturation throughout the 40-day experimental duration to mimic realistic soil moisture conditions. To track the characteristics of both soil and leachate over time, samples were taken at two significant intervals for analysis (after 20 and 40 days). The measurements in soil and leachate samples are presented in Fig 2. All collected data were statistically analyzed using Duncan's Multiple Range Test according to **Gomez and Gomez, (1984).**

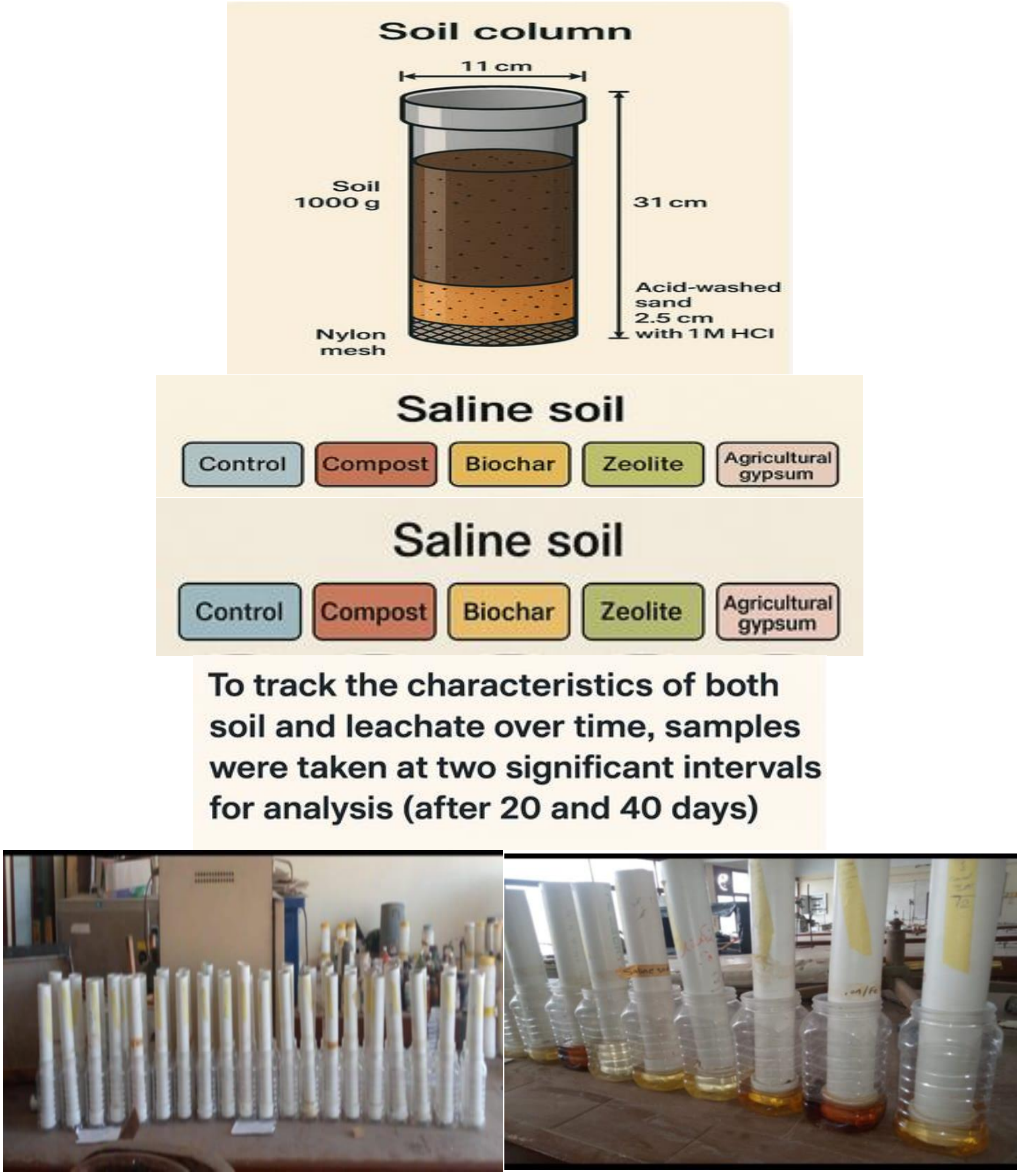

Fig. 1. Soil column used and the experimental flowchart.

Parameter	Purpose of Analysis	Reference
Bulk Density	To assess improvements in soil structure	Tandon, (2005)
Total Porosity	To evaluate enhancement in aeration and water retention	Tandon, (2005)
Water Holding Capacity	To measure soil moisture retention capacity	Tandon, (2005)
Electrical Conductivity (EC)	To monitor soil salinity levels	Tandon, (2005)
	To evaluate soil acidity or alkainity	Tandon, (2005)
pH	To evaluate soil fertility and organic enrichment	Tandon, (2005)
Leachate Volume (Na^+) content	To determine nutrient loss through leaching	Jackson, (1973)

Fig. 2. The measurements in soil and leachate samples.

3. Results

3.1. Physical and hydro physical properties

There was a significant effect of the studied treatments on soil bulk density (g cm^{-3}), total porosity (%) and water holding capacity (WHC,%) across two studied soil types (saline and sandy), as shown in Tables 3 and 4. Regarding the saline soil, compost application significantly reduced bulk density from 1.24 to 1.152 g cm^{-3} after 40 days and improved porosity, reaching 55.9% after 40 days. Biochar and zeolite amendments also lowered bulk density but were slightly less effective than compost; moreover, they contributed to increased porosity, though to a lesser extent than compost. Agricultural gypsum had the least effect on reducing bulk density as well as a minor effect on porosity enhancement. Regarding water holding capacity (WHC), the compost showed the most significant increase, achieving 47.4% after 40 days from the start of the experiment, with zeolite following closely at 47.0% and biochar at 46.6%. Agricultural gypsum resulted in a moderate increase but had the smallest effect among the amendments. Generally, it can be noticed that significant among the studied amendments was between weak to average.

Concerning sandy soil, compost led to the most significant reduction, bringing bulk density down to 1.582 g cm^{-3}. Additionally, biochar and zeolite contributed to bulk density reduction but to a lesser extent. The impact of agricultural gypsum amendment was minimal. In contrast, compost produced the most significant effect, boosting porosity to 43.3% after 40 days from the experiment's start, followed by biochar and zeolite. Agricultural gypsum, however, exhibited the least influence. Sandy soil, which typically lacks water retention capacity, showed marked enhancements with amendments (Table 4). Biochar and zeolite also improved water retention, achieving final values of 15.3% and 14.8%, respectively. Although agricultural gypsum had the least effect, it still yielded some improvement in comparison to the control.

3.2. Chemical properties

The changes in electrical conductivity (EC, dSm^{-1}), soil pH value, organic matter (%), available NPK ($mgkg^{-1}$) across both soil types due to various soil amendments were statistically significant (Tables 5,6 and 7). Under saline soil conditions, all the amendments were successful in reducing EC over time except biochar and zeolite amendments. The amendment that had the most pronounced effect was agricultural gypsum, bringing EC down to 7.25 dSm^{-1} after 40 days, while compost followed with a measurement of 7.69 dSm^{-1}. On the contrary, biochar and zeolite didn't contributed to a decrease in EC, it was somewhat less effective. The saline soil's initial pH was measured at 7.9 (see Table 5), with only minor variations observed among the different treatments over time. The use of compost and agricultural gypsum led to a gradual slight decline in soil pH, which reached 7.80, after 40 days. On the other hand, the application of biochar caused a slight rise in pH to 7.96, suggesting that its alkaline characteristics helped to keep the pH stable. Zeolite also showed a non-significant effect on pH values. Generally, it can be noticed that significant among the studied amendments was between weak to average in terms of EC and pH, while it was strong in terms of organic matter and nutrients.

Table 3. Effect of the studied treatments on bulk density (g cm^{-3}) and total porosity (%).

Treatments	Incubation period (days)					
	Initial soil	After 20 days	After 40 days	Initial soil	After 20 days	After 40 days
	Bulk density (g cm^{-3})			Total porosity (%)		
Saline soil						
No addition (Control)	1.24a	1.243a	1.245a	52.3a	52.2e	52.3e
Compost at rate of 10%	1.24a	1.182b	1.152e	52.3a	54.6a	55.9a
Biochar at rate of 10%	1.24a	1.202b	1.172c	52.3a	53.9c	55.0c
Zeolite at rate of 10%	1.24a	1.191b	1.161d	52.3a	54.1b	55.3b
Agricultural gypsum at rate of 10%	1.24a	1.230a	1.220b	52.3a	52.8d	53.3d
F-test	NS	*	**	NS	**	**
Sandy soil						
No addition (Control)	1.70a	1.712a	1.701a	39.3a	39.0e	38.9e
Compost at rate of 10%	1.70a	1.621b	1.582e	39.3a	41.6a	43.3a
Biochar at rate of 10%	1.70a	1.642b	1.602d	39.3a	40.9b	42.4b
Zeolite at rate of 10%	1.70a	1.660a	1.630c	39.3a	40.3c	41.8c
Agricultural gypsum at rate of 10%	1.70a	1.681a	1.661b	39.3a	39.9d	40.6d
F-test	NS	*	**	NS	**	**

F-test of incubation period

		Control	Compost	Biochar	Zeolite	Gypsum
Saline soil	Bulk density (g cm^{-3})	NS	**	**	**	*
	Total porosity (%)	NS	**	**	**	*
Sandy soil	Bulk density (g cm^{-3})	NS	**	**	**	*
	Total porosity (%)	NS	**	**	**	*

Table 4. Effect of the studied treatments on water holding capacity (%).

Treatments	Incubation period (days)		
	Initial soil	After 20 days	After 40 days
	Water holding capacity (%)		
Saline soil			
No addition (Control)	43.05a	42.7e	42.2e
Compost at rate of 10%	43.05a	45.6a	47.4a
Biochar at rate of 10%	43.05a	44.9c	46.6c
Zeolite at rate of 10%	43.05a	45.3b	47.0b
Agricultural gypsum at rate of 10%	43.05a	43.9d	44.6d
F-test	NS	**	**
Sandy soil			
No addition (Control)	11.22a	11.0e	10.6e
Compost at rate of 10%	11.22a	14.9a	16.6a
Biochar at rate of 10%	11.22a	13.6b	15.3b
Zeolite at rate of 10%	11.22a	13.1c	14.8c
Agricultural gypsum at rate of 10%	11.22a	12.1d	13.1d
F-test	NS	**	**

F-test of incubation period

		Control	Compost	Biochar	Zeolite	Gypsum
Saline soil	Water holding capacity (%)	NS	**	**	**	*
Sandy soil	Water holding capacity (%)	NS	**	**	**	*

Table 5. Effect of the studied treatments on EC (dS m^{-1}) and pH .

Treatments	Incubation period (days)					
	Initial soil	After 20 days	After 40 days	Initial soil	After 20 days	After 40 days
	EC,dSm^{-1}			pH		
Saline soil						
No addition (Control)	8.10	8.10a	8.10b	7.9	7.92	7.91
Compost at rate of 10%	8.10	7.70c	7.69c	7.9	7.85	7.80
Biochar at rate of 10%	8.10	8.15a	8.19a	7.9	7.9	7.96
Zeolite at rate of 10%	8.10	8.06b	8.10b	7.9	7.89	7.88
Agricultural gypsum at rate of 10%	8.10	7.55d	7.25d	7.9	7.85	7.80
F-test	NS	*	*	---	----	----
Sandy soil						
No addition (Control)	1.20	1.22a	1.21a	7.9	7.90	7.91
Compost at rate of 10%	1.20	1.05d	0.95d	7.9	7.80	7.78
Biochar at rate of 10%	1.20	1.10c	1.00c	7.9	7.92	7.97
Zeolite at rate of 10%	1.20	1.15b	1.04b	7.9	7.91	7.92
Agricultural gypsum at rate of 10%	1.20	1.02e	0.93e	7.9	7.86	7.84
F-test	NS	**	**	-----	----	----

F-test of incubation period

		Control	Compost	Biochar	Zeolite	Gypsum
Saline soil	EC,dSm^{-1}	NS	*	*	*	*
	pH	NS	*	*	*	*
Sandy soil	EC,dSm^{-1}	NS	*	*	*	*
	pH	NS	*	*	*	*

Table 6. Effect of the studied treatments on organic matter (%) and nitrogen (mg kg^{-1}).

Treatments	Incubation period (days)					
	Initial soil	After 20 days	After 40 days	Initial soil	After 20 days	After 40 days
	Organic matter (%)			Nitrogen (mg kg^{-1})		
Saline soil						
No addition (Control)	1.80	1.780b	1.770c	50.00	48.10e	45.60e
Compost at rate of 10%	1.80	2.20a	2.150a	50.00	55.60a	58.30a
Biochar at rate of 10%	1.80	1.95ab	1.900b	50.00	53.90b	56.50b
Zeolite at rate of 10%	1.80	1.79 b	1.75cd	50.00	52.60c	54.90c
Agricultural gypsum at rate of 10%	1.80	1.78b	1.72d	50.00	50.90d	52.40d
F-test	NS	*	**	NS	**	**
Sandy soil						
No addition (Control)	0.40	0.38c	0.37c	20.00	18.60e	16.90e
Compost at rate of 10%	0.40	0.60a	0.55a	20.00	24.60a	27.30a
Biochar at rate of 10%	0.40	0.55b	0.51b	20.00	23.30b	25.70b
Zeolite at rate of 10%	0.40	0.40c	0.38c	20.00	22.10c	24.30c
Agricultural gypsum at rate of 10%	0.40	0.39c	0.37c	20.00	21.60d	22.90d
F-test	NS	*	*	NS	**	**

F-test of incubation period

		Control	Compost	Biochar	Zeolite	Gypsum
Saline soil	Organic matter (%)	*	**	**	**	**
	Nitrogen (mg kg^{-1})	**	**	**	**	**
Sandy soil	Organic matter (%)	*	**	**	**	**
	Nitrogen (mg kg^{-1})	**	**	**	**	**

Table 7. Effect of the studied treatments on phosphorus and potassium (mg kg^{-1}).

Treatments	Incubation period (days)					
	Initial soil	After 20 days	After 40 days	Initial soil	After 20 days	After 40 days
	Phosphorus (mg kg^{-1})			Potassium (mg kg^{-1})		
Saline soil						
No addition (Control)	12.00	11.6d	11.4e	180	180.2e	180.2e
Compost at rate of 10%	12.00	13.6a	14.9a	180	191.2a	201.2a
Biochar at rate of 10%	12.00	13.1b	14.3b	180	186.2b	196.2b
Zeolite at rate of 10%	12.00	12.6c	13.6c	180	183.2c	191.2c
Agricultural gypsum at rate of 10%	12.00	12.4c	12.9d	180	181.7d	186.2d
F-test	NS	**	**	NS	**	**
Sandy soil						
No addition (Control)	5.00	4.9d	4.75d	80	79.77e	79.70e
Compost at rate of 10%	5.00	6.3a	7.2a	80	91.20a	101.2a
Biochar at rate of 10%	5.00	6.1b	6.9ab	80	86.20b	96.20b
Zeolite at rate of 10%	5.00	5.8c	6.6b	80	83.20c	91.20c
Agricultural gypsum at rate of 10%	5.00	5.6cd	6.1c	80	81.70d	86.20d
F-test	NS	**	**	NS	**	**

F-test of incubation period						
		Control	Compost	Biochar	Zeolite	Gypsum
Saline soil	Phosphorus (mg kg^{-1})	*	**	**	**	**
	Potassium (mg kg^{-1})	NS	**	**	**	**
Sandy soil	Phosphorus (mg kg^{-1})	*	**	**	**	**
	Potassium (mg kg^{-1})	NS	**	**	**	**

Table 8 illustrates that compost and biochar significantly improved organic matter content compared to other treatments, as zeolite and gypsum had no significant impacts. The organic matter level in saline soil decreased slightly in the control treatment from 1.80% to 1.77% after 40 days. Nevertheless, the use of compost greatly boosted organic matter, achieving 2.20% and 2.15% at both studied stages, respectively, which underscores its importance in improving soil fertility and microbial activity. Biochar also played a role in increasing organic matter content to 1.95 and 1.90 % at both studied stages, respectively, likely because of its high stability as a long-lasting carbon source. On the other hand, zeolite and gypsum showed minimal impact, as the organic matter levels remained almost the same, indicating that their function is more focused on enhancing soil's physical and chemical characteristics instead of directly contributing organic carbon. According to Tables 6 and 7 compost at a 10% application rate resulted in the greatest availability of nitrogen, phosphorus, and potassium, followed by biochar, then zeolite, and finally agricultural gypsum. This indicates that the use of compost is especially effective for boosting nutrient retention in saline soils.

Regarding sandy soil, compost and agricultural gypsum proved to be the most effective in lowering EC, achieving levels of 0.95 dSm^{-1} and 0.93 dSm^{-1}, respectively, after a period of 40 days. Biochar and zeolite also played a role in reducing pH, although to a lesser degree. The initial pH of sandy soil was measured at 7.9, with slight variations seen among the different treatments. The application of compost resulted in a minor decrease in pH (7.78) after 40 days, whereas biochar exhibited a slight rise (7.97), which corresponds with its alkaline characteristics. Agricultural gypsum caused a moderate reduction (7.84), likely due to its function in increasing calcium availability and displacing sodium ions. The use of zeolite ensured pH stability, consistent with its established ability for ion exchange and buffering. In sandy soil, the compost led to a notable improvement, with the organic matter rising to 0.55% after 40 days from starting the experiment, highlighting its unique role in improving soil carbon levels. Additionally, the biochar amendment played a part in this improvement, reaching a level of 0.51%, whilst the zeolite and agricultural gypsum amendments had minimal influence, with organic matter levels recorded at 0.38% and 0.37%, respectively.

Sandy soil showed a notable decrease in nitrogen availability in the control group, dropping from 20.00 mg kg^{-1} to 16.90 mg kg^{-1} over 40 days. The application of compost resulted in the highest nitrogen retention at 27.30 mg kg^{-1}, followed by biochar at 25.70 mg kg^{-1} and zeolite at 24.30 mg kg^{-1}. In untreated sandy soil, phosphorus availability was the lowest among all examined soil types, falling from 5.00 mg kg^{-1} initially to 4.60 mg kg^{-1} after 40 days. Compost significantly enhanced phosphorus retention, reaching 7.2 mg kg^{-1}, while biochar and zeolite offered moderate increases. The potassium levels showcased a comparable trend, with soil treated with compost showing the greatest retention at 101.2 mg kg^{-1}, while biochar followed at 96.2 mg kg^{-1} and zeolite at 91.2 mg kg^{-1}. These findings highlight the significant importance of organic amendments, particularly compost, in sandy soil for enhancing nutrient retention and minimizing leaching losses.

3.3. Leachate characteristics

A notable decrease in leachate volume (Table 8 and Fig 3) is observed after applying soil amendments in comparison to the control group (no amendments added) for both soil types investigated. This decrease emphasizes the significance of these amendments in improving soil water retention and reducing water loss. Among the treatments evaluated, zeolite and biochar demonstrated the most significant impact, recording the lowest volumes of leachate, which can be linked to their substantial water-holding capacity and capability to keep moisture within the soil structure. Conversely, the application of gypsum led to an increase in leachate volume, likely due to its function in forming soil aggregates which enhance soil permeability and promoting water movement throughout the soil profile carrying out excess salts.

Table 8. Effect of the studied treatments on leachate volume collected and leachate sodium (Na^+, meq L^{-1}) over the incubation period.

Treatments	Incubation period (days)			
	After 20 days	After 40 days	After 20 days	After 40 days
	Leachate volume (mL)		Na^+ (meq L^{-1})	
Saline soil				
No addition (Control)	251.2b	201.2b	39.55c	39.95c
Compost at rate of 10%	221.2c	181.2c	40..85b	41..30b
Biochar at rate of 10%	201.2d	161.2d	37.25e	36.50e
Zeolite at rate of 10%	191.2e	151.2e	38.15d	37.60d
Agricultural gypsum at rate of 10%	261.2a	211.2a	41.65a	42.00a
F-test	**	**	**	**
Sandy soil				
No addition (Control)	401.2b	351.2b	18.55c	19.05c
Compost at rate of 10%	361.2c	311.2c	19.95b	20.10b
Biochar at rate of 10%	331.2d	281.2d	16.35e	17.45e
Zeolite at rate of 10%	311.2e	261.2e	17.15d	18.40d
Agricultural gypsum at rate of 10%	421.2a	371.2a	20.95a	21.55a
F-test	**	**	**	**

F-test of incubation period						
		Control	Compost	Biochar	Zeolite	Gypsum
Saline soil	Leachate volume (mL)	**	**	**	**	**
	Na^+ (meq L^{-1})	**	**	**	**	**
Sandy soil	Leachate volume (mL)	**	**	**	**	**
	Na^+ (meq L^{-1})	**	**	**	**	**

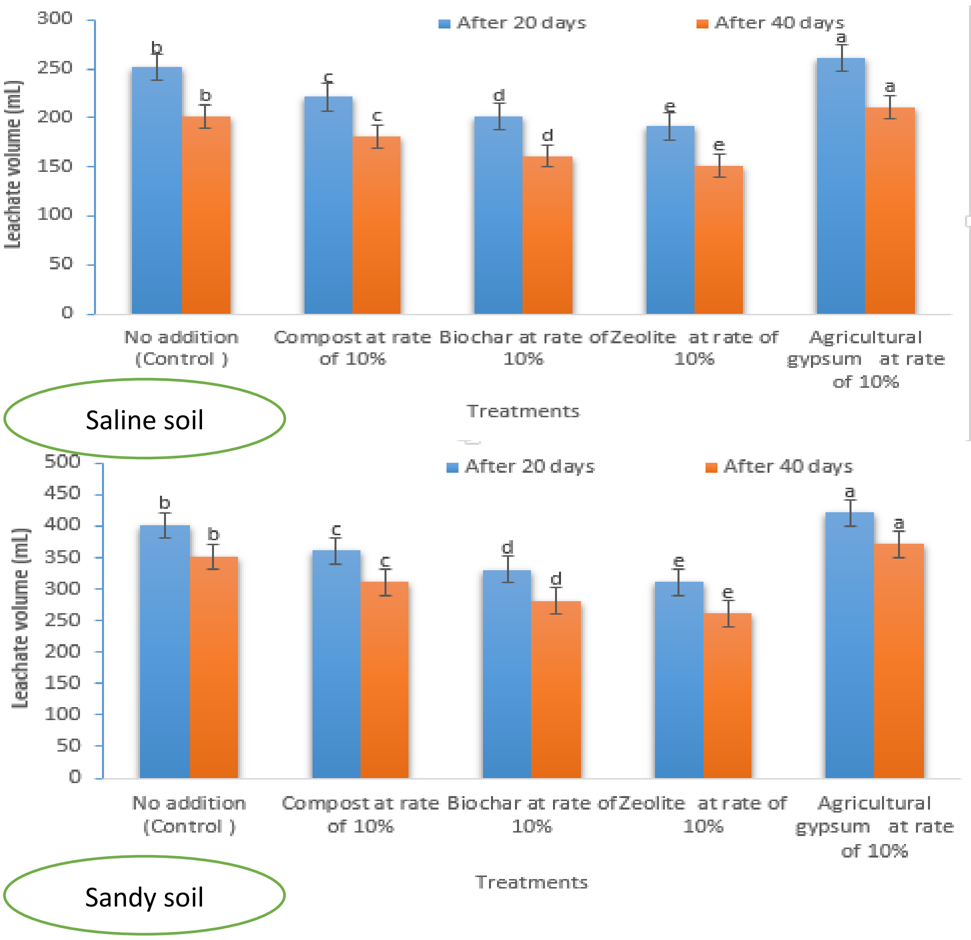

Fig. 3. Effect of the studied treatments on leachate volume collected over the incubation period.

As shown in Table 8, sodium concentration in the leachate decreased with biochar and zeolite amendments compared to the control, indicating the effectiveness of these soil amendments in holding the sodium. On the contrary, sodium concentration in the leachate increased with compost and gypsum amendments compared to the control, indicating the effectiveness of these soil amendments in leaching the sodium. biochar was the most effective treatment in lowering sodium concentrations in the leachate of both soil types, emphasizing its role in sodium stabilization and soil structure improvement. In comparison, using gypsum led to significant increases in sodium levels in the leachate. This phenomenon can be explained by the replacement of sodium ions (Na^{+}) with calcium ions (Ca^{2+}), which temporarily moves sodium into the soil solution prior to leaching.

4. Discussion

In this research, organic materials such as biochar and compost, and inorganic materials such as zeolite and agricultural gypsum were selected to evaluate the response of degraded soils in Egypt for them. This is due to their economic and environmental properties. All of these materials are locally available and relatively low-cost, making them suitable for Egyptian farmers. In addition to being environmentally friendly, they have great potential to improve the properties of degraded soils without causing harmful side effects or accumulating pollutants. The ability of these materials to improve the properties of saline and sandy soils will be explained later. Therefore, these materials may constitute an integrated approach that combines efficiency, economic feasibility, and environmental sustainability.

Physical properties

The obtained results indicated a slight decline in bulk density after applying compost, biochar, and zeolite can primarily be linked to the natural physical characteristics of the studied amendments. Their lightweight and porous structure may have aided in enhancing soil aggregation. Compost added organic matter to both studied soils (saline and sandy), thus improving the aggregation and fostering a better structure for both studied soils. Likewise, biochar, which has low density and high porosity, may have enhanced the aeration of both studied soils, as well as it may have boosted the irrigation water retention. On the other hand, the zeolite amendment, which characterized by its crystalline and porous nature, may have assisted in reducing the compacted soils and raising the pore space under both studied soils. On the other conjunction, the agricultural gypsum possessed a little effect on the bulk density of both studied soils, likely attributed to the non-sodic nature of the soil used in this investigation, as its primary benefits are more evident in the sodic soils. It is well known that the unique role of agricultural gypsum lies in its ability to replace calcium ions with sodium ions in the soil colloids. Furthermore, the agricultural gypsum used doesnot add low-density or highly porous substances such as biochar or compost, and therefore does not directly reduce the soil density. Perhaps a period of 40 days is not sufficient for the agricultural gypsum to have a significant impact on apparent density.

The obtained results are in harmony with several previous investigations which documented the unique impact of both compost and biochar amendments on reducing the soil bulk density as well as improving the root penetration **(Lin *et al.* 2015; Obia *et al.* 2018).** Likewise, zeolite amendment has been reported to enhance the degraded soil physical conditions by enhancing its porosity as mentioned by **(Noori *et al.* 2006); Seddik *et al.* (2019).** Whilst agricultural gypsum is more effective in reclaiming the saline-sodic soils *via* improving the soil aggregation, it doesn't pronouncedly alter bulk density in the other soil types **(Chen *et al.* 2004; Wahdan *et al.* 2009).** The improvement in the soil porosity of saline and sandy soils recorded across treatments was closely associated with better soil structure and aggregation, as the compost may have encouraged the microbial activity due to the increase of organic matter, thereby enhancing pore formation and aeration in both studied soils **(Zhang, 2014; Aranyos *et al*. 2016).** Biochar amendment may have contributed to promoting water and air movement, and this is attributed to its structured porosity. On the other hand, zeolite amendment, with its ability to retain air and water, may have improved porosity via expanding air-filled pores as well as by reducing compaction. On the other hand, agricultural gypsum possessed a limited influence on porosity under the two soil types. These findings are consistent with the studies highlighting the unique role of both compost and biochar amendments in improving porosity and structure of soils such as **Aranyos *et al.* (2016)** who studied the effect of compost on sandy soil properties and **Sun *et al.* (2018)** who studied the effect of biochar on salt affected soil properties**.** Additionally, **Mola-Abasi & Shooshpasha (2016)** who confirmed that zeolite amendments has an unique impact on both porosity and water retention, especially in sandy soil.

Regarding water-holding capacity, each amendment contributed uniquely based on its physicochemical characteristics. Compost, which is rich in humic materials and organic compounds, may have increased the soil aggregation as well as micro porosity under both studied soils, thereby retaining more moisture in these soils (**Abouhussien *et al.* 2019**). Biochar's sponge-like nature may have assisted in holding substantial amounts of irrigation water, especially under sandy soil circumstances (**Baiamonte *et al.* 2019**). While the zeolite's high surface area may have supported irrigation water retention via absorbing and slowly releasing moisture **(Ravali *et al.* 2020).** Despite the agricultural gypsum improved the structure and infiltration, especially in saline soil, its impact on the WHC was relatively limited (**Ahmed, 2011).**

Chemical properties

The reduction in the values of EC observed in the treated soils reflects the ability of the studied amendments to lessen the salinity stress. Both compost and biochar amendments showed significant efficacy under sandy soil conditions, while zeolite and agricultural gypsum amendments were more effective under saline circumstances. This variation underscores the importance of choosing amendments according to the soil type. The reduction in the values of EC was due to the improved infiltration and salt leaching and enhanced soil structure. These findings are in accordance with **Khadem *et al.* (2021) and Saleh *et al.* (2023).** Variations in soil pH values across treatments reflect a potential complex interaction among the studied amendment traits and soil characteristics. Compost leads to lower pH via the release of organic acids over the decomposition process. Biochar amendment generally increases soil pH and this is attributed to its alkaline nature. On the other hand, the zeolite amendment may have contributed to pH stabilization *via* buffering excessive fluctuations. It has a high ion exchange capacity and a large surface area, which allows it to adsorb or release (H^+) or (OH^-) ions when needed, thus maintaining the pH within a relatively constant range **(Ravali *et al.* 2020)**. In other words, zeolite prevents sharp changes resulting from dissolution processes or chemical reactions in the soil. Moreover, the agricultural gypsum slightly reduced the values of pH *via* Ca^+ -driven Na^+ displacement, particularly under saline soil conditions (**Obia *et al.* 2018; Aiad, 2019 and Mohamed *et al.* 2020).**

Concerning the soil organic matter (OM), the positive response of both compost and biochar amendments was noteworthy. Compost, due to its rapid decomposability, enhanced the microbial activity under both studied soils as well as added labile carbon, leading to an immediate rise in soil OM values (**Abouhussien *et al.* 2019**). Biochar also may have acted as a source of stable carbon with long-term benefits for saline and sandy soils structure and nutrient retention (**Obia *et al.* 2018**). Zeolite and agricultural gypsum didnt not play a role in increasing the soil's organic matter or organic carbon content, but they may have supported circumstances conducive to its stabilization (**Ahmed, 2011; Ravali *et al.* 2020).** Generally, it can be said that the compost was the superior amendment because it may have boosted microbial activity under saline and sandy soil conditions more over its unique role in nutrient cycling, while biochar amendment may have enhanced the stability of organic carbon (**Othman, 2021 and Lakhdar *et al.* 2009).**

Under sandy soil conditions, which have a low organic matter and nutrient leaching as the main challenges, the vital role of both compost and biochar amendments was crystal clear due to their role in adding organic carbon and organic matter. Compost improved the nutrient retention (NPK) *via* supplying active organic compounds and raising CEC. While Biochar amendment contributed to improving the soil structure and may have reduced NPK loss due to its high surface area. Contrarily, the zeolite and agricultural gypsum amendments had a lesser influence on the accumulation of carbon due to their mineral nature. The results are in harmony with those of **Baiamonte *et al.* (2019).**

Leachate traits

Lastly, leachate composition analysis at 20 and 40 days after addition revealed that agricultural gypsum and compost caused an increase in the sodium content in the leachate, or in other words, they caused sodium leaching. The effect of gypsum on sodium leaching was greater than that of compost. As for compost, it may have helped in improving the soil aggregates and thus worked to increase aeration, thus increasing the downward movement of salts. Regarding agricultural gypsum, using it led to significant increases in sodium levels in the leachate. This phenomenon can be explained by the replacement of sodium ions (Na^+) with calcium ions (Ca^{2+}), which temporarily moves sodium into the soil solution prior to leaching. Generally, it can be said that agricultural gypsum amendment, although temporarily raising leachate sodium content due to Na^+ displacement, eventually improved soil structure and contributed to long-term stabilization. On the other hand, zeolite and biochar amendments significantly reduced the Na^+ concentration s in the leachate over time and this impact may be attributed to their ability in adsorbing considerable amounts of ions on their surfaces. In other words, biochar and zeolite have a large cation exchange capacity as well as negative charges that attract sodium and cause it to adsorb and thus be fixed on the surface of both the biochar and zeolite instead of being free in the soil solution, and thus its harm is reduced despite not being leached. These results support the findings of **Ahmed (2011); Hafez *et al.* (2015); El-Sanat *et al.* (2017); Khadem *et al.* (2021).**

5. Conclusion

According to the obtained results, it can be concluded that all the amendments were successful in reducing EC over time except biochar and zeolite amendments. The amendment that had the most pronounced effect was agricultural gypsum, bringing EC down to 7.25 dSm^{-1} after 40 days in saline soil. Compost and biochar significantly improved organic matter content compared to other treatments, as zeolite and gypsum had no significant impacts. Biochar and zeolite also improved water retention, achieving final values of 15.3% and 14.8%, respectively in sandy soil. Generally, integrating these amendments into soil management practices can boost agricultural productivity in Egypt’s degraded soils. Farmers and policymakers should implement customized amendment strategies suited to specific soil conditions. Future studies should investigate the long-term effects of these applications in the field and the synergistic impacts of organic and mineral amendments across various cropping systems and climate scenarios to promote sustainable agricultural progress.

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Author contribution:

Ahmed A. Taha Contributing to the development of the scientific methodology, provided critical scientific review and performed language editing as well as contributed to writing specific sections.

Mohamed A. El-Sherpiny participated in manuscript revision and contributed to writing specific sections.

Amal A. Helmy conducted the statistical analyses and supported the implementation as well as contributed to writing specific sections.

Dalia A. I. Ahmed executed the column experiments and chemical analysis

All authors contributed equally to the design and implementation of the research and approved the final version of the manuscript.

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