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# Bio-Organic Fertilizer Combined with Different Amendments Improves Nutrient Enhancement and Salt Leaching in Saline Soil: A Soil Column Experiment

**Meng Xiao [1,2], Guangming Liu [2,*], Shengguo Jiang [3], Xuewei Guan [1,2], Jinlin Chen [1,*], Rongjiang Yao [2] and Xiuping Wang [4]**

1. Co-Innovation Center for Sustainable Forestry in Southern China, School of Forestry, Nanjing Forestry University, Nanjing 210037, China
2. State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China
3. Tianjin North China Geological Exploration Bureau, Tianjin 300170, China
4. Institute of Coast Agriculture, Hebei Academy of Agriculture and Forestry Sciences, Caofeidian 063200, China

* Correspondence: gmliu@issas.ac.cn (G.L.); jlchen@njfu.edu.cn (J.C.)

**Abstract:** Salt-affected soils frequently experience leaching and desalination issues, which severely restrict plant growth and water uptake. Hence, in this experiment, four treatments including CG (no amendments addition); OF (organic fertilizer addition); OH (organic fertilizer and Hekang amendment addition); and OB (organic fertilizer and fulvic acid addition) were designed to examine the effect of organic amendment on soil chemical properties, water and salt transport, and soil desalination laws of coastal saline soil. The results showed that the addition of organic amendments significantly reduced soil pH (8.47–8.52) and salt content (2.06–2.34 g kg$^{-1}$), while increasing soil organic matter content, available phosphorus, and available potassium. OH treatment has a higher available phosphorus content than other treatments. OH and OB treatments elevated the soil desalination ratio (32.95% and 32.12%, respectively) by raising the leaching volume and leaching rate. Organic amendments significantly promoted $Na^+$ (4.5–32%) and $SO_4^{2-}$ (12–27%) leaching compared to CG. Organic treatments, particularly OB treatment, not only increased the content of soil organic matter and available nutrients but also promoted salt ion leaching, improved soil permeability and increased soil desalination and water leaching rates. Our results may provide a theoretical basis for revealing the desalination law of coastal saline soil.

**Keywords:** coastal saline soil; organic fertilizer; organic amendment; soil nutrient content; water and salt migration; desalinization rate

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## 1. Introduction

Global agricultural production and food security face enormous threats due to soil salinization, which is a widespread phenomenon of soil degradation [1,2]. It is normally caused by the accumulation of water-soluble salts in the soil resulting from the interaction between prevailing landscape and weather conditions as well as improper irrigation management [3,4]. Excessive soil salinity facilitates the absorption of $Na^+$ and $Cl^-$ in plants and impacts photosynthesis by reducing carbon (C) assimilation and water use efficiency, which results in water loss, atrophy, and necrosis of plants, leading to crop failure and desertification of land [4,5]. Currently, over 900,0000 km$^2$ of the world's total land is salt-affected, and affected land is growing at a rate of 10% per year [6,7]. Consequently, it has become very pertinent to ameliorate and re-utilize salt-affected soils to curb this development.

Salt-affected soils usually exhibit lower availability of soil nutrients due to poor soil structure and low organic matter content [8]. The exogenous amendments application is a common and effective method for salt-affected soils to improve soil nutrient availability and soil fertility [7,9]. Many researchers have reported that soil productivity and fertility can be improved by adding organic materials such as compost, green manures, food processing waste, and farmyard and poultry manures [10]. Bio-organic fertilizer is produced by fermentation with the above materials and a small amount of functional microbial strains [11,12] and has always been considered as a remediation material for improving soil nutrient content and soil fertility, promoting nutrient uptake by vegetation and reducing the toxicity of salt to plants [2,3,7,13]. In addition, considerable studies have suggested that organic fertilizer plays a crucial role in stimulating $Na^+$ leaching and electrical conductivity (EC) reduction [7,14]. However, some researchers have also pointed out that long-term use of organic fertilizers may reduce the effectiveness of bio-organic fertilizers leading to salt accumulation [1]. Meanwhile, some organic materials have been used for soil remediation and vegetation restoration due to their efficiency. HeKang (HK) is an acid conditioner that contains an amount of hydrolyzed maleic anhydride, and it has been shown to reduce soil salt content but also improve soil physical and chemical properties [15,16]. Fulvic acid (HA) is a type of organic aromatic substance soluble in acidic and alkaline water solutions, and it has a significant influence on alleviating salt stress, promoting nutrient absorption, and regulating soil microorganisms [17,18]. Some studies have reported that the combined application of organic acid amendment and organic fertilizer efficiently improves nutrient availability and promotes soil desalination [9]. Liu et al. [18] reported that the combined application of FA and inorganic fertilizer reduced soil EC and pH of coastal saline soil, and increased nitrogen uptake of wheat. However, few studies are available on the synergistic effect of the combined application of bio-organic fertilizer and acid amendment in saline soils, especially in reducing salt and enhancing nutrients.

Water leaching is another measure of soil reclamation; it reduces soil water salinity by discharging salts from the upper horizons to the lower soil layers [3,5]. In general, salt always migrates with the movement of water, and the amount of leaching water to a large extent affects the redistribution of soil salt [19]. Excessive water leaching could lead to the loss of soil nutrients resulting in low nutrient utilization [20]. Improper leaching and irrigation practices could adversely affect some environmental pollution problems, such as unavoidable waste and pollution of water resources [21]. Therefore, it is crucial to determine the amount of leaching water and the migration of salt ions during leaching. For saline-sodic and sodic soils, it is important to increase soil permeability by altering the quantity and structure of soil aggregates to promote the passage of water required to remove salts [22]. Previous studies have reported that adding soil amendments can improve soil physical structure by increasing soil permeability and promoting water leaching and utilization efficiency [7,8]. However, the effects of organic amendments combined with organic fertilizers on water and salt migration and desalination efficiency of saline soils under leaching conditions are still unclear.

Overall, to reveal the synergistic effect of various amendment materials and organic fertilizers on coastal saline soil and the regularity of salt migration under leaching conditions. In this study, a soil column leaching experiment of organic amendments combined with organic fertilizer was designed. The chemical properties after organic amendments addition were measured, the migration and transformation of salt ions in the leaching state were studied, and the desalination rate and water volume requirement of the soil column under different treatments were monitored. The aim of this study was (1) to determine the improvement effect of the organic fertilizer and amendments on chemical properties of coastal saline soil; (2) to clarify the influence of organic amendments on the dynamics of water and salt distribution of coastal saline soils; and (3) to reveal the effect of organic amendments on desalting efficiency and law of soil column under leaching conditions. We hypothesized that the addition of organic fertilizer combined with acid amendments would reduce soil salt content, improve soil nutrient content, and promote the removal of salt ions.

## 2. Materials and Methods

### 2.1. Site Description and Soil Properties

The sampling site is located on a farm in Ninghe District (117°30′4″ N, 39°25′54″ E), Tianjin City, China. The study area belongs to fluvial alluvial and surface alluvial sedimentary soils, which are mostly salinized tidal soils. The study area has the typical characteristics of a semi-arid and semi-humid monsoon climate in a warm continental temperate zone, with four distinct seasons, high temperatures, rainy summers, drought, and little rain in winter. The annual average temperature is 11.4–12.9 °C, the annual average precipitation is 520–660 mm, and the average number of precipitation days per year is 63.8 days. The annual potential evapotranspiration is 1500–2000 mm, and the annual sunshine duration is 2470–2900 h. The annual solar radiation is 4935 MJ $m^{-2}$. Average relative humidity is the highest in July and August at about 80%. Nine representative soil profiles were selected to collect soil samples at 0–20 cm and 20–40 cm soil layers. All soil samples were taken back to the laboratory for soil column experiments. The soil sample of the same layer was thoroughly mixed and air dried and passed through a 4 mm sieve to fill the soil column. The sample soil has a pH (8.4–8.8) and bulk density (1.40–1.45 g $cm^{-3}$). The soil has 14.77–15.19% sand, 31.60–33.78% silt, and 51.03–53.63% clay, which is classified as clay by United States soil texture classification standards (United States Department of Agriculture). Other soil properties are shown in Table 1.

**Table 1.** Basic soil properties of the study area.

| Soil Depths (cm) | pH | EC (μs $cm^{-1}$) | Salt Content (g $kg^{-1}$) | SOM (g $kg^{-1}$) | Bulk Density (g $cm^{-3}$) | Soil Texture | | | AN (mg $kg^{-1}$) | AK (mg $kg^{-1}$) | AP (mg $kg^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Sand (0.02–2 mm) | Silt (0.002–0.02 mm) | Clay (<0.002 mm) | | | |
| 0–20 | 8.80 | 634.00 | 2.26 | 7.29 | 1.45 | 15.19 | 33.78 | 51.03 | 26.20 | 110.67 | 6.05 |
| 20–40 | 8.40 | 598.00 | 2.03 | 6.85 | 1.40 | 14.77 | 31.60 | 53.63 | 30.70 | 93.00 | 6.19 |

Note: SOM represents soil organic matter; AN represents soil available nitrogen; AP represents soil available phosphorus; AK represents soil available potassium; EC represents soil conductivity.

### 2.2. Experimental Material and Design

Bio-organic fertilizer was jointly developed by Nanjing Ningliang Bio-fertilizer Co., Ltd. and Jiangsu Academy of Agricultural Sciences of Nanjing Agricultural University. It contains high-quality chicken manure, Chinese medicine drugs, and other materials; high-efficiency compound strains are added after full fermentation. Fulvic acid is a macromolecular organic compound with a small molecular weight [20]. Fulvic acid contains hydroxyl and carboxyl groups, which can combine with alkaline substances to form fulvic acid to regulate soil pH and effectively improve saline-alkali soil [18]. Fulvic acid, produced by Shandong Yupin High-tech Biotechnology Co., Ltd. Hekang (Hk), is a type of liquid fertilizer specifically used for saline-alkali land improvement. The main component of HK is Hydrolytic Polymaleic Anhydride (HPMA) which was hydrolyzed by maleic anhydride and is non-toxic to the environment and algae [23]. HK is produced by Beijing Feiying Greenland Science and Technology Co., Ltd. The above amendments materials can be purchased as commercial fertilizers. The organic fertilizer and amendments are shown in Table 2.

**Table 2.** Basic composition and content of amendment material.

| Amendment | pH | EC (ms $cm^{-1}$) | SOM (g $kg^{-1}$) | N (g $kg^{-1}$) | $P_2O_3$ (g $kg^{-1}$) | $K_2O$ (g $kg^{-1}$) | Basic Component | Carboxyl (mg $kg^{-1}$) | Density (g $cm^{-3}$) |
|---|---|---|---|---|---|---|---|---|---|
| Organic fertilizer | 8.2 | 23.2 | 515 | 25.6 | 22.4 | 18.6 | - | - | - |
| Fulvic acid | 7.5 | 15.6 | 600 | 12.5 | 10.8 | 120 | - | - | - |
| Hekang | 2.1 | 0.77 | - | - | - | - | polymaleic anhydride | 180 | 1.15 |

We set up 4 groups in the soil column experiment: (1) CG, without amendment addition; (2) OF, soil with organic fertilizer of 60 g m$^{-2}$; (3) OH, soil with organic fertilizer of 60 g m$^{-2}$ and Hekang amendment of 4.5 g m$^{-2}$; and (4) OB, soil with organic fertilizer of 60 g m$^{-2}$ and fulvic acid of 7.5 g m$^{-2}$. Each of the above treatments was repeated three times, and soil water and salt monitoring sensors and data collectors were installed to monitor and record water and salt data.

### *2.3. Soil Column Experiment*

Soil column experiments were conducted using plexiglass columns of 20 cm in internal diameter and 50 cm in height in December 2020. First, a 5 cm layer of quartz sand was placed as a filter layer to prevent the column outlet from becoming blocked by soil in the bottom of the column. Then, a layer of nylon mesh was evenly spread over the quartz sand in each column. According to the original bulk density (1.4 g cm$^{-3}$), the required soil of 0–20 cm was weighed, and the organic fertilizer and amendments were sprayed or applied to the original soil according to the experimental design. After mixing evenly, it was evenly divided into 4 equal parts and filled in the soil column. The soil of the 20–40 cm layer was weighed according to the original bulk density (1.45 g cm$^{-3}$) and no material was added (Table 1). Each layer of soil was filled 4 times, with 5 cm each time, and a 5 cm layer of irrigation water was set aside above the soil column. The materials were evenly mixed in the topsoil (0–20 cm). To collect the leachate, a 1 cm diameter hole was drilled in the bottom of each column (Figure 1).

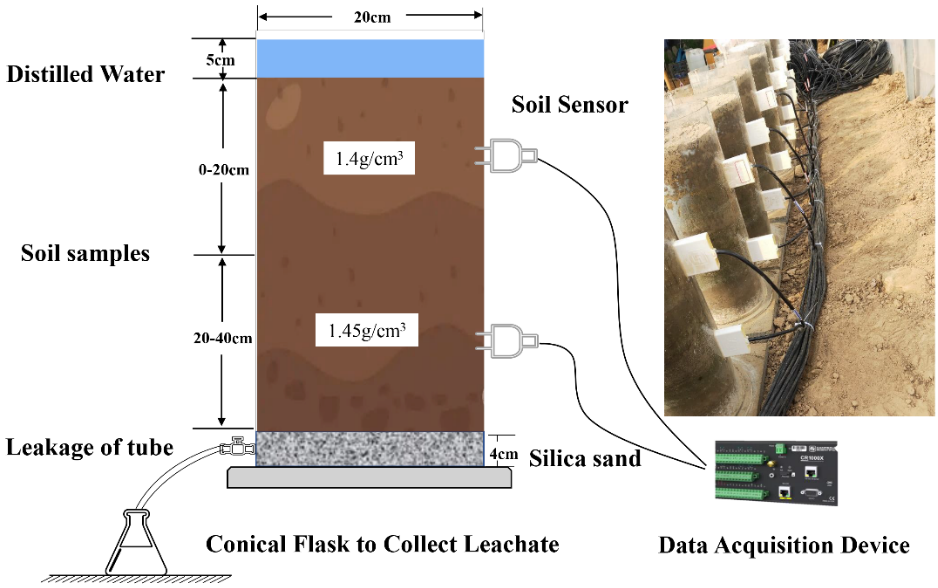


**Figure 1.** Design diagram of soil column experiment.

A rectangular hole about 6.2 cm long and 1.5 cm wide was drilled at 10 cm and 30 cm of each soil column. To monitor soil moisture and salinity dynamics at 0–20 cm and 20–40 cm, the soil sensor (CS655) was inserted vertically, and glass glue was evenly applied to the connection between the sensor and the soil column to prevent water leakage. The data collector (CR3000), which can record and store data for 3 months, was connected to the end of the soil sensor. Data reading began one week after stable installation. The volumetric water content and electrical conductivity were monitored by salt sensors (CS655) and a data processor (CR3000). In addition, soil sensors were installed in 0–20 cm and 20–40 cm layers of soil columns, and a set of data was collected at 15 min intervals, and the sensors were calibrated before installation. Soil sensors and data collectors were purchased from Nanjing Ubaida Technology Co., Ltd., and calibrated one week before installation (Figure 1).

The soil column was filled with water equivalent to 80% of the saturated water capacity in the field and sealed with plastic film so that the water could fully penetrate the saturated state, then left to stand for 24 h. Intermittent leaching was used, and the leaching process was initiated every 12 h. In addition, 500 mL of leaching water was added each time, and the number of leaching times was based on the leakage rate of each soil column. Leachate from each soil column was recorded and collected each time it exceeded 100 mL to measure the conductivity. At the same time, the 5 d, 10 d, 15 d, and 20 d leakages were collected, and the leaching solution was configured according to the soil-water ratio of 1:5 to determine the content of soil salt ions in each soil column. Water and salt data were recorded by the water and salt sensor every 7 days. The desalination ratio ($V_R$) and desalination efficiency ($E_M$) were used as indices to measure the desalination performance of the organic amendments; the following formulas were used for calculation.

$$V_R = \frac{m_1 - m_2}{m_1} \tag{1}$$

$$E_M = \frac{m_2 - m_1}{w} \tag{2}$$

where $m_1$ represents the salt content of the initial soil column, g kg$^{-1}$; $m_2$ represents the salt content of the soil column after leaching, g kg$^{-1}$; and $w$ represents the amount of leaching water.

### 2.4. Soil and Water Sampling and Analysis

Before (February 2021) and after (March 2021) the leaching experiment, soil samples were collected at 0–20 cm and 20–40 cm layers using a small borehole soil auger (diameter 38 mm, length 100 cm). A total of 30 soil samples were collected from 12 soil columns for laboratory analysis at each sampling time. To evaluate the improvement of organic amendments on salt-affected soils, soil pH, salt content, electronic conductivity, and soil organic matter, available phosphorus, and available potassium of 0–20 cm layer were analyzed in the Lab. Leachate from each soil column was recorded and collected each time it exceeded 100 mL and brought back to the laboratory to measure electrical conductivity and salt ions content. During the leaching experiment, soil volumetric water content and electrical conductivity in 0–20 cm and 20–40 cm layers were measured by salt sensors in situ.

The pH value and salt content of soil samples were determined. Leaching filtrate was prepared with a 1:5 soil-water mass ratio extract to determine salt ions. The soil pH value was measured by the pH meter method. The salt content of the soil was measured by mass method. The organic matter (SOM) was oxidized by potassium dichromate and heated by an external heating method. The available phosphorus (AP) was measured by the 0.5 mol L$^{-1}$ $NaHCO_3$ extraction molybdenum antimony colorimetric method. The available potassium (AK) was determined by $NH_4Ac^-$ extraction-flame photometry. Soil urease activity, soil catalase activity, and soil alkaline phosphatase activity were determined using the method described by Liu et al. [18]. Soluble $CO_3{}^{2-}$ and $HCO_3{}^-$ were analyzed using neutral titration. Soluble $Cl^-$ was analyzed by the silver nitrate titration method, and soluble $SO_4{}^{2-}$ was measured by barium sulfate turbidimetric method. The concentrations of soluble $K^+$, $Na^+$, $Ca^{2+}$, and $Mg^{2+}$ were measured as described by Liu et al. [18].

### 2.5. Statistical Analysis

Soil physical and chemical indexes were processed with Microsoft Excel 2007 (version 8.0.1 for Windows). Significant differences between different treatments were compared by using a one-way ANOVA with Duncan's new multiple-comparison test ($p \leq 0.05$) using SPSS (version 20.0, IBM, Armonk, New York, NY, USA). The significant difference between the initial and final salt content of the soil column under different treatments was analyzed by the one-way ANOVA and Tukey test ($p < 0.01$). All figures were drawn by Origin 2022b (version 9.65.169, Origin Lab Corporation, Northampton, MA, USA)

## 3. Results

### 3.1. Effect of Soil Properties after Adding Modified Materials

Significant differences in soil pH and salt content were observed in the different treatments (Table 3). Treatments with organic amendments addition had a lower pH value (8.47–8.52) than control in topsoil (0–20 cm). Except OF, the salt content of other organic treatments was lower than the control, ranging from 2.06 g $kg^{-1}$ to 2.13 g $kg^{-1}$. There were significant differences between the various treatments in SOM, AP, and AK ($p < 0.05$). The organic matter content of OF, OH, and OB was 8.3 g $kg^{-1}$, 7.58 g $kg^{-1}$ and 7.47 g $kg^{-1}$, respectively, which increased by 13.8, 5.7, and 2.5% compared to CG, respectively. The contents of AK and AP in organic treatment increased by 51–71 and 14–37% to control, respectively, and ranked OF > OH > OB > CG. There was a significant difference in AKP between organic treatments and control ($p < 0.05$). The AKP activity in the treatments followed the order OF > OH >OB > CG.

**Table 3.** Variation of chemical properties between different treatments in 0–20 cm layer.

| Treatments | pH | Salt Content (g $kg^{-1}$) | SOM (g $kg^{-1}$) | AK (mg $kg^{-1}$) | AP (mg $kg^{-1}$) |
|---|---|---|---|---|---|
| OF | $8.49 \pm 0.07^{b}$ | $2.34 \pm 0.26^{a}$ | $8.30 \pm 0.06^{ab}$ | $188 \pm 6.97^{a}$ | $8.35 \pm 0.66^{a}$ |
| OH | $8.52 \pm 0.12^{b}$ | $2.06 \pm 0.32^{ab}$ | $7.58 \pm 0.32^{bc}$ | $182 \pm 5.71^{a}$ | $7.15 \pm 0.15^{b}$ |
| OB | $8.47 \pm 0.12^{b}$ | $2.13 \pm 0.08^{a}$ | $7.47 \pm 0.18^{bc}$ | $166 \pm 2.86^{a}$ | $6.98 \pm 0.42^{b}$ |
| CG | $8.87 \pm 0.11^{a}$ | $2.27 \pm 0.22^{a}$ | $7.29 \pm 0.41^{c}$ | $110 \pm 17.91^{b}$ | $6.10 \pm 0.06^{c}$ |

Note: different lowercase letters in the same column indicated significant differences ($p < 0.05$, $n = 3$). AK: available potassium; AP: available phosphorus; SOM: soil organic matter; OF: organic fertilizer alone; OH: organic fertilizer and HK addition; OB: organic fertilizer and FA addition; CG: control group. All the data are expressed as mean value ± standard deviation.

### 3.2. Dynamics and Difference of the Soil Volumetric Water Content and EC during Leaching

The dynamics of soil volumetric water content (SVWC) and EC with leaching time in different treatments are shown in Figure 2. The SVWC of different treatments was 0.2–0.3 $m^3$ $m^{-3}$ in 0–20 cm layer at 2 d and gradually increased by 0.40–0.48 $m^3$ $m^{-3}$ with leaching time. The SVWC of these treatments in the 20–40 cm layer had a similar trend to the 0–20 cm layer. Except for CG, leakage was observed in different treatments at 3 d, and SVWC was ranked CG > OH > OB > OF. With increasing leaching time, soil EC of 0–20 cm soil layer increased between 2–4 d. OH and OF treatments increased rapidly over time, at 2.5 dS $m^{-1}$ and 1.75 dS $m^{-1}$, respectively. Subsequently, soil EC gradually decreased due to increasing leakage volume, and ranked CG > OH > OF > OB. The soil EC in the 20–40 cm layer was higher than that in the 0−20 cm layer. OB treatment increased the fastest with leaching time increased, and it had the highest conductivity of 2.8 dS $m^{-1}$, while it decreased gradually with increasing leachate volume.

Change in SVWC (soil volumetric water content) and EC between different treatments under cumulative infiltration water (2, 4, 6 L) are presented in Table 4. SVWC increased with the increase in infiltration water volume. The SVWC in the 0–20 cm soil layer was lower than in the 20–40 cm soil layer when leaching water was 4 L and 6 L. After adding 6 L of water, SVWC ranged from 0.40 to 0.45 $m^3$ $m^{-3}$ and significantly differed between treatments, ranking CG > OH > OB > OF in the 0–20 cm and CG > OH > OB > OF in the 20–40 cm. The variation of soil EC increased with the increase in soil depth and decreased with the increasing infiltration of water, which is the opposite of SVWC. There were significant differences in EC between different treatments ($p < 0.05$). Soil EC ranged from 0.63 to 0.97 dS $m^{-1}$ in the 0–20 cm and from 1.03 to 1.37 dS $m^{-1}$ in the 20–40 cm soil layer when infiltration water volume was 6 L.

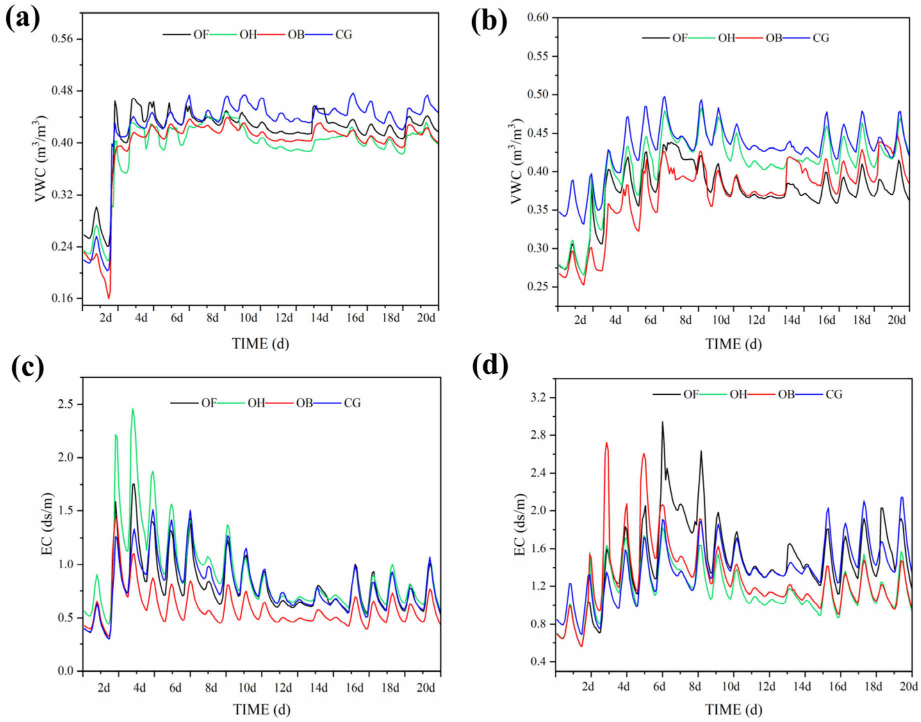


**Figure 2.** Variations of soil volumetric water content ((**a**): 0–20 cm; (**b**): 20–40 cm) and electrical conductivity ((**c**): 0–20 cm; (**d**): 20–40 cm) over time in different treatments.

**Table 4.** Variation of SWC and EC under different cumulative infiltration water amounts.

| Treatments | Soil Layer (cm) | Cumulative Infiltration Volume (2 L) | | Cumulative Infiltration Volume (4 L) | | Cumulative Infiltration Volume (6 L) | |
|---|---|---|---|---|---|---|---|
| | | SVWC ($m^3$ $m^{-3}$) | EC (dS $m^{-1}$) | SVWC ($m^3$ $m^{-3}$) | EC (dS $m^{-1}$) | SVWC ($m^3$ $m^{-3}$) | EC (dS $m^{-1}$) |
| OF | 0–20 | $0.45 \pm 0.01^{a}$ | $1.24 \pm 0.27^{a}$ | $0.46 \pm 0.00^{a}$ | $1.22 \pm 0.11^{a}$ | $0.45 \pm 0.01^{a}$ | $0.78 \pm 0.02^{ab}$ |
| | 20–40 | $0.38 \pm 0.03^{A}$ | $1.45 \pm 0.24^{BC}$ | $0.41 \pm 0.00^{B}$ | $1.64 \pm 0.02^{B}$ | $0.40 \pm 0.00^{B}$ | $1.29 \pm 0.04^{A}$ |
| OH | 0–20 | $0.45 \pm 0.00^{a}$ | $1.47 \pm 0.22^{a}$ | $0.42 \pm 0.00^{bc}$ | $1.23 \pm 0.03^{a}$ | $0.43 \pm 0.00^{bc}$ | $0.89 \pm 0.11^{a}$ |
| | 20–40 | $0.43 \pm 0.03^{A}$ | $1.87 \pm 0.02^{A}$ | $0.43 \pm 0.01^{B}$ | $1.50 \pm 0.01^{C}$ | $0.44 \pm 0.00^{A}$ | $1.15 \pm 0.03^{A}$ |
| OB | 0–20 | $0.35 \pm 0.00^{b}$ | $1.20 \pm 0.08^{a}$ | $0.42 \pm 0.00$ c | $0.88 \pm 0.01^{b}$ | $0.42 \pm 0.00$ c | $0.63 \pm 0.12^{b}$ |
| | 20–40 | $0.30 \pm 0.00^{B}$ | $1.29 \pm 0.07^{C}$ | $0.42 \pm 0.01^{B}$ | $1.17 \pm 0.05^{D}$ | $0.44 \pm 0.01^{A}$ | $1.03 \pm 0.00^{B}$ |
| CG | 0–20 | $0.35 \pm 0.04^{b}$ | $1.37 \pm 0.06^{a}$ | $0.43 \pm 0.00^{b}$ | $1.21 \pm 0.07^{a}$ | $0.44 \pm 0.00^{ab}$ | $0.97 \pm 0.12^{a}$ |
| | 20–40 | $0.39 \pm 0.04^{A}$ | $1.69 \pm 0.06^{AB}$ | $0.48 \pm 0.01^{A}$ | $1.97 \pm 0.03^{A}$ | $0.45 \pm 0.01^{A}$ | $1.37 \pm 0.13^{A}$ |

Note: SVWC represents soil volumetric water content and EC represents soil electrical conductivity. Different lowercase letters represent significant differences between treatments under the same cumulative water volume in the 0–20 cm layer, and different capital letters represent significant differences between different treatments under the same cumulative water volume in the 20–40 cm layer ($p < 0.05$). All data are expressed as mean ± standard deviation.

### *3.3. Desalination Ratio and Efficiency of Different Treatments*

At the end of the leaching experiment, the final soil salt content was significantly reduced ($p < 0.01$), ranging from 1.42 g to 1.87 g kg$^{-1}$. There was a significant difference in final soil salt content between control and organic treatments ($p < 0.05$), showing CG > OF > OH > OB (Figure 3). The soil salt content of different soil columns decreased with leaching volume (Table 5). Leaching water from different treatments ranged from 5.8 L to 7 L, and the highest water consumption was OF and OH treatments. Leaching rates ranged from 0.06 mL h$^{-1}$ to 22.4 mL h$^{-1}$ and showed OB > OH > OF > CG. The desalinization ration $V_R$ and desalinization efficiency $E_M$ showed the effect of organic amendments on soil permeability. The desalination rates of OF, OH, and, OB treatments were 32.61%, 32.95%, and 32.12%, respectively, which were higher than control. There was no significant difference in $E_M$ between different treatments. The desalination efficiency of OH was the highest, and the CG was the lowest.

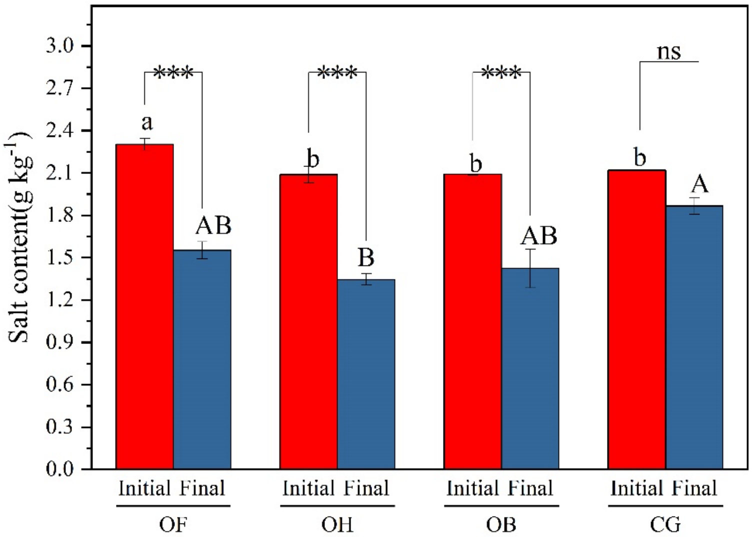


**Figure 3.** Variation of salt content between different treatments before and after leaching. Different lowercase letters represent significant differences between treatments under the same cumulative water volume in the 0–20 cm layer, and different capital letters represent significant differences between different treatments under the same cumulative water volume in the 20–40 cm layer ($p < 0.05$). *** means a significant difference between initial salt content and final salt content under the same treatment ($p < 0.01$); ns means no significant difference.

**Table 5.** Desalination efficiency in different columns.

| Treatment | Leachate Volume (L) | Leaching Rate (mL h$^{-1}$) | $V_R$ (%) | $E_M$ (g kg$^{-1}$ mL$^{-1}$) |
|---|---|---|---|---|
| OF | $7.00 \pm 0.70^{a}$ | $18.3 \pm 3.8^{a}$ | $32.61 \pm 2.32^{a}$ | $0.108 \pm 0.01^{a}$ |
| OH | $7.00 \pm 0.40^{a}$ | $21.2 \pm 7.80^{a}$ | $32.95 \pm 4.16^{a}$ | $0.101 \pm 0.01^{a}$ |
| OB | $6.80 \pm 0.47^{a}$ | $22.4 \pm 9.68^{a}$ | $32.12 \pm 6.70^{a}$ | $0.098 \pm 0.02^{a}$ |
| CG | $5.80 \pm 0.23^{a}$ | $0.06 \pm 0.00^{b}$ | $18.44 \pm 1.23^{b}$ | $0.060 \pm 0.00^{a}$ |

Note: Different lowercase letters in the same column indicated significant differences between different treatments ($p < 0.05$, $n = 3$); $V_R$ represents desalination ratio; $E_M$ represents desalination efficiency. All data are expressed as mean ± standard deviation.

### *3.4. Leakage Volume and Salt Ion Accumulation of Different Treatments*

The conductivity of soil leachate can represent the soluble salt content in the soil column. Figure 4 shows the change of leachate EC with leaching water volume. With the increase in leaching water, the soil conductivity of the different treatments decreased significantly. The soil leachate EC ranged from 0.06 to 0.21 dS m$^{-1}$. At the end of leaching, the leachate EC in OH and OB were 0.07 dS m$^{-1}$ and 0.11 dS m$^{-1}$, respectively, which were significantly lower than control and OF. The accumulated leakchate collected from OH and OB treatments was 1913 mL and 1533 mL, respectively, which was significantly higher than that of the control.

As shown in Figure 5, the salt ion content of leachate collected from different columns decreased with leaching time. The main soil salt ions under the different treatments were $Na^+$, $Mg^{2+}$, $Ca^{2+}$, $SO_4{}^{2-}$, $Cl^-$, and a small amount of $HCO_3{}^-$ ions. $SO_4{}^{2-}$, $Na^+$, and $Mg^{2+}$ were the most affected by leaching water volume. There was a significant difference in $Na^+$, $SO_4{}^{2-}$, $Mg^{2+}$, and $Cl^-$ between different treatments ($p > 0.05$). Total ions between the different treatments were ranked as OF > CG > OB > OH at 5 d, and changed to CG > OF > OB > OH at 10 d. At the end of leaching, $Na^+$ in the OF, OB, and OH treatments were 4.5, 12.6, and 32% lower than that of CG, respectively. The $SO_4{}^{2-}$ content in OF, OB, and OH treatments were 12, 13.3, and 27% lower than in the control, respectively.

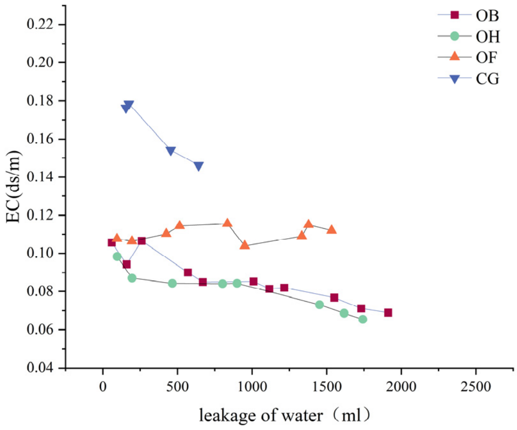


**Figure 4.** Variation of leachate EC with the amount of leaching water.

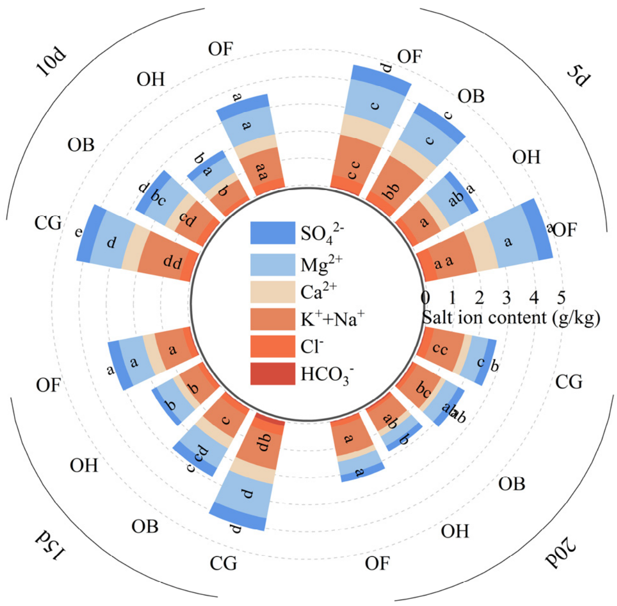


**Figure 5.** Variation of salt ion content in leachate with leaching time. Different lowercase letters at the same time indicated significant differences among different treatments ($p < 0.05$).

## 4. Discussion

Numerous studies have demonstrated that the use of organic fertilizers or chemical amendments not only reduces soil salinity but also improves soil fertility in salt-affected soils [4,8,9]. Similar results were found in our study, with the addition of organic fertilizer and amendments significantly reducing soil pH and salt content (Table 3). This could explain by the following reasons: (1) the release of carbon dioxide, hydrogen ions (H+) and organic acids from organic manure under the decomposition of microorganisms neutralized the alkaline ions in the soil [24] and (2) the $H^+$ released from the decomposition of organic fertilizer reacts with salt and carbonate, making them more soluble and flowing out with water [4,25]. Our study showed that organic amendments also significantly increased soil organic matter, and AP (Table 3). After compound fermentation of straw, chicken manure, and microbes, bio-organic fertilizer contains a significant amount of organic matter, including free humic acid, and various biopolymer residues [26]. It continuously provides plants with vital nutrients including N, P and K through decomposition and mineralization [27]. It should be noted that organic amendments had a higher nutrient content than control (CG), particularly available phosphorus, which is consistent with Liu et al. [18] suggested that the addition of fulvic acid enhanced the availability of phosphorus by promoting the conversion of inorganic phosphorus in salt-affected soils. The possible mechanism of this result is that a large number of anions contained in organic amendments compete with phosphates to chelate $Al^{3+}$, $Ca^{2+}$, $Fe^{3+}$, etc. in the soil, which reduces the number of adsorption sites and leads to phosphorus release and improved fertility [18,28].

It was found that the soil water content of the organic treatments increased with leaching time and was lower than that of the control (Figure 2a,b; Table 4). This result appears to differ from Sun et al. [29], which found that biochar addition increased soil water content at different soil depths in coastal saline soils. This difference is not only related to the types of amendment materials, but also has a significant relationship with soil texture [30]. Larney et al. [11] noted that the addition of organic amendments may not increase the moisture content of clay compared to degraded sandy soil due to its greater inherent water-holding capacity. The addition of organic amendment may reduce soil volumetric water holding capacity on a silt loam due to higher bulk density than sandy soil [31]. Zhou et al. [30] indicated that the effects of organic amendments mainly affected the retention of capillary water but not hygroscopic water. In this study, experimental soil was classified as clay soil that contains high capillaries and micro-pores, and few air pores, resulting in poor water and air permeability. Capillary pores contain capillary water that can be effectively absorbed by roots, representing soil water retention capacity, while micro-pores and air pores contain mostly hygroscopic water and gravity water [32]. Organic materials, particularly organic fertilizer, have been demonstrated to increase connectivity by altering antra- and inter- aggregate pore structure [33]. Therefore, we speculate that the addition of organic amendments may have resulted in lower soil water content than the control by promoting soil leaching ineffective water from non-capillary porosity. Another result of our study verified this phenomenon, in which the leaching rate and leachate of the treatment with acid amendments addition (OH, OB) were significantly higher than those of the control. This result indicated that the addition of organic amendments improved soil permeability, which is similar to Shi et al. [34] who observed that the addition of organic fertilizer improves the permeability between aggregates by better balancing macro-pores. In addition, the hydrophobic nature of other organic modifications may have facilitated this process [11]. However, the mechanisms need further exploration.

In this study, we observed that soil columns with different treatments formed significant salt peaks of 10 and 30 cm (Figure 2c,d). The soil EC in the 0–20 cm layer was lower than the soil EC in the 20–40 cm layer, and both decreased with the increase of infiltration water (Table 4). This result indicated salt accumulation and desalting with leaching time. The final salt content and salt accumulation of OH treatment was lower than other treatments, but the desalting rate was higher than other treatments (Figure 3; Table 5). This may be due to the addition of amendments, which improved soil permeability and promoted the replacement of $Na^{+}$ and $SO_4^{2-}$ in soil, resulting in the dissolution of salt and its removal with water [15,35]. Our results showed that the desalination rate of different treatments ranged from 18.3 to 33%, slightly higher than the study of Heng et al. [36] (15–32% drip irrigation). These differences may be due to the types of amendment materials and leaching methods. In addition, the original soil bulk density and salinity may be crucial factors for leaching results [37]. Moreover, we found that the organic amendment addition increased the desalination efficiency and leaching rate (Table 5). Improving desalination efficiency and flow rate is an important way to save water [38]. Through an ion exchange reaction, the organic acids, humic acid, and so on produced from the breakdown of the organic amendment swap out the insoluble ions, such as $Na^{+}$ in the salt, causing the water to flow out faster and increasing the soil column's desalination efficiency [37,39].

Previous studies have introduced many effective methods and alternative materials for improving saline-sodic soils [29,34,40]. However, research is still being conducted to determine the types and quantities of salt ions that will leave the water after the amendment material has been added. Our study showed that the major leaching salt ions were $Na^{+}$, $Mg^{2+}$, and $SO_4^{2-}$, and $SO_4^{2-}$ leaching in soil profiles was strong (Figure 5). In addition, leachate EC and $Na^{+}$ and $SO_4^{2-}$ content in leachate gradually decreased over leaching time (Figure 4), and the salt ions concentration in organic treatments was lower than in the control. This is consistent with Du et al. [37], which indicated that water leaching removes a large number of harmful salt ions, such as $Na^+$ and $SO_4^{2-}$, and organic amendments increased soil permeability and promoted salt ion leaching. It is worth mentioning that at the early stage of leaching, the application of organic fertilizer alone increased the content of soluble salt in the soil (Figure 4), which may be due to the generation of salts in the composting process of bio-organic fertilizer [13].

## 5. Conclusions

Organic fertilizer combined with acid amendments improved soil chemical properties by reducing soil pH and EC, and increasing SOM, AP, and AK content. Organic fertilizer combined with organic amendments promoted soil permeability properties by improving cumulative infiltration volume and leaching rate. OH, and OB treatments reduced soil salt content by promoting the removal of $Na^+$, $SO_4^{2-}$, and $Mg^{2+}$ from salt-affected soil. OB and OH had a higher desalination efficiency and rate than CK. This study preliminary explained the migration characteristics of water and salt—and the desalination law under the synergistic effect of organic amendments addition and water leaching—and may provide effective measures and techniques for coastal saline soil improvement. Future studies should concentrate on the principles and mechanisms of salt and water transport in the context of organic soil amendments applied in natural fields.

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