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Original Research

Effect of Coal Fly Ash and Green Waste Compost on Salt Ions Leaching in Coastal Saline Soils

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Abstract

With the increasing output of coal fly ash (CFA) and garden waste, it is of great significance for environmental protection and resource utilization to establish if it can be recycled. The saline soil is widely distributed in the coastal areas of northern China, with high salt content and poor physical and chemical properties, which seriously affects the development of local agriculture and forestry and causes the waste of arable land. If CFA and garden waste compost (GWC) can be applied to saline soil improvement, it not only improves the local soil problem, but also helps environmental protection. Leaching salt is an important measure to reduce salt content in saline-alkali soil. The purpose of this study was to explore the effect of CFA and GWC on salt leaching of coastal saline-alkali soil through a soil column simulation test. The use of CFA and GWC promoted leaching and reduced leaching time. The addition of CFA and GWC to the soil suppressed the increase of HCO_3^- and CO_3^{2-} during leaching, but increased the salt ion content of the soil after leaching. The addition of CFA to the soil reduced the ion retention of GWC in the soil, but the application of CFA and GWC had no significant effect on the leaching sequence of salt ions. CFA and GWC added to the soil improved the physicochemical properties and the quality of saline soils, but GWC was less effective than CFA in improving soil physicochemical properties. Application of CFA reduced the leaching time of soil salt ions by about 25%, as well as reduced the pH, EC, SAR, and total salt ion content of the soil by 2.18%, 20.83%, 56.63%, and 38.95%, respectively.

Keywords: coastal saline-alkali soil, coal fly ash, green waste compost, leaching, saline soil restoration

Introduction

Coastal saline-alkali soil is a transitional zone connecting the land and the sea, formed by the interaction between the sea and the land through extensive sedimentation. The coastal tidal flats in China cover an area of 2×10^4 km^2 and are distributed with a large amount of saline-alkali soil [1]. Saline-alkali soil has disadvantages such as high pH value, poor permeability, surface compaction, and low nutrient content [2]. Due to the poor soil quality of saline-alkali land, it has low land productivity [3], and the land resources are difficult to be fully developed [4]. Studies have shown that chemical improvement measures can increase the porosity of

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coastal saline-alkali soil to a certain extent, reduce Na^+ toxicity, and enhance soil nutrient content [5]. However, due to the variety and high cost of chemical improvement materials, they are not suitable for large-scale application, Therefore, it is of great significance to research on environmentally friendly and effective improvement materials that promote green economy.

Coal fly ash (CFA) is a solid waste residue discharged by coal-fired enterprises during the production process [6, 7]. With the increasing use of coal, the amount of CFA emissions is also increasing [8]. Therefore, it is necessary to take appropriate measures for safe disposal and utilization of these waste to achieve sustainable management [9]. CFA is a type of particle that have a honeycomb structure and have different sizes and irregular shapes, with more than 50% of its particles having a diameter of 50-100 μm, a density of 1.8-2.4 g cm^{-3}, and a volumetric mass (including pores) 0.55-0.88 g cm^{-3} [10]. CFA particles have characteristics such as small diameter, light mass, porosity, large specific surface area, abundant active groups, and strong adsorption capacity [11], which can promote soil particle agglomeration and improve soil structure [12]. However, there were few studies on the application of CFA in saline-alkali land improvement. Green waste compost (GWC) has the characteristics of high organic matter content and loose texture. It is used as fertilizer and soil amendment to promote the formation of soil aggregate, improve soil aeration, lower soil pH, and enhance soil fertility and microbial activity [13]. In addition, GWC can also improve the physical structure and chemical properties of soil [14, 15]. Irrigation is one of the simplest and most effective methods to reduce the salt content in saline-alkali soil. The primary task to enhance the efficiency of salt leaching is to improve soil permeability[16]. CFA and GWC have shown significant effects in improving soil permeability. Research shows that CFA and GWC exhibit excellent performance in modifying soil physical and chemical properties. Selecting them as amendment materials and exploring their effects on coastal saline-alkali soil can verify the feasibility of applying CFA and GWC for soil improvement in coastal saline-alkali areas.

The purpose of this study is to investigate the effect of CFA and GWC on the improvement of saline-alkali soil through leaching experiments. It aims to provide a theoretical basis for the future application of CFA and GWC in soil remediation and saline-alkali land improvement, in order to broaden the utilization of CFA and garden waste, and to simultaneously improve their utilization efficiency while reducing environmental pollution.

Materials and Methods

Study Area

The study area is Huanghua City (38°09′-38°39′ N, 117°05′-117°49′ E), located on the west bank of Bohai Sea in China. This area belongs to a warm temperate semi-humid continental monsoon climate, with four distinct seasons and the same period of rain and heat. The soil parent material is mainly river delta alluvial deposit, the soil texture is heavy, the salt content is high and the closer to the coastline, the higher the degree of salinity, soil salinity has obvious surface aggregation. The groundwater level in this area is high, and the average salinity of groundwater can reach 4 g L^{-1}, resulting in high soil salinity and affecting tillage.

Experiment Material

The test soil was taken from the surface soil (≤ 20 cm) of Zhongjie Farm (N 38°22’, E 117°23’) in Huanghua City, China. The bulk density of the soil under natural conditions is 1.52 g cm^{-3}, and the field water capacity was 20%. CFA was taken from Guodian Chengde Thermal Power Co., Ltd., China. GWC was the pruning residue or litter of white wax (*Fraxinus chinensis Roxb*), poplar (*Populus*), willow (*Salix babylonica*) and weeds, etc. Preparation of GWC by Secondary Composting [17]. The basic physical and chemical properties are given in Table1.

Experimental Design

The experiment was conducted in the greenhouse of the teaching nursery of Beijing Forestry University from March to June 2019. There were 4 treatments in the experiment: CK control group; T1, adding 10% soil volume fraction of CFA; T2, adding 4% soil mass fraction of GWC; T3, adding 10% CFA with soil volume fraction and GWC with 4% soil mass fraction, each was repeated 3 times. The improved materials were evenly mixed with the test soil, and the soil column (made of PVC pipe, with a thickness of 2 mm, a height of 40 cm, and an inner diameter of 8 cm) was filled from the bottom. In order to avoid the difference in soil compactness caused by each treatment, the soil was added in four times, each time with a height of 5 cm, adding to a total of 20 cm of soil. The bottom of the soil column device was sealed with a PVC plate with a hole with a diameter of 2 mm in the middle position, and a soft plastic pipe was connected to the hole to receive the leaching solution. In order to reduce the interface effect and achieve a constant filtering effect, 2 cm thick quartz sand (particle size 3 mm) was installed on the surface and bottom of the soil layer.

Each treatment group had 200 ml of deionized water added, and was then cultured in constant temperature and humidity for 2 weeks. Thereafter, deionized water was dripped into the soil column with a medical bottle at a rate of 20 drops min^{-1}, and the hydrostatic head was kept about 1 cm (stagnant water layer). Every 4 days, the electrical conductivity (EC) of the leaching solution was measured, collected and stored. The pH and EC values of the eight major salt ions (K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, CO_3^{2-} and HCO_3^-) in the soil were measured in the leaching solution and at the end of the leaching, as well as the bulk weight, porosity, hydraulic conductivity and the

Table 1. Basic physical and chemical properties of test materials.

Experiment material	pH	EC (mS cm^{-1})	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}	CO_3^{2-}+HCO_3^-
			(g kg^{-1})						
Coastal saline-alkali soil	8.35	3.56	1.66	0.23	0.22	0.11	4.16	0.89	0.62
CFA	8.01	1.20	0.30	1.01	0.21	0.09	0.45	2.23	0.42
GWC	7.56	5.53	0.43	1.06	0.48	0.38	3.93	4.06	1.09

Note: CFA and GWC means coal fly ash, green waste compost, respectively.

content of water-stable agglomerates ≥2 mm (WR_2) and ≥0.25 mm ($WR_{0.25}$) in the soil after the leaching.

Sample Analyses

Refer to Soil Agrochemical Analysis (3rd edition) [18]: EC values of soil leaching solutions were determined directly with an MP521 conductivity meter (SHANGHAISANXIN). The soil was extracted by negative pressure filtration at a ratio of 5:1 by volume and mass of water and soil, and the leachate was obtained. pH values were determined using a pH meter (OHAUS Starter 3C type) and EC values were determined using an electrical conductivity meter. The eight major salt ions in the extract and leaching solution were determined by FP 6410 flame photometer (SHANGHAI JINGKE) for K^+ and Na^+, by EDTA complex titration for Ca^{2+}, Mg^{2+} and SO_4^{2-}, by silver nitrate titration for Cl^-, and by double indicator neutralization titration for HCO_3^- and CO_3^{2-}.

The sodium adsorption ratio (SAR) was calculated as:

$$SAR=Na^+(c) / (Ca^{2+}_{(c)} + Mg^{2+}_{(c)})^{1/2}$$

The ring-knife method was used to determine the bulk weight of the soil and the total porosity of the soil, and a KSAT-type infiltrator (GEPTOP TECHNOGY) was used to determine the saturated hydraulic conductivity according to the constant head method. Soil water-stable agglomerate content was determined by wet sieve method using LK-2601 agglomerate analyzer (Beijing Eco-Mind Technology). After the soil sample was fully wetted (about 20 min), it was poured into the sieve set with the pore size of 2 and 0.25 mm in order, and the agglomerate analyzer was turned on and adjusted to 20 r min^{-1} for 15 min (the sieve set could not be exposed to water). Then, the agglomerates left on the sieve were rinsed through a funnel into an aluminum box with deionized water, dried and weighed, and the content of water-stable agglomerates ≥2 mm (WR_2) and ≥0.25 mm ($WR_{0.25}$) were calculated.

Data Processing and Analysis

Excel 2019 and SPSS 20.0 were used for basic statistical data analyses and to conduct Duncan's multiple comparison tests ($P < 0.05$), respectively. Origin 8 software was used for mapping.

Results

Electrical Conductivity of Leaching Solution

The change in EC of the soil leaching solution can visually indicate the change in the dissolution of soluble salts in the soil. Compared with EC of CK, the T1 was most obviously 3.65 times that of the CK, the T2 was twice that of CK, the T3 was 2.78 times that of the CK (Fig. 1). Wilcox [19] suggested that when the EC value of soil saturated leachate is less than 2 mS cm^{-1}, there is no salt damage to the crop. According to this, the EC value of the leaching solution of CK, T1, T2, and T3 were lower than 2mS cm^{-1}, and the required days were 28, 16, 26, and 28 days, respectively. The application of CFA and GWC can rapidly promote salt leaching in the early stage. The leaching rate of the experimental groups with T1, T2, and T3 were significantly higher than that of the CK in terms of the rate of change from the sharp drop to the slow drop. At the end of leaching, the EC value of the leaching solution tends to stabilize at about 0.6 mS cm^{-1}, and the required days for the four treatments were 48, 32, 48, and 38 days. It was found that the promoting effect of fly ash on soil salt leaching was more significant.

Changes of Ion Concentration in Leaching Solution

The cations in the soil column leaching solution were mainly Na^+ and Mg^{2+}, followed by Ca^{2+}, and the K^+ content was very low (Fig. 2). In the first 10 days of leaching, the concentration of all ions was relatively high. The highest content of Mg^{2+} and Na^+ in the initial leaching solution were 3.9×10^3 mg L^{-1} and 5.3×10^3 mg L^{-1}, respectively, and the decline rate of Mg^{2+} was greater than Na^+. Compared with CK, T1 significantly increased the leaching rate of K^+, Na^+, Mg^{2+}. When the leaching was carried out for 10 days, the contents of other cations except Ca^{2+} in the leaching solution of T1 was lower than the CK. The leaching time of T1 was 32 days, compared with CK, the leaching rate increased by 33.3%. T2 significantly increased the K^+ content in the soil, until the end of leaching, the K^+ content in the leaching solution was higher than other treatment groups. When the leaching lasted for 10 d, the contents of other cations in

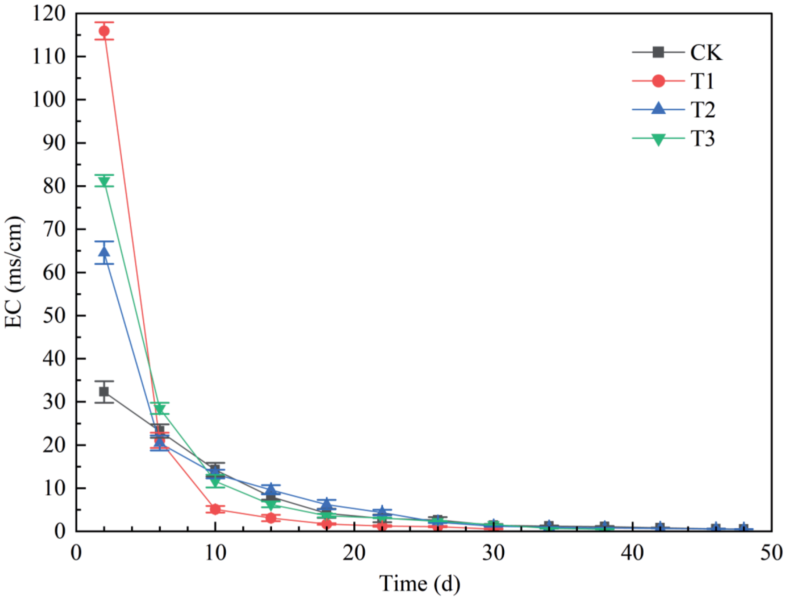

Fig. 1. Change of conductivity of leaching solution after application of coal fly ash and green waste compost in saline soil column. CK (control group), T1 (coal fly ash added 10% soil volume fraction), T2 (green waste compost added 4% soil mass fraction), T3 (coal fly ash added 10% soil volume fraction + green waste compost added 4% soil mass fraction).

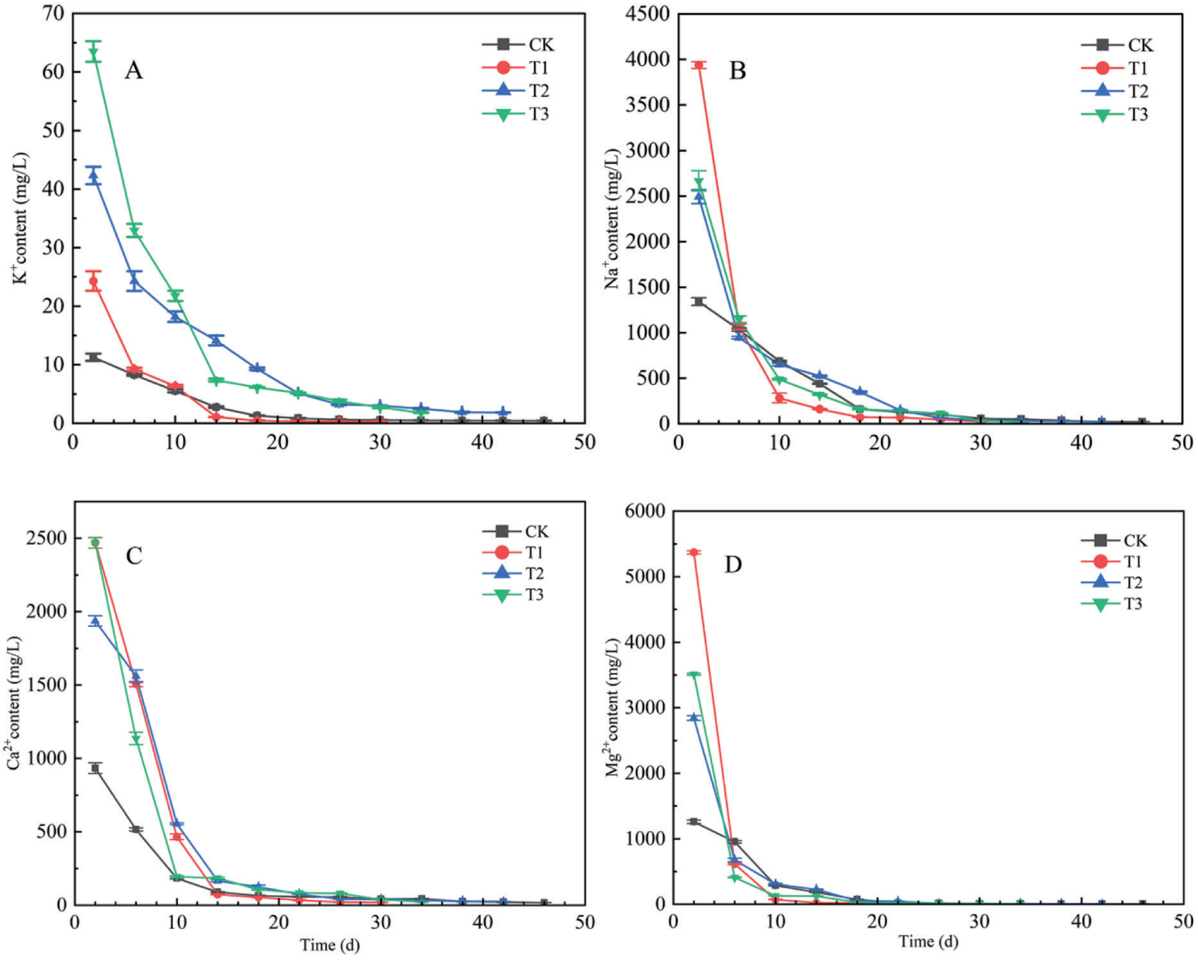

Fig. 2. Changes of K^+, Na^+, Ca^{2+} and Mg^{2+} contents in leaching solution after coal fly ash and green waste compost were applied in saline soil column. The meanings of CK, T1, T2, and T3 are the same as in Fig. 1.

the leaching solution of T2 were lower than those of CK except Ca^{2+}, and the leaching time was the same as CK. T3 significantly promoted the leaching of cations in the soil, compared with CK for 48 d, the total leaching time was shortened to 34 d. The leaching rate of K^+ in T3 was significantly higher than that in other treatment groups.

The anions in the leaching solution of each treatment were mainly Cl^- and SO_4^{2-}, followed by HCO_3^- and CO_3^{2-}. The highest content of Cl^- was 4.6×10^4 mg L^{-1}, which was 1.6-5.6 times that of SO_4^{2-}, indicating that chloride and sulfate were the main anions in the tested soil (Fig. 3). During the leaching process, Cl^- and SO_4^{2-} in the leaching solution of each treatment rapidly decreased with the first 5 days of leaching, and the decrease rate decreased slowly after 5 days. The contents of HCO_3^- and CO_3^{2-} in the leaching solution of each treatment increased first and then decreased. When the leaching lasted for 18-26 d, the content of HCO_3^- in the leaching solution reached the highest. When the leaching lasted for 14-26 days, the content of CO_3^{2-} in the leaching solution reached the highest. The peak time of different treatments was different, and the peak of HCO_3^- was 4.4 times that of CO_3^{2-}. Compared with CK, the peak value of HCO_3^- in the leaching solution of T1 decreased by 20.3%, the peak value of CO_3^{2-} reduced by 43.3%. The leaching rate of Cl^- and SO_4^{2-} was significantly increased in the first 6 days of T1. When the leaching lasted to 10 d, Cl^- and SO_4^{2-} in the solution of T1 entered a slow decrease stage. Compared with CK, the leaching time of T1 was shortened by 16 d, and the leaching rate was increased by 53.3%. In addition, the change trend of HCO_3^- and CO_3^{2-} contents in T1 had no significant effect. T2 significantly increased the leaching rate of Cl^-, HCO_3^- and CO_3^{2-}, not only made the peak of HCO_3^-, CO_3^{2-} advance, but also reduced the peak, but the total leaching time was not significantly reduced. The content of SO_4^{2-} in the leaching solution of T2 was significantly increased, the SO_4^{2-} content in the leaching solution was lower than that of CK after 26 d of leaching. Compared with CK, the peak time of CO_3^{2-} in T3 was 8 days earlier, and the peak value of HCO_3^- content was 0.6 times higher. There was no significant difference in the leaching rates of Cl^- and SO_4^{2-} between T3 and T2. The leaching rate of Cl^- in T1 was the most obvious.

Chemical Properties Characteristics of the Soil After Leaching

As shown in Table 3, there were significant differences in soil pH after leaching under different treatments

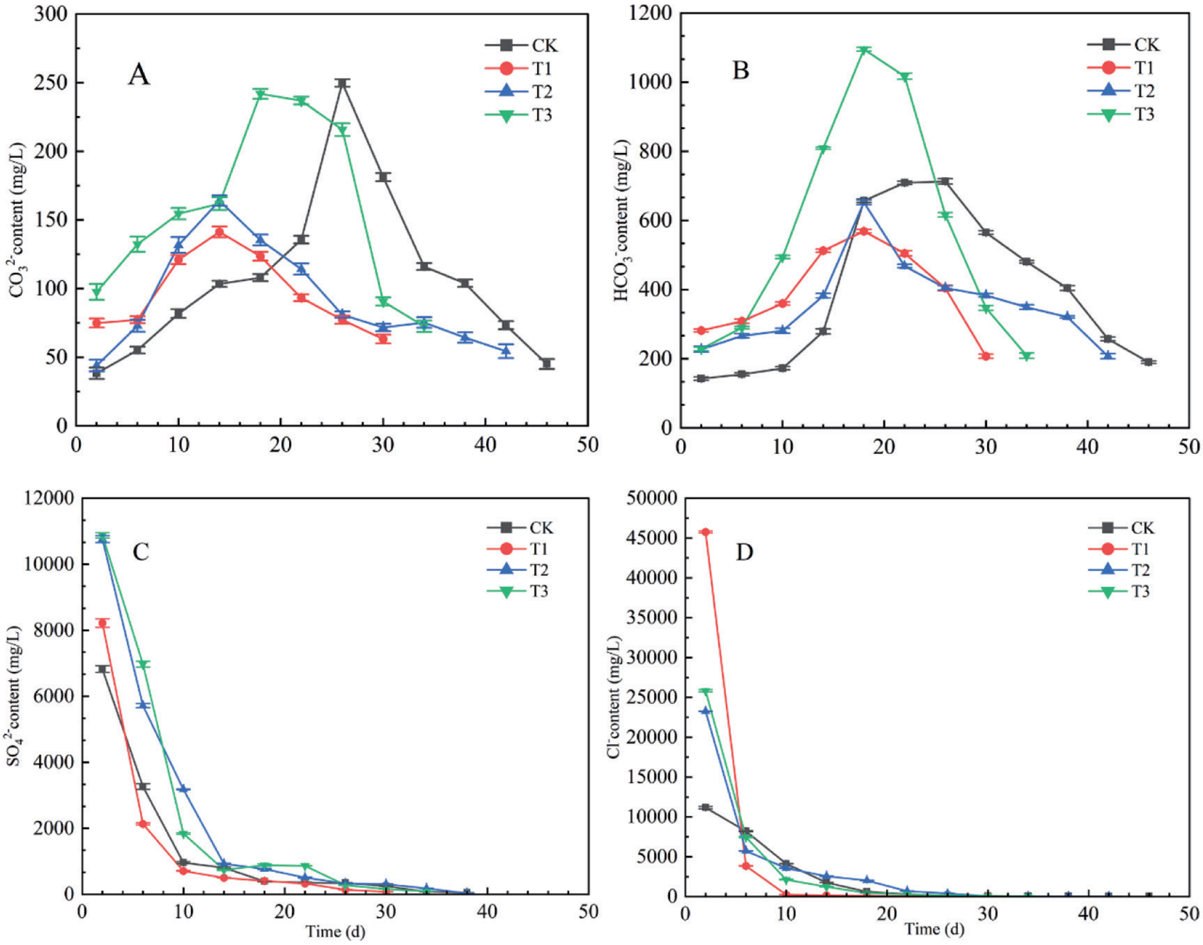

Fig. 3. Changes of Cl^-, SO_4^{2-}, CO_3^{2-} and HCO_3^- contents in leaching solution after coal fly ash and green waste compost were applied in saline soil column. The meanings of CK, T1, T2, and T3 are the same as in Fig. 1.

Table 2. Salinity indexes of soil after leaching in different treatments.

Treatment	pH	EC (mS cm^{-1})	SAR
CK	7.93±0.13a	0.24±0.05c	13.19±0.13c
T1	7.71±0.07c	0.19±0.05d	5.72±0.08d
T2	7.77±0.08b	0.29±0.09b	15.14±0.04a
T3	7.72±0.13c	0.30±0.16a	13.45±0.12b

Note: The data in the table are mean ± standard deviation, and the different letters indicate significant differences ($P < 0.05$). CK (control group), T1 (coal fly ash added 10% soil volume fraction), T2 (green waste compost added 4% soil mass fraction), T3 (coal fly ash added 10% soil volume fraction + green waste compost added 4% soil mass fraction), EC (electrical conductivity), SAR (sodium adsorption ratio).

($P < 0.05$). The pH of soil after leaching with T1-T3 was lower than that of CK. After leaching, the soil pH in the T1 was the lowest, followed by the T3, and then the T2. There was a significant difference between the T1, T3 and other treatments ($P < 0.05$). In the soil after leaching, the EC value of T1 was significantly lower than that of CK, and the EC values of T2, T3 were significantly higher than those of CK, and there were significant differences among groups. The greater the SAR value is, the greater the harm to soil is. From Table 3, T1 significantly reduced the SAR value of soil after leaching ($P < 0.05$), which was 2.3 times lower than CK. Compared with CK, T2 increased the SAR value of soil after leaching by 2.0%, and T3 increased the SAR value of soil after leaching by 14.8%. The results showed that the application of GWC could not reduce the harm of salt and alkali, and application of CFA can significantly reduce saline-alkali hazards.

After leaching, the contents of ions in T1 were significantly lower than those in CK, and the contents of ions in T2 and T3 were significantly higher than those in CK ($P < 0.05$). T2 significantly increased the ion content in Table 4, with the highest increase of 97.8% for K$^+$ and the lowest increase of 10.7% for SO$_4^{2-}$. Although the ion leaching in soil was relatively complete after leaching, the EC value of GWC was high, and the ion leaching in GWC was not complete, so the ion content in T2 was higher than that in CK after forest leaching. In Table 3, the contents of each ion in T2 were lower than those in T3, and higher than those in CK, indicating that CFA can promote the leaching of ions in GWC, thereby inhibiting its salt toxicity.

Physical Property Characteristics of the Soil After Leaching

As shown in Table 4, the bulk density, porosity and hydraulic conductivity of T1-T3 were significantly lower than those of CK ($P < 0.05$), and T3 decreased soil bulk density by 0.14 g cm^{-3} and increased porosity by 20.83%. However, T1 was the most effective in improving soil hydraulic conductivity, which was 6.64 times more effective than CK. In conclusion, GWC was superior to CFA in improving soil bulk and porosity, but CFA was superior in improving soil hydraulic conductivity. Soil aggregates are important for maintaining soil productivity [20]. Soil aggregate structure is generally characterized by WR$_2$ and WR$_{0.25}$, and the higher the content, the higher the degree of soil agglomeration. The levels of WR$_2$ and WR$_{0.25}$ in T1-T3 were significantly higher than those in CK ($P < 0.05$). It was found that CFA was superior to GWC in improving WR$_{0.25}$ in soil, but GWC was more effective in improving WR$_2$ in soil.

Discussion

Due to the honeycomb structure and large specific surface area in the CFA particles, With the application of CFA, the saturated hydraulic conductivity of the soil was significantly increased and its permeability improved, as the iron contained in CFA formed membranous iron, which promoted the formation of soil aggregates, improved the structure of soil aggregates, increased soil porosity, and promoted leaching [21–23]. In our experiments, CFA reduced the drenching time by about 25%. After the application of CFA and GWC to the soil, the soil porosity was increased, and the leaching effect was promoted due to the purely physical doping effect [24, 25]. On the one hand, CFA had an ion exchange

Table 3. Salinity indexes of soil after leaching in different treatments.

Treatment	K$^+$	Na$^+$	Ca^{2+}	Mg^{2+}	Cl$^-$	SO$_4^{2-}$	CO$_3^{2-}$+HCO$_3^-$
	(mg kg^{-1})						
CK	21.39±0.12c	113.58±0.03c	83.21±0.09c	65.11±0.16c	58.43±0.12c	89.02±0.03c	60.02±0.06c
T1	18.39±0.11d	42.58±0.10d	68.54±0.14d	42.28±0.05d	23.60±0.05d	68.40±0.07d	35.84±0.09d
T2	42.30±0.14b	141.67±0.07a	98.62±0.11a	76.46±0.07b	62.14±0.06b	98.51±0.09a	78.68±0.11a
T3	47.68±0.15a	124.50±0.12b	90.82±0.16b	80.46±0.14a	64.18±0.11a	92.32±0.10b	63.02±0.13b

Note: The data in the table are mean ± standard deviation, and the different letters indicate significant differences ($P < 0.05$). The meanings of CK, T1, T2, and T3 are the same as in Table 2.

Table 4. Physical properties of soil after leaching under different treatments.

Treatment	Weight capacity (g cm^{-3})	Porosity (%)	Saturated hydraulic conductivity (10^{-4} cm s^{-1})	WR_2 (%)	$WR_{0.25}$ (%)
CK	1.47±0.02a	30.13±4.6d	0.43±0.05d	0.31±0.03d	3.46±0.35c
T1	1.41±0.01b	41.73±1.4c	2.95±0.15a	1.35±0.10c	15.71±0.29a
T2	1.38±0.01b	44.11±1.7b	1.76±0.15c	1.73±0.08b	12.37±0.68b
T3	1.33±0.01c	50.96±1.3a	2.60±0.11b	2.04±0.14a	16.12±0.87a

Note: The data in the table are mean ± standard deviation, and the different letters indicate significant differences ($P < 0.05$). The content of ≥2 mm water-stable agglomerates in the soil (WR_2). The content of ≥0.25 mm water-stable agglomerates in the soil ($WR_{0.25}$). The meanings of CK, T1, T2, and T3 are the same as in Table 2.

effect with soil, which contains Ca^{2+} to exchange the adsorbed Na^+ on soil colloid made it enter the soil solution and leached out with water [26, 27]. On the other hand, CFA can promote the formation of soil aggregates, and improved the soil porosity and permeability [28, 29], increase the leaching rates of K^+, Na^+, Mg^{2+}, Cl^- and SO_4^{2-} in soil, and significantly reduced the EC value of soil. The GWC improved the soil porosity, so the leaching rate of K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^- and SO_4^{2-} increased significantly after applying GWC. The application of compost in soil can promote the improvement of aggregate stability by stimulating soil microbial activity and increasing soil organic carbon content [30]. In our experiment, GWC increased soil WR_2 content by 458.1% and $WR_{0.25}$ content by 257.5%, which significantly increased the content of soil agglomerates and improved soil permeability, thus promoting leaching and decreasing soil EC value. Due to the large amount of K^+ and SO_4^{2-} in GWC, the K^+ and SO_4^{2-} content of T3 was significantly higher than that of other treatments. All treatments' concentrations of CO_3^{2-} and HCO_3^- in leaching solution increased gradually and then decreased gradually. On the one hand, it may be related to the equilibrium of $CaCO_3$ precipitation and dissolution; on the other hand, it was due to the equilibrium of soil ion adsorption and exchange. After the removal of Cl^- and SO_4^{2-} with the leaching solution, in order to maintain the charge balance in the soil, the carbonate in the soil was decomposed to produce CO_3^{2-} and HCO_3^-, and then decreased with the deepening of leaching.

After leaching, the pH and EC values of soil in each treatment decreased, but T1 pH decreased the most with 2.18%, which was significantly better than the other treatments. In the treatment with CFA, because Al_2O_3 and SiO_2 in CFA can react with OH^-, OH^- is consumed continuously, thereby reducing the pH value of soil [31, 32]. The decrease of soil pH in the T2 and T3 were due to the fact that humic acids (ammonium nitrohumic acid and nitrohumic acid) [33] in GWC could regulate soil pH. The SAR value can intuitively reflect the content relationship of Ca^{2+}, Mg^{2+} and Na^+ in soil. The larger the SAR value is, the higher the Na^+ content is. When the SAR value exceeds 10, salt toxicity occurs. In our study, we found that application of CFA decreased the SAR value of soil by 56.63%. With the application of CFA, the content of Ca^{2+} and Mg^{2+} increased, and exchangeable Ca^{2+} and Mg^{2+} exchanged Na^+ into soil colloid, while Na^+ was leached. It also resulted in a significant decrease in soil EC, which decreased by 20.83% compared to CK. In addition, we also verified the effect of GWC and CFA application to improve the physical properties of saline soil [28-30], and the mixture of GWC and CFA had the most obvious effect, which not only decreased the bulk weight by 9.52%, increased the porosity by 69.13%, and increased the hydraulic conductivity by 504.6%, but also improved the soil's agglomerate content, with an increase of WR_2 and $WR_{0.25}$ by 558.1% and 365.9%, respectively.

GWC applied to soil improvement, economic and environmental protection, but its dosage needs to be studied due to its high salt content. Studies have shown that when the application ratio of CFA does not exceed 10% of the soil mass, it will not cause crop toxicity [34, 35]. At this time, the average values of Hg, Cd, pH, As and Cr in the soil are close to the soil background values, and the mass fractions of Hg, Cd, pH, As and Cr in grain do not exceed the relevant standards set at home and abroad. Nevertheless, the application of CFA should strengthen the detection to avoid secondary pollution.

Conclusions

The application of CFA rapidly reduced the ion content in soil in a short time, significantly shortened the leaching time of salt, shortened the leaching time by 25%; the pH of the soil decreased by 2.18%, EC by 20.83%, SAR by 56.63%, and total salt ion content by 38.95% after leaching. Although the application of GWC can promote the leaching of salt in soil, the salt content in soil after leaching is higher, especially the high content of Na^+, which leads to the high SAR value of soil and the risk of salt toxicity affecting plant development. However, the application of GWC was more significant in improving the soil bulk density and porosity as well as the content of aggregates. In a comprehensive comparison, although both GWC and CFA were effective in the improvement of coastal saline soils, CFA was more effective. Comprehensively, although both GWC and CFA are effective in improving coastal saline-alkaline land, CFA is more effective. In conclusion, our experiments showed the feasibility of applying GWC and CFA to coastal saline-alkaline land reclamation. It provides more ways for the reuse of CFA and garden waste, but the dosage of GWC and CFA in saline-alkaline land improvement and the ratio of these two materials need to be further studied.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. LI N., SHAO T., ZHU T., LONG, X., GAO, X., LIU, Z., RENGEL Z. Vegetation succession influences soil carbon sequestration in coastal alkali-saline soils in southeast China. Scientific Reports. **8** (1), 9728, **2018**.
2. ZHANG J. Coastal saline soil rehabilitation and utilization based on forestry approaches in China. Berlin–Heidelberg, Springer. 145, **2014**.
3. LIU S., HOU X., YANG M., CHENG F., COXIXO A., WU X., ZHANG Y. Factors driving the relationships between vegetation and soil properties in the Yellow River Delta, China. Catena. **165**, 279, **2018**.
4. LU Q., BAI J., GAO Z., ZHAO Q., WANG J. Spatial and Seasonal Distribution and Risk Assessments for Metals in a Tamarix Chinensis Wetland, China. Wetlands. **36** (S1), 125, **2016**.
5. ZHAO W., ZHOU Q., TIAN Z., CUI Y., LIONG Y., WANG H. Apply biochar to ameliorate soda saline-alkali land, improve soil function and increase corn nutrient availability in the Songnen Plain. Sci. Total Environ. **722**, 137428, **2020**.
6. PAUL S.C. Use of Fly Ash in Agriculture. In Sustainable Agriculture (pp. 319-334). Apple Academic Press. **2020**.
7. SIDDIPUI Z.A., KHAN M.R., AHAMAD L. Effects of fly ash on growth, productivity, and diseases of crop plants. Handbook of Fly Ash. **2022.**
8. Pandey V.C. Fly ash application in reclamation of degraded land: opportunities and challenges. **2020**.
9. HADAS E., MINGELGRIN U., FINE P. Economic cost–benefit analysis for the agricultural use of sewage sludge treated with lime and fly ash. Int. J. Coal Sci. Technol. **8**, 1099, **2020**.
10. YAO Z.T., JI X.S., SARKER P.K., TANG J.H., GE L.Q., XIA M.S., XI Y.Q. A comprehensive review on the applications of coal fly ash. Earth-Sci. Rev. **141**, 105, **2015**.
11. PANDEY V.C., BAJPAI O., SINGH N. Plant regeneration potential in fly ash ecosystem. Urban Forestry & Urban Greening. **15**, 40, **2016**.
12. USMAN M., ANASTOPOULOS I., HAMID Y., WAKEEL A. Recent trends in the use of fly ash for the adsorption of pollutants in contaminated wastewater and soils: Effects on soil quality and plant growth. Environ. Sci. Pollut. Res. **30** (60) 1, **2022**.
13. LASHARI M.S., YE Y., JI H., LI L., KIBUE G.W., LU H., PAN G. Biochar–manure compost in conjunction with pyroligneous solution alleviated salt stress and improved leaf bioactivity of maize in a saline soil from central China: a 2-year field experiment. J. Sci. Food Agric. **95** (6), 1321, **2015.**
14. ZHANG L., SUN X., TIAN Y., GONG X. Effects of brown sugar and calcium superphosphate on the secondary fermentation of green waste. Bioresour. Technol. **131**, 68, **2013**.
15. SOMERVILLE P.D., MAY P.B., LIVESLEY S.J. Effects of deep tillage and municipal green waste compost amendments on soil properties and tree growth in compacted urban soils. J. Environ. Manage. **227**, 365, **2018**.
16. LIU M., WANG C., LIU X., LU Y., WANG Y. Saline-alkali soil applied with vermicompost and humic acid fertilizer improved macroaggregate microstructure to enhance salt leaching and inhibit nitrogen losses. Applied Soil Ecology. **156**, 103705, **2020**.
17. ZHANG L., SUN X. Effects of earthworm casts and zeolite on the two-stage composting of green waste. Waste Management. **39**, 119, **2015**.
18. BAO S.D. Analysis of soil agrochemistry (*3rd edition*). Beijing, China: China Agriculture Press. 188, **2005**. [In Chinese]
19. WILCOX L. Classification and use of irrigation waters. US Department of Agriculture. 969, **1995**.
20. QUIJANO L., SIX J., NAVAS A., VAN OOST K. Effect of soil redistribution on soil aggregate stability and soil organic carbon in Mediterranean cultivated soils. In Geophysical Research Abstracts. **21**, 1, **2019**.
21. PANDA R.B., BISWAL T. Impact of fly ash on soil properties and productivity. International Journal of Agriculture, Environment and Biotechnology. **11** (2), 275, **2018**.
22. PARAB N., SINHA S., MISHRA S. Coal fly ash amendment in acidic field: Effect on soil microbial activity and onion yield. Applied Soil Ecology. **96**, 211, **2015**.
23. NAYAK A.K., RAJA R., RAO K.S., SHUKLA A.K., MOHANTY S., SHAHID M., TRIPATHI R., PANDA B.B., BHATTACHARYYA P., ANJANI KUMAR, LAL B., SETHI S.K., PURI C., NAYAK D., SWAIN C.K. Effect of fly ash application on soil microbial response and heavy metal accumulation in soil and rice plant. Ecotoxicol. Environ. Saf. **114**, 257, **2015**.
24. BARUS J. Utilization of crops residues as compost and biochar for improving soil physical properties and upland rice productivity. Journal of Degraded and Mining Lands Management. **3** (4), 631, **2016**.
25. SHAHEEN S.M., HOODA P.S., TSADILAS C.D. Opportunities and challenges in the use of coal fly ash for soil improvements – A review. J. Environ. Manage. **145**, 249, **2014**.
26. AMRHEIN C., HAGHNIA G.H., KIM T.S., MOSHER P.A., GAGAJENA R.C., AMANIOS T., DE LA Torre L. Synthesis and properties of zeolites from coal fly ash. Environ. Sci. Technol. **30** (3), 735, **1996**.
27. SINGER A., BERKGAUT V. Cation exchange properties of hydrothermally treated coal fly ash. Environ. Sci. Technol. **29** (7), 1748, **1995**.
28. DHINDSA H.S., SHARMA R.D., KUMAR R. Role of fly ash in improving soil physical properties and yield of wheat (Triticum aestivum). Agric. Sci. Dig. **36** (2), 97, **2016**.
29. Yadav V.K., PANDITA P.R. Fly ash properties and their applications as a soil ameliorant. In Amelioration Technology for Soil Sustainability pp. 59, IGI Global, **2019**.
30. AMJADI M., EMAMI H., FARAHANI E., GHOLOUBI A. Effect of Vermicompost and Urban Waste Compost on Stability of Soil Aggregates by High Energy Moisture

Characteristic Curve. Journal of Agricultural Science and Technology. **23** (6), 1379, **2021**.

31. GOLLAKOTA A.R. Transmutation of coal fly ash with conceivable applications. Journal of Innovative Technology. **2** (1), 35, **2020**.
32. BHATT A., PRIYADARSHINI S., MOHANAKRISHNAN A.A., ABRI A., SATTLER M., TECHAPAPHAWIT S. Physical, chemical, and geotechnical properties of coal fly ash: A global review. Case Studies in Construction Materials. **11**, e00263, **2019**.
33. EL-GALAD M.A., SAYED D.A., EL-SHAL R.M. Effect of humic acid and compost applied alone or in combination with sulphur on soil fertility and faba bean productivtiy under saline soil conditions. Journal of Soil Sciences and Agricultural Engineering. **4** (10), 1139, **2013**.
34. SHAHEEN S.M., HOODA P.S., TSADILAS C.D. Opportunities and challenges in the use of coal fly ash for soil improvements–a review. J. Environ. Manage. **145**, 249, **2014**.
35. ANTONKIEWICZ J., POPLAWSKA A., KOLODZIEJ B., CIARKOWSKA K., GAMBUS F., BRYK M., BABULA J. Application of ash and municipal sewage sludge as macronutrient sources in sustainable plant biomass production. J. Environ. Manage. **264**, 110450, **2020**.