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Combined Application of Desulfurization Gypsum and Biochar for Improving Saline-Alkali Soils: A Strategy to Improve Newly Reclaimed Cropland in Coastal Mudflats

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Abstract: This study investigated the effects of combined (mixed) application of desulfurization gypsum and biochar on crop growth and soil properties in the saline-alkali soils of coastal mudflats through indoor pot experiments and eight experimental ameliorant treatments. Among them, CK was the control of newly reclaimed cropland in the study area with no added ameliorator, treatment A was desulfurization gypsum applied alone, and treatment F was biochar applied alone, while treatments B, C, D, and E were set as a combination of desulfurization gypsum and biochar treatments with different ratios, and treatment G was a local multi-year improved farmland soil with no added ameliorator. Additionally, an evaluation index system was established for evaluating the saline-alkali soil improvement in the newly reclaimed cropland. Finally, the improvement effect was evaluated by assessing soil physical and chemical indicators, as well as nutrient and crop growth indicators. Based on the results, the following conclusions were drawn: (1) Desulfurization gypsum and biochar significantly improved the soil physicochemical properties. Both single and mixed application of desulfurization gypsum significantly increased soil Ca^{2+}, $SO_4{}^{2-}$, and Mg^{2+} contents and significantly reduced soil pH, sodium adsorption ratio, and bulk density. Both single and mixed application of biochar significantly reduced soil bulk density and significantly increased water-soluble K^+, field capacity (water-holding capacity), available phosphorus, available potassium, and organic matter contents. (2) Both single and mixed application of desulfurization gypsum and biochar demonstrated effectiveness in promoting crop growth, where the fresh weight, dry weight, plant height, and leaf area of peanut were higher than those of treatments CK and G. Treatment A (desulfurization gypsum 100 g/kg) was the most effective ameliorant treatment, in terms of improving the fresh and dry weight of peanut. Treatment C (desulfurization gypsum 75 g/kg, biochar 20 g/kg) had the most significant effect on peanut plant height and leaf area. (3) After 60 days of planting, the improvement effect of each treatment was ranked as C > A > E > B > D > F > G > CK. The treatments with a desulfurization gypsum–biochar combination and desulfurization gypsum alone had the best improvement effect, followed by the treatment with biochar alone.

Keywords: desulfurization gypsum; biochar; coastal mudflat; saline-alkali soil; TOPSIS

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1. Introduction

Coastal mudflat, also called the intertidal zone, is a tidal inundation zone present between high-tide and low-tide areas along the coast [1]. Coastal mudflats are an important part of the coastal zone and are generally distributed in a circular shape along the continental margin. Mudflats, also known as tidal flats, encompass a minimum area of 127,921 km^2

globally. Approximately 70% of the worldwide expanse of tidal flats is distributed across three continents, namely Asia (accounting for 44% of the total), North America (15.5% of the total), and South America (11% of the total). Notably, nearly half of this extent, amounting to 49.2%, is contained within eight specific countries: Indonesia, China, Australia, the United States, Canada, India, Brazil, and Myanmar [2]. Many countries have utilized mudflats as an important land resource. In the Netherlands, mudflats have been successfully reclaimed to develop cattle grazing and agriculture [3].

In China, coastal mudflats are extensively distributed in various regions. According to the data of the national comprehensive survey of coastal zone and sea coast resources, mudflats are distributed across 21,709 km^2, covering 11 coastal provinces and urban areas in four major sea areas, from the mouth of the Yalu River in Liaoning Province in the north to the mouth of the Beilun River in Guangxi Zhuang Autonomous Region in the south [4]. Coastal mudflats are also extensively distributed in coastal zones with sediment abundance. China's coastal mudflats provide silt of approximately 300 km^2 each year, and the total amount of mudflats is large [5]. Fujian province, located in the southeast coast of China, has more than 200,000 hectares of coastal mudflat resources, and the substrate composition of most of these mudflats mainly involves mud, silt, or sandy mud, which makes it feasible to develop and utilize these areas [6]. Mudflats, as a renewable resource, silt up by approximately 12 km^2 every year, providing a good material basis for enclosing tideland for cultivation. China has a large population, which over time has led to a shortage in arable land per capita. Owing to large-scale construction, a large amount of arable land has been utilized and occupied, and the quality of arable land is decreasing each year [7]. To protect the red line of 1.8 billion mu of arable land, it is highly important to effectively and rationally use mudflat resources to reclaim arable land. Coastal mudflats are continuously washed by seawater. Therefore, the retention of salt brought by seawater leads to a high salinity in the soil, low nutrient content, and poor physical structure, all of which hinder plant growth [8]. Although soils reclaimed from coastal mudflats can be completely desalinated through natural leaching and plant succession, the entire process is time consuming [9]. Coastal mudflats can be improved through physical improvement, hydraulic improvement, biological improvement, and chemical improvement. Physical improvement is a slow process, technological advances are slowly being upgraded, and the required space for development is limited. Hydraulic improvement requires extensive human effort and material, financial, and freshwater resources, and the P, Fe, Mn, and Zn present in the soil will also be washed away. Biological improvement has a long cycle time and a slow effect. By contrast, chemical ameliorants are widely used because of their flexible formulations, quick results, and convenient operation [10]. Therefore, carrying out detailed research on the improvement of newly reclaimed arable land in coastal mudflats can help improve the quality of arable land and food production, thus reducing the contradiction between economic and social development and arable land shortage.

Desulfurization gypsum is a product of flue-gas desulfurization of harmful gases produced during coal combustion in thermal power plants [11]. Since the 1990s, more attention has been paid to the improvement of saline-alkali soils by utilizing desulfurization gypsum [12]. Desulfurization gypsum can significantly increase Ca^{2+} and $SO_4{}^{2-}$ concentrations in saline-alkali soils [13]. The Ca^{2+} present in desulfurization gypsum can replace Na^+ in saline-alkali soils and convert the toxic compounds sodium carbonate and sodium bicarbonate salts to the less toxic neutral salt sodium sulfate [14]. Therefore, the use of desulfurization gypsum can provide essential nutrients such as calcium and sulfur to the soil; increase soil aggregate stability, electrical conductivity, soil water-holding capacity, and porosity; and promote the improvement of both acidic and alkaline soils [15–17].

Biochar is a carbon-rich, porous, and stable polycyclic aromatic hydrocarbon product formed by high-temperature pyrolysis of biomass organic matter such as straw and bamboo under anaerobic or anoxic conditions at a temperature below 700 °C [18]. The use of biochar can effectively improve the physical, chemical, and biological properties of saline soils; increase soil porosity and field water-holding capacity; enhance the calcium content of the soil; improve the effectiveness of nutrients such as nitrogen, phosphorus, and potassium for plants; and increase the survival rate of microorganisms and improve the growth environment of plants [19,20]. Biochar can also directly increase organic carbon content and promote cation exchange in the soil, thereby stabilizing soil structure [21]. The higher level of water-soluble potassium present in biochar [22] is considered one of the most important potential mechanisms through which biochar promotes the growth of salinity-affected plants [23,24]. To date, the use of chemical ameliorants to improve coastal reclaimed soils has gained increasing attention. Common chemical ameliorants include weathered coal, desulfurization gypsum, phosphogypsum, calcium superphosphate, humic acid, aluminum sulfate, iron sulfate, biochar, and various organic and inorganic fertilizers. However, most of the published studies have focused on the improvement effect using a single improver or a combination of improvers mixed in simple ratios. Additionally, only a few studies have focused on the improvement effect of combined desulfurization gypsum and biochar on the saline-alkali soils of coastal mudflats.

Currently, the improvement effect on saline-alkali soil is often evaluated based on single indicators such as nutrient content, alkalinity, and pH value. However, various factors influence the effect of soil improvement, and they should be considered when developing an arable land quality evaluation system. Ma Ruiming et al. [25] divided the indicators of arable land quality evaluation into four aspects: climatic conditions, land conditions, engineering conditions, and limiting factors. Zhao Xiaojuan et al. [26] divided the indicators of arable land quality evaluation into four aspects: soil physical and chemical properties, agricultural production conditions, location conditions, and soil environment. Zhang Chao et al. [27] divided the indicators of arable land quality evaluation into three aspects: topographic conditions, soil properties, and field utilization. Sun Xiaobing et al. [28] divided the indicators of arable land quality evaluation into six aspects: climatic conditions, topographic conditions, soil properties, utilization characteristics, tenure attributes, and infrastructure. Therefore, a single index cannot completely characterize the improvement effect. Different amounts of desulfurization gypsum and biochar may have different effects on the resulting improvement. To select a suitable proportioning scheme, a comprehensive evaluation of the improvement effect is needed.

To fill this research gap, the following hypotheses were made in this study: (1) Desulfurization gypsum and biochar can reduce soil pH, sodium adsorption ratio (SAR), and soil bulk density and increase field water-holding capacity and soil nutrient content; (2) the improvement effect of the combined application of desulfurization gypsum and biochar is better than that of desulfurization gypsum and biochar when applied alone, and the two components can act through synergistic effects. To test these hypotheses, in this study, the improvement effect of the combined application of desulfurization gypsum and biochar on saline-alkali soils and plant growth in coastal mudflats was evaluated through indoor pot experiments and eight different experimental treatments. Additionally, the improvement effect was assessed by measuring soil physical and chemical indicators, soil nutrient indicators, and crop growth indicators. Finally, an evaluation index system was established to perform a comprehensive evaluation of newly reclaimed cropland in coastal mudflats.

2. Materials and Methods

2.1. Overview of Study Area

Pingtan Island is located on the southeast coast of China, with the latitude position 25°15′–25°45′ N and longitude position 119°23′–120°10′ E. It is bounded by the Haitan Strait on the west side, near the provincial capital Fuzhou, and the Taiwan Strait on the east side, across the sea from Taiwan Province. Given that this island is located in the subtropics, the subtropical monsoon climate confers a distinctly maritime character to this region. Despite an annual precipitation of nearly 1000 mm, this region has an uneven distribution of precipitation and is often affected by droughts and tropical storms. This region experiences high winds (above a magnitude of 7) for 125 days in a year, which makes it an area with strong wind. The study area is located on the west side of Pingtan Island (Figure 1), which has been newly reclaimed from coastal mudflats in recent years. This area has a high degree of salinity and relatively poor fertility. The basic physicochemical properties of the soil in the study area are listed in Table 1.

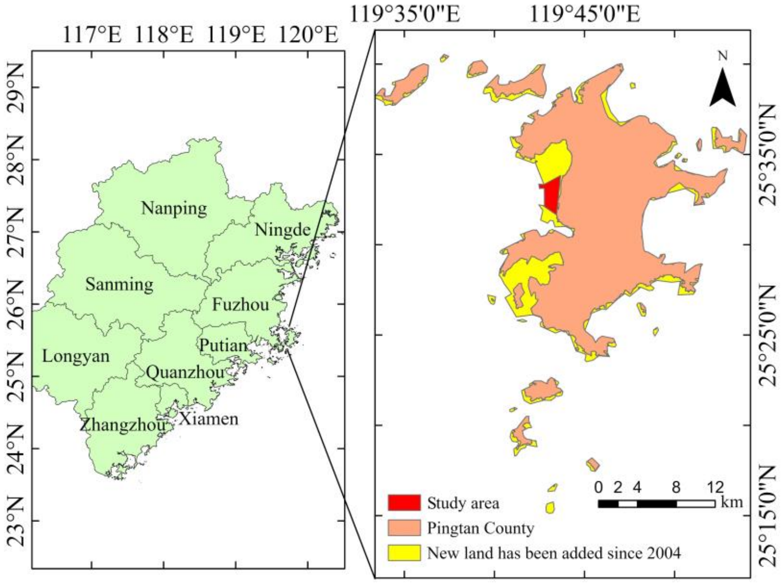


Figure 1. Geographical location of the study area.

Table 1. Basic physicochemical properties of the soil in the study area.

Alkali-Hydrolyzable Nitrogen (mg/kg)	Available Phosphorus (mg/kg)	Available Potassium (mg/kg)	Organic Matter (g/kg)	pH	Electrical Conductivity (µs/cm)	Bulk Density (g/cm^3)	Clay (%)	Silt (%)	Sand (%)
6.05	3.86	72.24	2.61	8.4	64.18	1.5	1.04	5.9	93.06

Note: Soil texture was classified according to the USDA system of textural classification.

2.2. Experimental Materials

The experimental materials used in this study were desulfurization gypsum and biochar, whose basic physicochemical properties are shown in Table 2. Desulfurization gypsum mainly comprises $CaSO_4 \cdot H_2O$, which has high levels of S, Ca, and other nutrients and contains 0.2% water. The biochar was made from bamboo by pyrolysis at 500 °C, with a pore size of 200 mesh. The test crop was peanut, and the variety was Baisha 1016.

Table 2. Basic physicochemical properties of the experimental materials.

Experimental Materials	pH	Electrical Conductivity (µs/cm)	Alkali-Hydrolyzable Nitrogen (mg/kg)	Available Phosphorus (mg/kg)	Available Potassium (mg/kg)
Desulfurization gypsum	7.69	1829	13.63	0.96	11.24
Biochar	9.43	569.4	7.91	199.43	623.5

2.3. Experimental Design

The experiment was conducted using the indoor pot test method in the laboratory of Fujian Agriculture and Forestry University. The pots measured 29 cm and 17.8 cm in diameter at the top and bottom, respectively, and were 19.5 cm tall; each pot was filled with 7 kg of soil. According to the literature [15,19], desulfurization gypsum application is optimal at around 5–8%, and biochar application is optimal at around 2–3%. The preliminary treatment scheme was obtained using an orthogonal experimental design, and then this was slightly adjusted according to the actual situation, and finally eight treatment groups were set up for the experiment (Table 3). CK was the control of newly reclaimed cropland in the study area with no added ameliorator, treatment A was desulfurization gypsum applied alone, and treatment F was biochar applied alone, treatments B, C, D, and E were set as a combination of desulfurization gypsum and biochar treatments with different ratios, and treatment G was a local multi-year improved farmland soil with no added ameliorator, in order to verify the amelioration effect. As the first step, desulfurization gypsum, biochar, and soil were mixed thoroughly. Then, intact, whole-grain peanut seeds were soaked overnight and then covered with wet towels for 2–3 days. Germinated peanut seeds were planted at a density of 2 seeds per hole (4 holes per pot) at a planting depth of 4 cm. Water was added to each experimental treatment once in the morning and once in the evening per day, to maintain the soil water content at approximately 70% of the field holding capacity. The sowing time started in late March 2021; thereafter, samples were collected every 20 days for a total of 3 times (i.e., seedling, flowering, and podding stages of peanut). Peanut plant growth and soil physicochemical properties were monitored. Soil bulk density and field water-holding capacity were determined by cutting-ring sampling after the third sampling was completed. Furthermore, moderately long peanuts were carefully dug out, with minimal damage to root whiskers. Subsequently, the soil surrounding the peanut samples was excavated to collect a soil sample, with half of the surface soil and half of the subsoil.

Table 3. Application amounts of desulfurization gypsum and biochar in the different treatment groups.

Ameliorant	**CK**	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Biochar (g/kg)	0	0	30	20	20	30	50	0
Desulfurization gypsum (g/kg)	0	100	75	75	50	50	0	0

2.4. Indicator Testing Methods

The collected soil samples were air dried and passed through a 2 mm sieve. Next, indicators of physical and chemical properties of the soil were determined, wherein organic matter was passed through a 0.149 mm sieve. Soil bulk density and field water-holding capacity were determined using the cutting-ring method [29]; pH was measured under a soil–water ratio of 1:5 using a pH meter; the water-soluble ions K^+, Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, and Cl^- were determined using ion chromatography, and the water-soluble ions CO_3^{2-} and HCO_3^- were determined through dual-indicator–neutralization titration [30]; alkali-hydrolyzable nitrogen was determined using the alkaline diffusion method; available phosphorus was determined using the $NaHCO_3$ leaching–molybdenum antimony anti-colorimetric method [31]; available potassium was determined using a NH_4OAc leaching-flame photometer [32]; organic matter was determined using the potassium dichromate volumetric method–outside heating method [33]. SAR refers to the relative amount of sodium ions and calcium and magnesium ions in irrigation water or soil solution [34] (Xu et al., 2022), which was calculated as follows:

$$\mathrm{SAR} = [\mathrm{Na}^+]/([\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}])^{1/2} \quad (1)$$

In the formula, $[Na^+]$, $[Ca^{2+}]$, and $[Mg^{2+}]$ are the concentrations of Na^+, Ca^{2+} and Mg^{2+} in soil solution, respectively. The units of these three ions are all mmol/L, while the unit of SAR is $(\mathrm{mmol/L})^{1/2}$.

A random sample of peanut plants was collected from each pot. Average values of the indicators of the same treatment were used. Plant height was determined using the straightedge method, wherein the distance from the part of the root exposed to the soil to the top of the crop before harvest was measured. Leaf area was determined using the weighing method, and the values were expressed as the ratio of leaf area to weight. Fresh weight was measured directly using an electronic balance. Dry weight was measured according to the drying method, wherein the green color was removed in an oven at 110 °C for 10 min and the leaves were dried at 80 °C to a constant weight [35].

The weighing method was performed as follows: Briefly, the known area S_1 of the paper blade was weighed (M_1, accurate to 0.0001 g). Then, the edge of the leaf was traced, after which it was fixed on the paper. The fixed leaf was cut out on the paper and then weighed (M_2, accurate to 0.0001 g). The leaf area S_2 was then calculated according to the following equation:

$$S\_2 = \backslash frac\{S\_1\backslash times\ M\_1\}\{M\_2\} \tag{2}$$

In addition, 10 representative leaf samples were cut out from the plant samples, and the length and width of each leaf sample was determined using the straightedge method. The leaf area was divided by the leaf length and width to calculate the length–width coefficient. Finally, the leaf area was derived from the leaf length and width.

2.5. Statistical Analysis

One-way analysis of variance was performed using R language. The least significant difference method was used to test the significant differences between treatments. Data visualization was achieved using OriginPro 2022 software.

2.6. Comprehensive Evaluation of the Improvement Effect of Newly Reclaimed Arable Land in Coastal Mudflats

Although no standard inclusion criteria exist for choosing arable land quality evaluation indicators, common features exist. Soil attributes form an essential part of evaluating the quality of arable land. The special nature of the newly reclaimed arable land in the coastal mudflats, which is influenced by the sea and has a high salt content, makes the evaluation of its improvement effect different from that in the general scenario. Additionally, the climatic and topographic conditions remain the same in each experimental plot. Therefore, the effects of climatic and topographic factors can be excluded, and the improvement effects on coastal mudflats are mainly influenced by the ameliorants. The effects of socioeconomic and locational factors were also not included. The newly reclaimed arable land in the coastal mudflats has high salinity. Therefore, this study established an evaluation system comprising physicochemical indicators, nutrient indicators, and biological indicators. Physicochemical indicators included Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, CO_3^{2-}, HCO_3^-, SO_4^{2-}, pH, SAR, field water-holding capacity, and soil bulk density. Nutrient indicators included alkali-hydrolyzable nitrogen, available phosphorus, available potassium, and organic matter. Biological indicators included fresh weight, dry weight, plant height, and leaf area. The specific indicators of the evaluation index system are presented in Table 4. The weight of each index was calculated using the entropy weight method.

Table 4. Evaluation index system of the newly reclaimed farmland in coastal mudflats.

Destination Layer	Criterion Layer	Index Layer	Unit	Weight
Improvement effect on coastal mudflats	Physicochemical indicators (0.3807)	Ca^{2+}	g/kg	0.0713
		Mg^{2+}	g/kg	0.0549
		Na^+	g/kg	0.0145
		K^+	g/kg	0.0512
		Cl^-	g/kg	0.0102
		CO_3^{2-}	g/kg	0
		HCO_3^-	g/kg	0.0214
		SO_4^{2-}	g/kg	0.0727
		pH	/	0.0347
		Sodium adsorption ratio	mmol/L	0.0094
		Field water-holding capacity	%	0.0213
		Bulk density	g/cm^3	0.0119

Table 4. *Cont.*

Destination Layer	Criterion Layer	Index Layer	Unit	Weight
	Nutrient indicators (0.2602)	Alkali-hydrolyzable nitrogen	mg/kg	0.1029
		Available phosphorus	mg/kg	0.0563
		Available potassium	mg/kg	0.0513
		Organic matter	g/kg	0.0496
	Growth indicators (0.3591)	Fresh weight	g	0.0852
		Dry weight	g	0.1103
		Plant height	cm	0.0554
		Leaf area	cm^2	0.1082

2.7. Technique of Order of Preference by Similarity to the Ideal Solution and Entropy Weight Model

The technique of order of preference by similarity to the ideal solution (TOPSIS) is a method for the comparative evaluation of multiple indicators and multiple solutions. This method determines the relative advantages and disadvantages of each evaluation object according to the degree of proximity or distance between the evaluation object and the positive or negative ideal solution. Therefore, it can objectively and comprehensively compare the differences in the advantages and disadvantages between different treatments of multiple indicators, to select the best treatment solution [36]. The entropy weight method is an analytical method used to determine the weights of different indicators based on the size of data information entropy. The entropy value can determine the degree of dispersion of a certain indicator, wherein a greater dispersion represents a greater effect and higher weight on the comprehensive assessment [37]. The entropy weight method not only can avoid the uncertainty caused by the artificial subjective determination of weights but also has strong objectivity, accuracy, and scientificity [38]. Therefore, this study combined the TOPSIS model and the entropy weight method to comprehensively evaluate the effect of saline-alkali soil improvement under different treatments. The specific operation steps were as follows:

(1) Nondimensionalization of raw index data

Some data are better when they are smaller, such as SAR, Na^+, Cl^-, $CO_3{}^{2-}$, and $HCO_3{}^-$. It is best when some parameters are closer to a specific value, such as pH. Therefore, these data underwent a forwarding treatment. In addition, minimal-type data were processed according to the following equation:

$${\widetilde{x}}_i = \max(x_i) - x_i \tag{3}$$

Intermediate-type data were processed according to the following equation:

$${\widetilde{x}}_i = 1 - \frac{|x_i - x_{best}|}{F} \tag{4}$$

where F is the absolute value of the difference between the best value of the indicator and the value farthest from the best value, which is calculated according to the following equation:

$$\mathrm{F} = \max\left\{|x_i - x_{best}|\right\} \tag{5}$$

As different data have different dimensionalities, the data were normalized according to the following equation for a comprehensive analysis:

$$z_{ij} = x_{ij}/\sqrt{\sum_{j=1}^{n}x_{ij}^2} \tag{6}$$

where x_{ij} is the jth treatment value of the saline-alkali soil improvement index C_i, and z_{ij} is the standardized value of x_{ij} (i = 1, 2,. . ., m, where m is the number of indicators, j = 1, 2,. . ., n, where n is the number of treatments).

(2) Calculation of information entropy

The entropy value of the *i*th indicator is calculated using the following equations:

$$e\_i = -(1/\mathrm{lnm})\backslash sum\_\{j = 1\}\hat{}\{n\}y\_\{ij\}\ln\{(y\}\_\{ij\}) \tag{7}$$

$$y\_\{ij\} = z\_\{ij\}/\backslash sum\_\{j = 1\}\hat{}\{n\}z\_\{ij\} \tag{8}$$

(3) Calculation of the entropy weight of each indicator

$$W\_i = 1 - e_i/\sum_{i=1}^{m} 1 - e_i \tag{9}$$

(4) Vectors of optimal and worst values of each indicator

$$\{\mathrm{N+}\} = \{max z_{ij}|i = 1,\ 2,\cdots,m\} \tag{10}$$

$$\hat{N}- = \{min z_{ij}|i = 1,\ 2,\cdots,m\} \tag{11}$$

(5) Calculation of weighted Euclidean distance

The distances D^+ (from the treatment value to the optimal value vector) and D^- (from the treatment value to the worst value vector) were calculated for each treatment according to the following equations:

$$D\_\hat{j}+ = \backslash sqrt\{\backslash sum\_\{i = 1\}\hat{}\{m\}\{(\{W\_i(N\}\_\hat{i}+ -N\_i))\}\hat{}2\} \tag{12}$$

$$D\_\hat{j}- = \backslash sqrt\{\backslash sum\_\{i = 1\}\hat{}\{m\}\{(W\_i\{(N\}\_\hat{i}- -N\_i))\}\hat{}2\} \tag{13}$$

(6) Calculation of the conjoint ratio C_i

$$C\_i = \backslash frac\{D\_\hat{j}-\}\{D\_\hat{j}- +D\_\hat{j}+\} \tag{14}$$

The C_i value is between 0 and 1. A C_i value closer to 1 indicates a closer distance to the optimal solution and a better evaluation effect. Conversely, a C_i value closer to 0 indicates a closer distance to the worst solution and a worse evaluation effect [39,40]. The specific evaluation criteria are presented in Table 5.

Table 5. Specific evaluation criteria for the improvement effect of newly reclaimed arable land in coastal mudflats.

Conjoint Ratio	Comprehensive Improvement Level
0~0.3	Poor
>0.3~0.6	Moderate
>0.6~0.8	Good
>0.8~1	Excellent

3. Results

3.1. Effect of Desulfurization Gypsum and Biochar on Soil pH and SAR

SAR is an important indicator of the degree of soil alkalinization. SAR is easier to measure than exchangeable sodium percentage. Significant differences in soil SAR were observed across the different treatment groups (Figure 2). The SARs in the control treatment CK, treatment F with biochar alone, and control farmland treatment G were significantly higher than those under treatments where desulfurization gypsum was added. Treatment B with desulfurization gypsum application alone produced the lowest SAR. Additionally, biochar application alone had no significant effect on SAR. Therefore, SAR decreased when desulfurization gypsum was added.

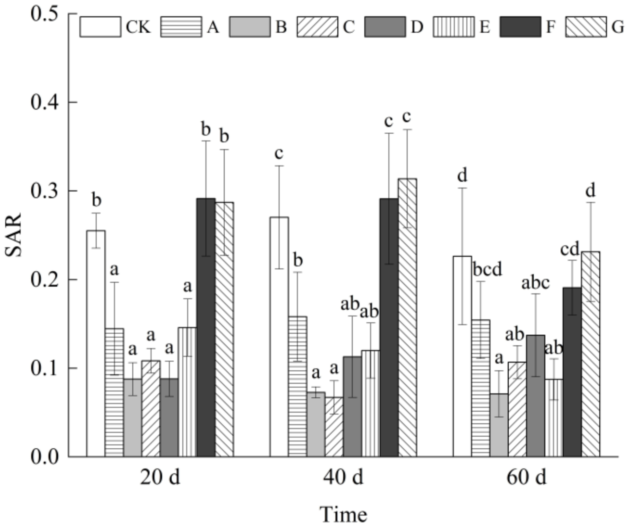


Figure 2. Effect of different treatments on the SAR of saline-alkali soils. Note: Values shown are the mean of all replicate treatments, and the error bar indicates standard deviation. Different lowercase letters indicate significant differences in indicators among the different treatments ($p < 0.05$).

Soil pH reduced when desulfurization gypsum was added to the different treatment groups (Figure 3). After 60 days of planting, the soil pH under treatments A, B, C, D, and E was 7.66, 7.71, 7.67, 7.67, and 7.68, respectively, which were significantly lower by 6.59%, 5.93%, 6.42%, 6.46%, and 6.3%, respectively, than treatment CK, and closer to the pH for normal plant growth. However, no significant difference was observed in the pH among the different treatment groups at the three periods when desulfurization gypsum was added. Moreover, no significant difference in pH existed between treatment F and treatment CK. Therefore, soil pH decreased when desulfurization gypsum was applied, and biochar application alone did not exert any significant effect on soil pH. Significant differences were observed between treatment G and the other treatments, demonstrating a higher pH than that under the treatment with desulfurization gypsum addition and a lower pH than that under treatment CK and treatment F.

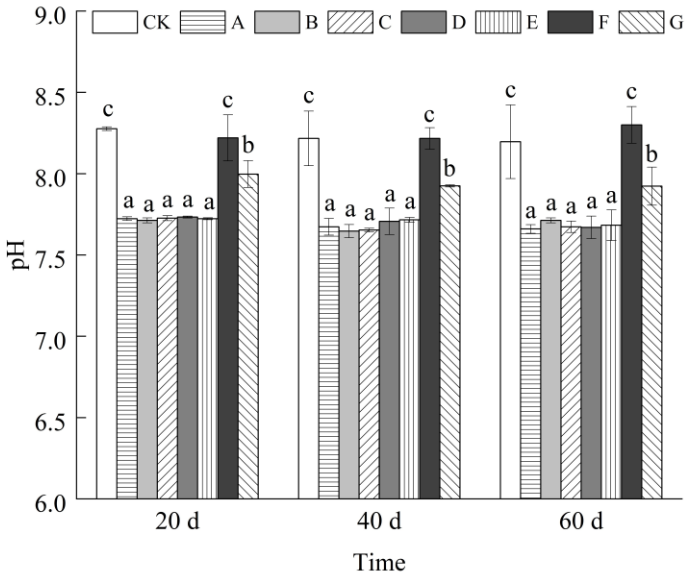
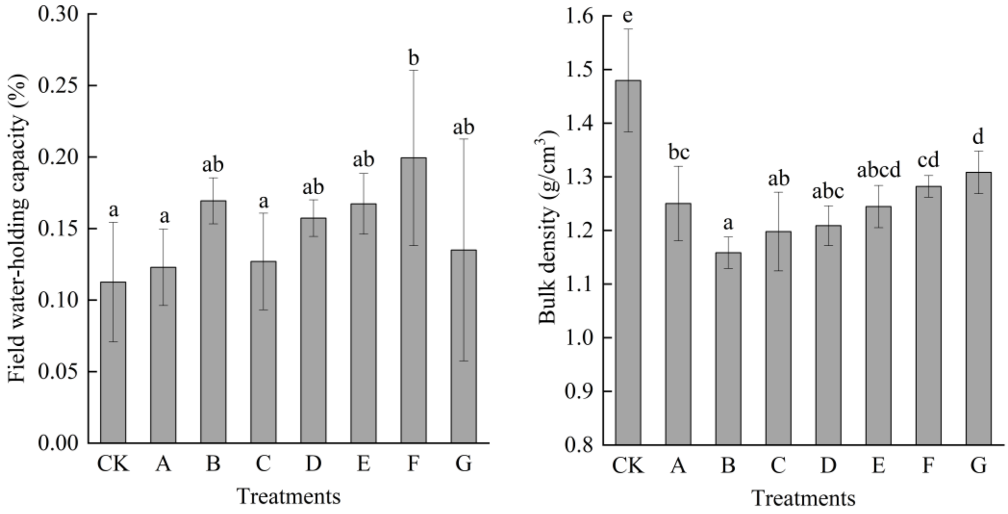


Figure 3. Effect of the different treatments on the pH of saline-alkali soils. Note: Values shown are the mean of all replicate treatments, and the error bar indicates the standard deviation. Different lowercase letters indicate significant differences in indicators among the different treatments ($p < 0.05$).

3.2. Effect of Desulfurization Gypsum and Biochar on Field Water-Holding Capacity and Soil Bulk Density

Treatments A, B, C, D, E, and F with different ameliorants increased the field water-holding capacity by 9.22%, 50.51%, 12.82%, 39.74%, 48.64%, and 77.19%, respectively. Treatment F demonstrated the most significant increase in field water-holding capacity, and the order of different treatments in terms of field water-holding capacity was F > B > E > D > G > C > A > CK. Field water-holding capacity increased as the biochar application increased, wherein biochar played a predominant role in the increase in field water-holding capacity. Additionally, desulfurization gypsum also exerted a small effect on field water-holding capacity. Treatments B, D, E, and F with biochar addition led to a higher field water-holding capacity than treatment G with multi-year improved farmland. The increase in field water-holding capacity increased the soil moisture, diluted salinity, and reduced the salt content and alkali pressure, which, in turn, improved the soil physical properties and plant growth environment (Figure 4a).



(a)

(b)

Figure 4. Effect of different treatments on field water-holding capacity and bulk density of saline-alkali soils. (**a**) Field water-holding capacity; (**b**) Bulk density. Note: Values shown are the mean of all replicate treatments, and the error bar indicates standard deviation. Different lowercase letters indicate significant differences in indicators among the different treatments ($p < 0.05$).

All treatments in which different ameliorants were added had a significantly reduced soil bulk density. Compared with treatment CK, treatments A, B, C, D, E, F, and G exhibited reductions in soil bulk density of 18.3%, 27.7%, 23.5%, 22.4%, 18.9%, 15.4%, and 13.1%, respectively. The most significant reduction was observed under treatment B, where the soil bulk density had reduced to 1.16 g/cm^3, which was 0.32 g/cm^3 lower than that under treatment CK. The soil bulk density in all treatment groups with the ameliorant was lower than that of treatment G (the multi-year improved agricultural soil), indicating that the soil bulk density in all treatments had reached the normal range. The reduction in soil bulk density was more significant with the combination of desulfurization gypsum and biochar than with desulfurization gypsum alone or biochar alone. The reduction in soil bulk density increased the soil porosity, maintained air and water circulation, and further improved the soil structure (Figure 4b).

3.3. Effect of Desulfurization Gypsum and Biochar on Water-Soluble Ions in the Soil

The effects of adding desulfurization gypsum and biochar on the different water-soluble ions present in the soil varied (Table 6). The total salt content of the treatments with desulphurization gypsum was significantly increased, and the total salt content of the treatments with biochar was increased to a certain extent, but there was no significant difference compared with CK.

Table 6. Content of water-soluble ions in saline-alkali soils in the different treatments g/kg.

Treatment	**Time (days)**	**Na^+**	**K^+**	**Mg^{2+}**	**Ca^{2+}**	**HCO_3^-**	**CO_3^{2-}**	**SO_4^{2-}**	**Cl^-**
CK	20	$0.06 + 0.009\ ^{ab}$	$0.065 + 0.011\ ^{a}$	$0.052 + 0.009\ ^{a}$	$0.09 + 0.017\ ^{a}$	$0.277 + 0.097\ ^{bc}$	0	$0.118 + 0.035\ ^{a}$	$0.21 + 0.128\ ^{b}$
A		$0.174 + 0.066\ ^{d}$	$0.11 + 0.017\ ^{a}$	$0.344 + 0.057\ ^{c}$	$2.797 + 0.147\ ^{b}$	$0.185 + 0.022\ ^{a}$	0	$4.624 + 0.523\ ^{b}$	$0.062 + 0.098\ ^{a}$
B		$0.114 + 0.021\ ^{c}$	$0.813 + 0.147\ ^{de}$	$0.265 + 0.097\ ^{b}$	$2.693 + 0.233\ ^{b}$	$0.241 + 0.084\ ^{abc}$	0	$4.564 + 0.64\ ^{b}$	$0.043 + 0.022\ ^{a}$
C		$0.118 + 0.032\ ^{c}$	$0.409 + 0.065\ ^{b}$	$0.205 + 0.038\ ^{b}$	$2.761 + 0.118\ ^{b}$	$0.181 + 0.024\ ^{a}$	0	$4.858 + 0.281\ ^{bc}$	$0.058 + 0.044\ ^{a}$
D		$0.107 + 0.014\ ^{bc}$	$0.614 + 0.116\ ^{c}$	$0.263 + 0.04\ ^{b}$	$2.622 + 0.42\ ^{b}$	$0.19 + 0.021\ ^{ab}$	0	$5.256 + 0.135\ ^{c}$	$0.047 + 0.035\ ^{a}$
E		$0.097 + 0.016\ ^{abc}$	$0.937 + 0.168\ ^{e}$	$0.228 + 0.036\ ^{b}$	$2.628 + 0.382\ ^{b}$	$0.185 + 0.005\ ^{ab}$	0	$5.368 + 0.021\ ^{c}$	$0.05 + 0.003\ ^{a}$
F		$0.036 + 0.02\ ^{a}$	$0.657 + 0.148\ ^{cd}$	$0.051 + 0.01\ ^{a}$	$0.094 + 0.016\ ^{a}$	$0.33 + 0.097\ ^{c}$	0	$0.163 + 0.034\ ^{a}$	$0.014 + 0.002\ ^{c}$
G		$0.056 + 0.007\ ^{ab}$	$0.204 + 0.041\ ^{a}$	$0.063 + 0.031\ ^{a}$	$0.115 + 0.044\ ^{a}$	$0.226 + 0.065\ ^{abc}$	0	$0.121 + 0.023\ ^{a}$	$0.003 + 0.006\ ^{a}$
CK	40	$0.08 + 0.028\ ^{a}$	$0.06 + 0.013\ ^{a}$	$0.05 + 0.013\ ^{a}$	$0.117 + 0.062\ ^{a}$	$0.271 + 0.079\ ^{b}$	0	$0.124 + 0.054\ ^{a}$	$0.156 + 0.066\ ^{b}$
A		$0.166 + 0.064\ ^{a}$	$0.1 + 0.014\ ^{a}$	$0.297 + 0.06\ ^{c}$	$2.931 + 0.012\ ^{b}$	$0.245 + 0.053\ ^{ab}$	0	$4.21 + 0.468\ ^{b}$	$0.075 + 0.06\ ^{a}$
B		$0.083 + 0.019\ ^{a}$	$0.571 + 0.222\ ^{cd}$	$0.159 + 0.062\ ^{b}$	$2.851 + 0.017\ ^{b}$	$0.2 + 0.013\ ^{ab}$	0	$5.264 + 0.175\ ^{b}$	$0.043 + 0.058\ ^{a}$
C		$0.079 + 0.022\ ^{a}$	$0.423 + 0.188\ ^{bc}$	$0.127 + 0.069\ ^{ab}$	$2.185 + 0.414\ ^{b}$	$0.235 + 0.098\ ^{ab}$	0	$5.232 + 0.23\ ^{b}$	$0.041 + 0.07\ ^{a}$
D		$0.102 + 0.006\ ^{a}$	$0.495 + 0.118\ ^{bc}$	$0.194 + 0.051\ ^{b}$	$2.643 + 0.216\ ^{b}$	$0.196 + 0.028\ ^{ab}$	0	$4.949 + 0.304\ ^{b}$	$0.026 + 0.011\ ^{a}$
E		$0.162 + 0.05\ ^{a}$	$0.891 + 0.342\ ^{e}$	$0.194 + 0.075\ ^{b}$	$2.657 + 0.267\ ^{b}$	$0.196 + 0.042\ ^{ab}$	0	$4.914 + 0.421\ ^{b}$	$0.069 + 0.051\ ^{a}$
F		$0.138 + 0.129\ ^{a}$	$0.751 + 0.132\ ^{de}$	$0.105 + 0.12\ ^{ab}$	$0.097 + 0.024\ ^{b}$	$0.267 + 0.055\ ^{b}$	0	$0.195 + 0.056\ ^{a}$	$0.016 + 0.001\ ^{a}$
G		$0.101 + 0.016\ ^{a}$	$0.227 + 0.003\ ^{ab}$	$0.044 + 0.003\ ^{a}$	$0.111 + 0.034\ ^{b}$	$0.159 + 0.037\ ^{a}$	0	$0.104 + 0.036\ ^{a}$	$0.002 + 0.003\ ^{a}$
CK	60	$0.056 + 0.014\ ^{a}$	$0.045 + 0.014\ ^{a}$	$0.047 + 0.019\ ^{a}$	$0.144 + 0.104\ ^{a}$	$0.266 + 0.029\ ^{a}$	0	$0.248 + 0.184\ ^{a}$	$0.131 + 0.062\ ^{c}$
A		$0.167 + 0.108\ ^{b}$	$0.084 + 0.032\ ^{a}$	$0.369 + 0.18\ ^{c}$	$2.805 + 0.068\ ^{c}$	$0.198 + 0.058\ ^{a}$	0	$4.434 + 0.556\ ^{b}$	$0.033 + 0.008\ ^{b}$
B		$0.097 + 0.049\ ^{a}$	0.514 + 0.154 bc	$0.116 + 0.033\ ^{ab}$	$2.589 + 0.171\ ^{bc}$	$0.196 + 0.026\ ^{a}$	0	$4.926 + 0.731\ ^{b}$	$0.014 + 0.023\ ^{ab}$
C		$0.089 + 0.022\ ^{a}$	$0.276 + 0.1\ ^{ab}$	$0.114 + 0.047\ ^{ab}$	$2.138 + 0.711\ ^{b}$	$0.216 + 0.043\ ^{ab}$	0	$4.966 + 0.377\ ^{b}$	$0.029 + 0.01\ ^{ab}$
D		$0.172 + 0.053\ ^{b}$	$0.628 + 0.314\ ^{c}$	$0.225 + 0.11\ ^{b}$	$2.701 + 0.247\ ^{c}$	$0.21 + 0.014\ ^{a}$	0	$4.99 + 0.567\ ^{b}$	$0.049 + 0.015\ ^{b}$
E		$0.114 + 0.073\ ^{a}$	$0.712 + 0.286\ ^{c}$	$0.149 + 0.069\ ^{ab}$	$2.542 + 0.352\ ^{bc}$	$0.2 + 0.06\ ^{a}$	0	$4.284 + 1.155\ ^{b}$	$0.033 + 0.023\ ^{b}$
F		$0.1 + 0.077\ ^{a}$	$0.508 + 0.265\ ^{bc}$	$0.171 + 0.122\ ^{ab}$	$0.105 + 0.019\ ^{a}$	$0.278 + 0.041\ ^{b}$	0	$0.206 + 0.011\ ^{a}$	$0.009 + 0.005\ ^{a}$
G		$0.047 + 0.003\ ^{a}$	$0.159 + 0.033\ ^{ab}$	$0.02 + 0.01\ ^{a}$	$0.066 + 0.042\ ^{a}$	$0.162 + 0.007\ ^{a}$	0	$0.114 + 0.077\ ^{a}$	$0.004 + 0.005\ ^{a}$

Note: Values shown are the mean and standard deviation of all replicate treatments. Different lowercase letters indicate significant differences in indicators among the different treatments ($p < 0.05$).

After 20 days of improvement, the Ca^{2+}, SO4^{2-}, and Mg^{2+} contents significantly increased in the treatments with added desulfurization gypsum. Additionally, the Ca^{2+}, SO4^{2-}, and Mg^{2+} contents were elevated by 29.2–31.2-fold, 38.6–45.3-fold, and 3.9–6.6-fold, respectively, when compared with those under treatment CK. However, the HCO3^{2-} content decreased by 12.9–34.8% when compared with treatment CK, with no significant difference. The Na^+ content increased by 60–188% when compared with that under treatment CK. Compared with treatment CK, biochar alone and combined application had a significant elevating effect on the soil K^+ content (6.1–15.8 times). The biochar content of treatments B and E with combined application was lower than that of treatment F with biochar alone, whereas the K^+ content was 23.7% to 42.6% greater than that of treatment F. Additionally, the Cl^- content was significantly reduced by 70.4–98.4% in the different treatment groups when compared with that under treatment CK.

After 40 days of improvement, the Ca^{2+}, SO_4^{2-}, and Mg^{2+} contents in the treatment soil with added desulfurization gypsum remained at high levels. The Ca^{2+}, SO_4^{2-}, and Mg^{2+} contents increased by 18.6–25-fold, 34–42.5-fold, and 96–27.6-fold, respectively, when compared with treatment CK. However, the HCO_3^{2-} content decreased by 9.6–27.6% when compared with that under treatment CK, with no significant difference. The Na^+ content was elevated by −2% to 106% when compared with treatment CK, with no significant difference. The soil K^+ contents under the treatments with biochar alone and combination application were still significantly elevated, being 7–14.8 times higher than that under treatment CK. Treatment E with combined application contained less biochar than treatment F with only biochar, but its K^+ content was 18.6% higher than that of treatment F. The Cl^- content was significantly reduced by 52.1–98.4% under the different treatments when compared with treatment CK.

After 60 days of improvement, the Ca^{2+}, SO_4^{2-}, and Mg^{2+} contents in the soil with added desulfurization gypsum were at high levels. The Ca^{2+}, SO_4^{2-}, and Mg^{2+} contents increased by 14.8–19.4-fold, 17.2–20.1-fold, and 2.4–7.8-fold, respectively, when compared with those under treatment CK. However, the HCO_3^{2-} content decreased by 18.8–26.3% compared with that under treatment CK, with no significant difference. The Na^+ content increased by 58.7–206.4% when compared with that under treatment CK, with no significant difference. The K^+ content in soil treated with biochar alone and the combination was found to show significant increases, being 6.1–15.8 times higher than that under treatment CK. Treatments D and E with combined application had less biochar than treatment F with biochar alone, but their K^+ content was 23.6% to 40.2% higher than that of treatment F. The Cl^- content was significantly reduced by 62.9–97.2% in the different treatment groups when compared with treatment CK.

3.4. Effect of Desulfurization Gypsum and Biochar on Soil Nutrient Indicators

The soil alkali-hydrolyzable nitrogen content in the desulfurization gypsum and biochar application treatments exhibited a decreasing trend (Figure 5a). After 60 days of planting, the soil alkali-hydrolyzable nitrogen content under treatments A, B, C, D, E, and F with ameliorants was lower than that of treatment CK by 3.01%, 18.85%, 28.14%, 27.6%, 34.7%, and 15.03%, respectively. Among them, treatments B, C, D, and E led to a significantly lower alkali-hydrolyzable nitrogen content. The alkali-hydrolyzable nitrogen content in multi-year improved farmland treatment G was 158.72% higher than that under treatment CK and significantly higher than that in the other treatments with ameliorants. The application of desulfurization gypsum and biochar did not increase the soil alkali-hydrolyzable nitrogen content and had a counter effect. According to the reference [41], the alkali-hydrolyzable nitrogen content in all treatments was at a very low level.

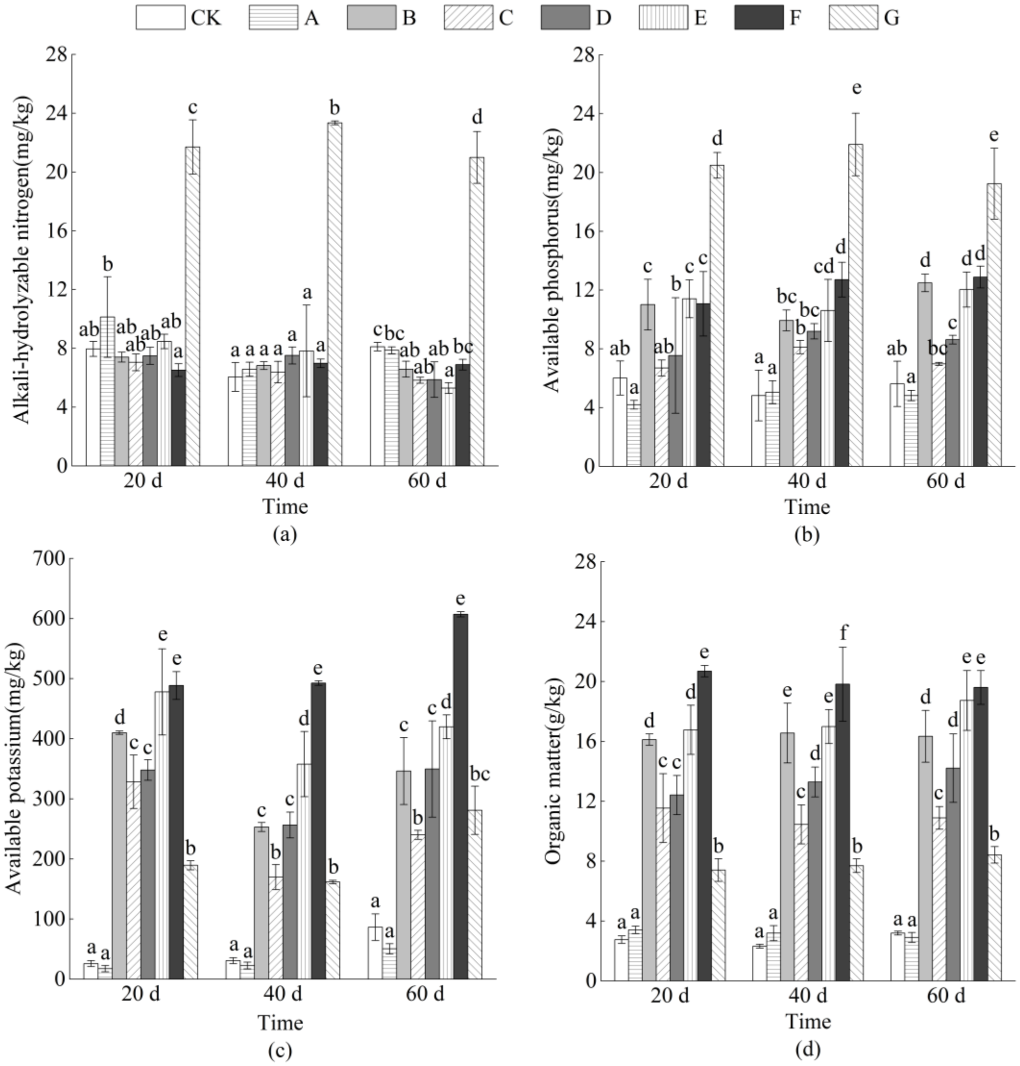


Figure 5. Effect of the different treatments on nutrient indicators in saline-alkali soils. (**a**) Alkali-hydrolyzable nitrogen; (**b**) Available phosphorus; (**c**) Available potassium; (**d**) Organic matter. Note: Values shown are the mean of all replicate treatments, and the error bar indicates the standard deviation. Different lowercase letters indicate significant differences in indicators among the different treatments ($p < 0.05$).

Significant differences were observed in the soil available phosphorus content among the treatments (Figure 5b). After 60 days of planting, when compared with treatment CK, treatments B, C, D, E, and F with biochar alone and the combination showed increased soil available phosphorus contents of 103.78%, 20.58%, 45.45%, 96.92%, and 109.79%, respectively. Among them, treatment F, where biochar was applied alone, led to the highest soil available phosphorus content. Treatment C with the least amount of biochar application led to the lowest increase in soil available phosphorus content, whereas treatment A with desulfurization gypsum application alone reduced the soil available phosphorus content. The soil available phosphorus content in the different treatment groups did not change much as time progressed, among which the soil available phosphorus content under treatments B, D, E, and F exhibited an increasing trend. The soil available phosphorus content increased with biochar application in each treatment, whereas the application of desulfurization gypsum reduced the soil available phosphorus content. Although a significant difference was noted in the soil available phosphorus content in each treatment when compared with the multi-year improved farmland treatment G; they reached the medium and upper-medium content standards according to the reference [41].

Significant differences were observed in the soil available potassium content in the different treatment groups (Figure 5c). After 60 days of planting, the soil available potassium content under treatment A with desulfurization gypsum alone was decreased by 41.61% when compared with that under treatment CK. However, treatments B, C, D, E, F, and G showed significantly increased soil available potassium contents when compared with treatment CK of 300.68%, 177.76%, 304.46%, 385.78%, 602.31%, and 225.31%, respectively, with the largest and smallest increases seen under treatment F and treatment C, respectively. According to the reference [41], soil available potassium contents under treatments B, D, E, and F with biochar alone and combination application exceeded that under treatment G of multi-year improved farmland, reaching the very-high content standard. The soil available potassium contents under biochar-added treatments B, C, D, E, and F exhibited a trend of decrease and then increase with the progression of time, whereas the other treatments, namely, CK, A, and G, also led to a small increase in the soil available potassium content. Therefore, the available potassium content in the soil increased as the biochar amount increased, while the addition of desulfurization gypsum reduced the available potassium content in the soil.

Significant differences were observed in the soil organic matter content among the treatments (Figure 5d). After 60 days of planting, soil organic matter content significantly increased in all treatments when compared with that under treatment CK, except treatment A, where the soil organic matter content was reduced by 9.09%. Treatments B, C, D, E, F, and G produced 16.34, 10.89, 15.03, 18.73, 19.60, and 8.42 g/kg of soil organic matter, respectively, increasing by 441.36%, 240.91%, 370.45%, 486.36%, 513.64%, and 163.64%, respectively. Among the treatments, the greatest increase in soil organic matter content was observed under treatment F. The soil organic matter content under treatments with biochar addition exceeded that of the multi-year improved farmland treatment G. No significant change was observed in the soil organic matter content in the different treatments as time progressed. Therefore, biochar application increased the soil organic matter content, whereas desulfurization gypsum application reduced the soil organic matter content. According to the reference [41], the organic matter contents of the biochar-treated soils reached the medium content standard. However, the organic matter content under control treatment CK was of a very low standard.

3.5. Effect of Desulfurization Gypsum and Biochar on Peanut Growth

Significant differences were observed in the fresh weight of peanut among the different treatments (Figure 6a). After 60 days of planting, treatments A, B, C, D, E, and F had a significantly increased fresh weight of peanut when compared with treatment CK, with increases ranging from 50.75% to 152.5%. Among these treatments, treatment A with desulphurization gypsum alone and treatment C with combined application of desulphurization gypsum and biochar demonstrated the highest increase in fresh weight, reaching 10.17 g and 9.17 g, respectively. Treatment F with biochar alone showed the lowest increase in fresh weight and was not significantly different from treatment CK, while treatment G led to a 40.75% decrease in fresh weight when compared with treatment CK. The fresh weight significantly increased in all treatment groups as time progressed. At 20 days of planting, no significant difference existed in the fresh weight among all treatments with ameliorant, but the difference started to become significant after 40 days of planting. Additionally, the fresh weight of peanut increased with the increase in desulphurization gypsum application among the different treatment groups.

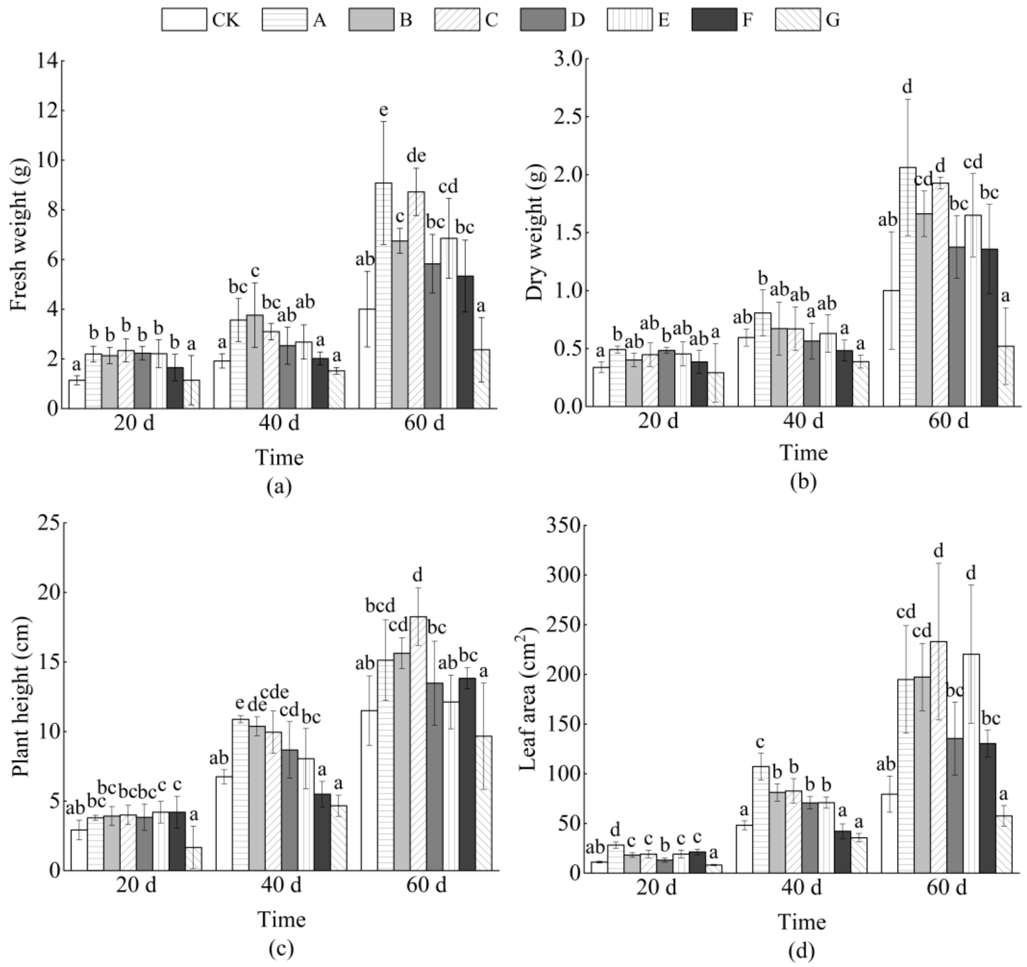


Figure 6. Effect of different treatments on peanut growth in saline-alkali soils. (**a**) Fresh weight; (**b**) Dry weight; (**c**) Plant height; (**d**) Leaf area. Note: Values shown are the mean of all replicate treatments, and the error bar indicates the standard deviation. Different lowercase letters indicate significant differences in indicators among different treatments ($p < 0.05$).

The dry weight of peanut in the different treatment groups increased significantly when compared with that of the CK group (Figure 6b). After 60 days of planting, the increase in dry weight in the different treatment groups ranged from 44% to 130%, with the most significant increase being noted under treatment A. Treatments B, C, and E also demonstrated significant increases, whereas treatments D and F showed a smaller increase in dry weight, and treatment G with multi-year improved farmland soil demonstrated a 48% lower dry weight than treatment CK. The change in dry weight with time in each treatment group was similar to that for the fresh weight. Significant differences began to occur among the treatment groups after 40 days of planting, with treatments A and C demonstrating the greatest increase in dry weight and treatments D and F demonstrating the lowest increase in dry weight.

The plant height of peanut also differed significantly across the different treatment groups (Figure 6c). At 40 days of planting, plant height increased with the increase in desulfurization gypsum application in the different treatment groups. However, after 60 days of planting, the plant height gradually reduced under treatment A with desulfurization gypsum alone, and the plant height under treatments B and C with a combination of desulfurization gypsum and biochar surpassed that under treatment A. Plant height under treatment C reached 18.25 cm, which was 58.7% higher than that under treatment CK. Moreover, the plant height under treatment F with biochar alone had a tendency to increase later. Compared with treatment CK, treatments D, E, and F led to an insignificant increase in plant height, ranging from 3.48% to 22.61%. Additionally, treatment G demonstrated a 15.91% decrease in plant height when compared with treatment CK. The plant height increased with time under all treatments.

The variation in peanut leaf area among the different treatments at different periods was highly significant (Figure 6d). At 20–40 days of planting, treatment A with desulfurization gypsum alone led to a larger leaf area than all other treatments. However, after 60 days of planting, the leaf area growth under treatment A with desulfurization gypsum alone slowed down, and the leaf area under treatments B, C, and E with desulfurization gypsum and biochar combination exceeded that under treatment A, with treatment C producing the largest leaf area growth (233 cm^2). After 60 days of planting, compared with treatment CK, peanut leaf area in the different treatment groups with different application rates showed a significant increase, ranging from 127.7% to 291.6%, with the largest and smallest increases being under treatments C and D, respectively. The peanut leaf area under treatments A, B, C, and E reached significant levels. Treatment G led to a 27.3% reduction in leaf area when compared with treatment CK.

3.6. Optimization of the Combined Improvement Effect of Desulfurization Gypsum and Biochar

The improvement effect of the newly reclaimed cropland in coastal mudflats in the different treatments was calculated according to the TOPSIS-entropy weight method, and all treatments effectively improved cropland quality (Table 7).

Table 7. Comprehensive evaluation of the indoor improvement effect of newly reclaimed arable land in coastal mudflats.

Treatment	Time (Days)	D_i^+	D_i^-	C_i	Rank
CK	20	0.114	0.008	0.066	8
A		0.100	0.036	0.267	6
B		0.100	0.042	0.297	2
C		0.098	0.037	0.276	4
D		0.099	0.037	0.272	5
E		0.095	0.045	0.322	1
F		0.104	0.029	0.217	7
G		0.106	0.041	0.279	3
CK	40	0.108	0.013	0.105	8
A		0.087	0.047	0.352	2
B		0.082	0.050	0.379	1
C		0.091	0.041	0.312	4
D		0.092	0.040	0.304	5
E		0.090	0.041	0.315	3
F		0.106	0.032	0.232	7
G		0.107	0.044	0.291	6
CK	60	0.098	0.024	0.199	8
A		0.053	0.095	0.645	2
B		0.053	0.076	0.588	4
C		0.047	0.094	0.664	1
D		0.069	0.058	0.456	5
E		0.053	0.082	0.607	3
F		0.075	0.051	0.404	6
G		0.108	0.031	0.221	7

According to the conjoint ratio, the ranking of the improvement effect after 20 days of planting was E (0.322) > B (0.297) > G (0.279) > C (0.276) > D (0.272) > A (0.267) > F (0.217) > CK (0.066). Treatment with ameliorants was better than treatment CK, and the scores under all treatments were significantly higher than those under treatment CK and similar to the score in treatment G. Combined treatment with desulfurization gypsum and biochar was better than treatments with desulfurization gypsum and biochar alone. Additionally, the improvement effect under treatment A with desulfurization gypsum alone was better than that under treatment F with biochar alone. Although the effect in each treatment was better than that in treatment CK, the improvement effect was poor, except for treatment E (Table 5).

The ranking of the improvement effect after 40 days of planting was B (0.379) > A (0.352) > E (0.315) > C (0.312) > D (0.304) > G (0.291) > F (0.232) > CK (0.105). Treatments with ameliorants scored significantly higher than treatment CK, and most of the scores were higher than that of treatment G. Combined treatments with desulfurization gypsum and biochar were better than treatment with biochar alone but not significantly different from desulfurization gypsum alone. The effect of treatment with desulfurization gypsum alone was better than treatment with biochar alone. In addition, the effect of most of the treatments improved, with treatments A, B, C, D, and E producing a conjoint ratio of more than 0.3, thereby reaching a medium level (Table 5).

The ranking of improvement effect after 60 days of planting was C (0.664) > A (0.645) > E (0.607) > B (0.588) > D (0.456) > F (0.404) > G (0.221) > CK (0.199). Treatments with ameliorants scored significantly higher than treatments CK and G. The effect under combined treatment with desulfurization gypsum and biochar was better than that with biochar alone but not significantly different from that with desulfurization gypsum alone. Additionally, the effect of treatment with desulfurization gypsum alone was better than that under treatment with biochar alone. As time progressed, the conjoint ratio in all treatments tended to increase and gradually became higher than that in treatment G, indicating a significant improvement effect of the ameliorant on the quality of arable land. Desulphurization gypsum was more effective than biochar in improving the newly reclaimed cropland in coastal mudflats, but not as effective as the combined application treatment. The conjoint ratio under treatments A, C, and E exceeded 0.6 and reached a good level. The conjoint ratio under treatment B was close to 0.6 and nearly reached a good level (Table 5).

4. Discussion

4.1. Effect of Desulfurization Gypsum and Biochar on Soil pH and SAR

All treatments with desulfurization gypsum significantly reduced the soil pH, whereas biochar had no significant effect on soil pH. Soil pH was primarily affected by the $NaHCO_3$ and $NaCO_3$ present in the soil. $NaSO_4$ was formed because Na^+ was replaced by Ca^{2+} in desulfurization gypsum as a neutral salt, which reduces the content of Na_2CO_3 and $NaHCO_3$ in the soil and produces less harmful salts such as $CaHCO_3$ and $CaCO_3$, thus lowering soil pH [42]. The soil Na ion content increased initially after the addition of desulfurization gypsum, but was not significantly different from CK in the later stages, and there was no significant effect on soil pH. The absence of significant changes in soil pH as time progressed indicated that the replacement reaction had been largely completed. Moreover, Ca^{2+} replaced the exchangeable H^+ in the soil, which lowered the soil pH [43]. Biochar addition did not have any significant effect on soil pH, and the soil pH tended to increase with time. The effect of biochar on soil pH depends primarily on the pH properties of the biochar itself [19]. Most biochar is alkaline in nature. Therefore, instead of lowering pH, its application to alkaline soils will increase the pH. The combined application of desulfurization gypsum and biochar counteracted the pH increase caused by biochar alone and was more beneficial to the soil properties than the application of biochar alone.

The addition of desulfurization gypsum in all experiments significantly reduced the soil SAR values. As SAR is affected by Ca^{2+}, Mg^{2+}, and Na^+, the addition of desulfurization gypsum led to Ca^{2+} replacing Na^+. Additionally, the excess Ca^{2+} remained in the soil to maintain the soil calcium content, thus maintaining the soil SAR at a low level for a long time and effectively protecting the soil from re-alkalization.

4.2. Effect of Desulfurization Gypsum and Biochar on Field Water-Holding Capacity and Soil Bulk Density

All treatments with desulfurization gypsum and biochar addition enhanced field water-holding capacity to different degrees. The addition of desulfurization gypsum slightly and insignificantly increased the field water-holding capacity. As the biochar application increased, the field water-holding capacity increased continuously, with the most significant increase in field water-holding capacity being noted under treatment F with biochar application alone. Biochar is a porous structure with a large surface area and high adsorption ability, and it has an adsorption effect on water. Therefore, it can improve the field water-holding capacity of soil [19]. When desulfurization gypsum and biochar are applied as a combination, the field water-holding capacity increases with biochar application and, consequently, dilutes the salinity through desulfurization gypsum application, thus reducing the salt and alkali pressure and promoting plant growth and development.

The addition of both desulfurization gypsum and biochar significantly reduced the soil bulk density, because desulfurization gypsum and biochar have a low bulk density in nature. Therefore, both these compounds can directly reduce soil bulk density when applied to the soil [44,45]. Moreover, desulfurization gypsum reduced the soil bulk density more significantly.

4.3. Effect of Desulfurization Gypsum and Biochar on Water-Soluble Ion Content of Soil

With the addition of desulphurization gypsum, the total salt content of soil increased significantly, as the primary component of desulphurization gypsum was $CaSO_4^{2-}$, which increased the salt content of soil. The total salt content of soil increased slightly after the addition of biochar, but the difference was insignificant. The content of water-soluble ions in the soil changed significantly after the addition of desulfurization gypsum and biochar. The addition of desulfurization gypsum directly increased the contents of Ca^{2+}, Mg^{2+}, and SO_4^{2-} in the soil. The SO_4^{2-} in the desulfurization gypsum replaced the HCO_3^- in the soil colloids and reduced the HCO_3^- content in the soil through irrigation and rainwater drip washing [15]. The soil K^+ content significantly increased in the biochar alone and combination treatments, because biochar contains a large amount of K^+ (Table 2), which directly increased the K^+ content in the soil. The amount of biochar added in the combined treatment of FGD gypsum and biochar was less than in the treatment with biochar alone, but the K^+ content was higher than in the treatment with biochar alone. This may have been due to the Ca^{2+} in the FGD gypsum being able to displace and leach out the K^+ in the biochar [13,46].

4.4. Effect of Desulfurization Gypsum and Biochar on the Soil Nutrient Indicators

The soil alkali-hydrolyzable nitrogen content was reduced to different degrees under the treatments with desulfurization gypsum and biochar. After 60 days of planting, the alkali-hydrolyzable nitrogen content in the soils treated with the ameliorants was lower than that of the soils without ameliorants, probably because the desulfurization gypsum and biochar improved the soil physicochemical properties. The improved growing environment and enhanced nutrient uptake by plants resulted in a decrease in alkali-hydrolyzable nitrogen content in the soil. Both desulfurization gypsum and biochar inhibited the soil N volatilization. Biochar particles increased the NH_4^+ adsorption and reduced the loss of N escaping to the atmosphere as NH_3 and N_2O [47,48]. Desulfurization gypsum inhibits the activity of ammonia–nitrogen-producing bacteria, by lowering the soil pH, and converts ammonium carbonate to ammonium sulfate, which makes it less likely to be lost as ammonia [49,50]. Biochar can increase the effectiveness of desulfurization gypsum, in terms of inhibiting ammonia, by adsorbing gypsum on its surface. Desulfurization gypsum can regulate soil pH and moisture around biochar, wherein it improves the effectiveness of biochar in adsorbing NH_4^+ [51]. Therefore, the application of desulfurization gypsum and biochar depletes the alkali-hydrolyzable nitrogen content in the soil within a short period. However, if nitrogen fertilizer is applied simultaneously, the properties of desulfurization gypsum and biochar for maintaining the nitrogen content are beneficial for plant growth.

The available phosphorus content in the soil likewise decreased after the addition of desulfurization gypsum. The available phosphorus content in desulfurization gypsum was very low (only 0.96 mg/kg). Additionally, desulfurization gypsum reacted with PO_4^{3-} in the soil to form insoluble calcium phosphate salts [52], resulting in a decrease in the available phosphorus content in the soil. Biochar treatment significantly enhanced the available phosphorus content in the soil. Biochar has a high available phosphorus content and can directly enhance the effective soil phosphorus content. Additionally, phosphorus availability primarily depends on soil pH and organic matter content [19]. When soil pH is greater than 7, phosphorus availability in soil decreases [53]. Desulfurization gypsum can reduce soil pH. Therefore, the combination of desulfurization gypsum and biochar can increase the availability and content of phosphorus.

The available potassium content in the soil was reduced under treatment with desulfurization gypsum alone, and was it reduced to a very low level (only 11.24 mg/kg). Therefore, its application to the soil resulted in further reduction in the available potassium content. Biochar, which contains a high amount of available potassium (Table 2), can increase the available potassium content in the soil after application. Additionally, the available potassium content increased as the biochar application increased [54,55]. In the indoor pot experiment, the available potassium content in the soil exhibited a decreasing and then increasing trend, which can be attributed to the soil physicochemical properties improved by desulfurization gypsum and biochar. Peanuts require a large amount of nutrients in the rapid growth period. The accelerated rate of available potassium uptake by peanuts was higher than the rate of available potassium provided by biochar. However, the available potassium content in the soil remained high in the biochar-alone and combination treatments.

The soil organic matter content in treatment A with desulfurization gypsum alone was not significantly different when compared with treatment CK, as both contained extremely small amounts of organic matter. The free Ca^{2+} in desulfurization gypsum contributes to the formation of calcium carbonate precipitation in the soil and reduces the loss of C owing to soil respiration [56]. This could have been the reason why the combined treatment of desulfurization gypsum and biochar demonstrated an increasing trend in organic matter content, whereas treatment with biochar application alone exhibited a decreasing trend in organic matter content. Biochar contains a large amount of organic matter. The soil organic matter content increased with the increase in biochar application. Additionally, biochar can adsorb CO_2 onto its surface to reduce the loss of C [57].

4.5. Effect of Desulfurization Gypsum and Biochar on Peanut Growth

All treatments with desulfurization gypsum and biochar addition significantly improved all growth indicators of peanut. The fresh weight, dry weight, plant height, and leaf area of peanut in all treatments were significantly higher than those under treatment CK, with treatments A and C being the most effective in improving the fresh and dry weight. The difference in plant height was not significant at the seedling stage. Plant height increased when the amount of desulfurization gypsum application increased at the flowering stage. Treatment A with desulfurization gypsum alone produced the highest plant height, whereas treatment F with biochar alone had a reduced plant height when compared with treatment CK. Treatment A with desulfurization gypsum alone produced the highest leaf area at the seedling and flowering stages. However, at the pod stage, the leaf area of peanut under treatments B, C, and E exceeded that under treatment A. Overall, treatment C was most effective, followed by treatment E. When desulfurization gypsum and biochar were first applied to the soil, the soil salinity was high and alkalinization was the primary factor that harmed plant growth. Excess Na^+ leads to high osmotic pressure and prevents water uptake by plants [58]. Plants can have reduced water loss when the leaf area and porosity are reduced [59]. Desulfurization gypsum displaces Na^+ and decreases the toxicity of CO_3^{2-} and HCO_3^- through Ca^{2+} replacement, which reduces the soil pH and alkalinity and improves peanut growth. Additionally, the increase in Ca^{2+} prevented soil dispersion and facilitated agglomerate formation [60]. The uptake of Ca^{2+} by peanuts facilitated an increased hydraulic conductivity and leaf area, thus enhancing the tolerance to salt stress [61]. Therefore, the peanut growth with the desulfurization gypsum treatment alone at the seedling and flowering stages was slightly better than that under treatment with biochar alone and combination. After a period of improvement, the degree of soil salinity was reduced under all treatments. At this time, the soil nutrient content began to play a dominant role in plant growth. Treatment of single-application desulfurization gypsum leads to nutrient deficiency. Additionally, biochar can increase water-holding capacity and porosity in the soil and reduce soil bulk density. Thus, the peanut growth improved in the combined treatment with desulfurization gypsum and biochar. Furthermore, the peanut growth in multi-year improved farmland treatment G was the worst. On the one hand, peanut is a drought-tolerant plant, suitable for growth in sandy soils. On the other hand, the soil under treatment G underwent agglomeration during the planting process, which is not conducive to peanut growth. This may be the primary reason why the peanut growth was better in the treatments with added ameliorant than in treatment G.

4.6. Mechanisms of Combined Desulfurization Gypsum and Biochar for the Improvement of Newly Reclaimed Cropland

According to the results of the comprehensive evaluation of the TOPSIS-entropy weight method, the combined treatment of desulphurization gypsum and biochar had a great effect on the newly reclaimed cropland, and the improvement effect increased with time. With the addition of desulphurization gypsum, the negative indicators such as pH, SAR and bulk density decreased significantly, while the field water-holding capacity, SO_4^{2-}, Ca^{2+}, fresh weight, dry weight, leaf area, and plant height increased significantly. The bulk density of the treatments with biochar addition decreased significantly, and the positive indicators, such as the available phosphorus, available potassium, organic matter, and field water-holding capacity, increased significantly. Although the content of alkali-hydrolyzable nitrogen decreased to some extent, it did not affect the overall improvement effect. With the progression of time, the improvement effect gradually improved. Therefore, the quality of cropland treated with desulphurization gypsum and biochar was significantly improved. Compared with biochar, desulphurization gypsum played a more important role in saline-alkali soil.

5. Conclusions

The soil properties and plant growth of peanut under different ratios of desulfurization gypsum and biochar treatments were analyzed through indoor pot-planting experiments. Additionally, a comprehensive evaluation was performed using the TOPSIS-entropy weight method. The following conclusions were drawn from this study:

(1) Both desulfurization gypsum and biochar were effective in improving newly reclaimed cropland in coastal mudflats. Both single and combined applications of desulfurization gypsum significantly increased soil Ca^{2+}, SO_4^{2-}, and Mg^{2+} contents and significantly reduced soil pH, SAR, and bulk density. Both single and combined biochar treatments significantly reduced the soil bulk density and significantly increased water-soluble K^+; field water-holding capacity; and soil available phosphorus, available potassium, and organic matter contents.

(2) The treatments with addition of desulfurization gypsum and biochar, as well as the combination of both, could effectively promote crop growth; and the fresh weight, dry weight, plant height, and leaf area of peanut in the aforementioned treatments were higher than those in treatments CK and G. Among them, treatment A (desulfurization gypsum 100 g/kg) had the most significant effect in increasing the fresh and dry weight of peanut. Treatment C (desulfurization gypsum 75 g/kg + biochar 20 g/kg) had the most significant effect in increasing the plant height and leaf area of peanut.

(3) According to the results of the comprehensive evaluation of the TOPSIS-entropy weight model, after 60 days of planting, the improvement effects of each treatment were ranked C > A > E > B > D > F > G > CK. Both combined treatment with desulfurization gypsum and biochar and single treatment of desulfurization gypsum were effective, followed by the single application of biochar. Treatment C (desulfurization gypsum 75 g/kg + biochar 20 g/kg) was the optimal-proportioned scheme.

(4) An evaluation index system for saline-alkali soil in coastal mudflats was established, the improvement effect of saline-alkali soil in coastal mudflats was comprehensively evaluated using the TOPSIS-entropy weight method, and the best scheme was selected according to the application amount of different ameliorants, avoiding singularity and subjectivity of evaluation. However, the improvement of newly reclaimed arable land from coastal mudflats should consider the influence of multiple factors. This study considered only the properties of soil and crop growth, excluding the influence of meteorological, topographical, and economic conditions, as well as other variables. Inevitably, a comprehensive evaluation of newly reclaimed arable land from coastal mudflats is insufficient, and in the future, more factors could be considered to evaluate the improvement effect in a more comprehensive manner.

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References

1. Andreu, V.; Gimeno-Garcia, E.; Pascual, J.A.; Vazquez-Roig, P.; Pico, Y. Presence of pharmaceuticals and heavy metals in the waters of a Mediterranean coastal wetland: Potential interactions and the influence of the environment. *Sci. Total Environ.* **2016**, *540*, 278–286. [CrossRef]
2. Murray, N.J.; Phinn, S.R.; DeWitt, M.; Ferrari, R.; Johnston, R.; Lyons, M.B.; Clinton, N.; Thau, D.; Fuller, R.A. The global distribution and trajectory of tidal flats. *Nature* **2019**, *565*, 222–225. [CrossRef] [PubMed]
3. Eertman, R.H.M.; Kornman, B.A.; Stikvoort, E.; Verbeek, H. Restoration of the Sieperda tidal marsh in the Scheldt estuary, the Netherlands. *Restor. Ecol.* **2002**, *10*, 438–449. [CrossRef]
4. Peng, J.; Wang, Y.L. A study on shoaly land in China. *Acta Sci. Nat. Univ. Pekin.* **2000**, *36*, 832–839.
5. Wang, Y. The mudflat coast of China. *Can. J. Fish. Aquat. Sci.* **1983**, *40*, 160–171. [CrossRef]
6. Zhang, W.K. A study on exploitation and utilization of tideland resources in Fujian Province. *Resour. Sci.* **2001**, *23*, 29–32.
7. Xu, M.G.; Lu, C.A.; Zhang, W.J.; Li, L.; Duan, Y.H. Situation of the quality of arable land in China and improvement strategy. *Chin. J. Agric. Resour. Reg. Plann.* **2016**, *37*, 8–14.
8. Zuo, W.G.; Huang, G.L.; Zhu, X.W.; Chen, Y.S.; Shen, Y.L.; Tao, T.Y.; Bo, Y.C.; Shan, Y.H.; Feng, K. Motivating effect of different dairy manure addition on soil initial fertility formation and ryegrass growth in coastal mudflat soil. *J. Plant Nutr. Fert.* **2016**, *22*, 372–379.
9. Zhang, M.; Gao, C.; Yin, A.J.; Bao, Z.Y.; Chen, G.G.; Liang, X.H.; Yong, T.J.; Zhu, Y.P.; Zhou, M. Variation in soil total salt and base ions content of tidal-flat reclamation with different years. *Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 118–126.
10. Chen, Y.Y.; Fu, Y.X.; Zhang, Z.K.; Zhang, L.H.; Xu, H.X. Review of the Chinese patents on coastal saline-alkali soil improvement. *Chin. Agric. Sci. Bull.* **2014**, *30*, 279–285.
11. Leiva, C.; Garcia Arenas, C.; Vilches, L.F.; Vale, J.; Gimenez, A.; Ballesteros, J.C.; Fernandez-Pereira, C. Use of FGD gypsum in fire resistant panels. *Waste Manag.* **2010**, *30*, 1123–1129. [CrossRef]
12. Clark, R.B.; Ritchey, K.D.; Baligar, V.C. Benefits and constraints for use of FGD products on agricultural land. *Fuel* **2001**, *80*, 821–828. [CrossRef]
13. Alva, A.K.; Prakash, O.; Paramasivam, S. Flue-gas desulfurization gypsum effects on leaching of magnesium and potassium from a candler fine sand. *Commun. Soil Sci. Plant Anal.* **1998**, *29*, 459–466. [CrossRef]
14. Mao, Y.; Li, X.; Dick, W.A.; Chen, L. Remediation of saline-sodic soil with flue gas desulfurization gypsum in a reclaimed tidal flat of southeast China. *J. Environ. Sci.* **2016**, *45*, 224–232. [CrossRef]

15. Wang, J.M.; Yang, P.L. Potential flue gas desulfurization gypsum utilization in agriculture: A comprehensive review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1969–1978. [CrossRef]
16. Chi, C.M.; Zhao, C.W.; Sun, X.J.; Wang, Z.C. Reclamation of saline-sodic soil properties and improvement of rice (*Oriza sativa* L.) growth and yield using desulfurized gypsum in the west of Songnen Plain, northeast China. *Geoderma* **2012**, *187*, 24–30. [CrossRef]
17. Yu, H.; Yang, P.; Lin, H.; Ren, S.; He, X. Effects of sodic soil reclamation using flue gas desulphurization gypsum on soil pore characteristics, bulk density, and saturated hydraulic conductivity. *Soil Sci. Soc. Am. J.* **2014**, *78*, 1201–1213. [CrossRef]
18. Lehmann, J.; Joseph, S. *Biochar for Environmental Management Science, Technology and Implementation*, 2nd ed.; Routledge: London, UK, 2015; pp. 1–11.
19. Dahlawi, S.; Naeem, A.; Rengel, Z.; Naidu, R. Biochar application for the remediation of salt-affected soils: Challenges and opportunities. *Sci. Total Environ.* **2018**, *625*, 320–335.
20. Gou, M.M.; Qu, Z.Y.; Wang, F.; Gao, X.Y.; Hu, M. Progress in research on biochar affecting soil-water environment and carbon sequestration-mitigating emissions in agricultural fields. *Trans. Chin. Soc. Agric. Mach.* **2018**, *49*, 1–12.
21. Rajkovich, S.; Enders, A.; Hanley, K.; Hyland, C.; Zimmerman, A.R.; Lehmann, J. Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. *Biol. Fertil. Soils* **2012**, *48*, 271–284. [CrossRef]
22. Lehmann, J.; da Silva, J.P.; Steiner, C.; Nehls, T.; Zech, W.; Glaser, B. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: Fertilizer, manure and charcoal amendments. *Plant Soil* **2003**, *249*, 343–357. [CrossRef]
23. Abbas, T.; Rizwan, M.; Ali, S.; Adrees, M.; Zia-ur-Rehman, M.; Qayyum, M.F.; Ok, Y.S.; Murtaza, G. Effect of biochar on alleviation of cadmium toxicity in wheat (*Triticum aestivum* L.) grown on Cd-contaminated saline soil. *Environ. Sci. Pollut. Res.* **2017**, *25*, 25668–25680. [CrossRef]
24. Akhtar, S.S.; Andersen, M.N.; Liu, F. Residual effects of biochar on improving growth, physiology and yield of wheat under salt stress. *Agric. Water Manag.* **2015**, *158*, 61–68. [CrossRef]
25. Ma, R.M.; Ma, R.H.; Han, D.M.; Yun, W.J. Construction of cultivated land quality evaluation system in provincial level based on multilevel indicators. *Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 249–257.
26. Zhao, X.J.; Ye, Y.; Zhou, J.H.; Liu, L.; Dai, W.J.; Wang, Q.X.; Hu, Y.M. Comprehensive evaluation of cultivated land quality and sensitivity analysis of index weight in hilly region of Pearl River Delta. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 226–235.
27. Zhang, C.; Gao, L.L.; Yun, W.J.; Li, L.; Ji, W.J.; Ma, J.N. Research Progress on Obtaining Cultivated Land Quality Evaluation Indexes by Remote Sensing. *Trans. Chin. Soc. Agric. Mach.* **2022**, *53*, 1–13.
28. Sun, X.B.; Kong, X.B.; Wen, L.Y. Evaluation index system of cultivated land quality and its development trend based on cultivated land elements. *Chin. J. Soil Sci.* **2019**, *50*, 739–747.
29. Gan, F.; Shi, H.; Gou, J.; Zhang, L.; Liu, C. Effects of bedrock strata dip on soil infiltration capacity under different land use types in a karst trough valley of Southwest China. *Catena* **2023**, *230*, 107253. [CrossRef]
30. Zhao, Y.Y.; Zhang, Z.Y.; Tang, X.D.; Zang, L.B.; Liu, X.Y.; Lu, J.L. Analysis of high content water-soluble salt cation in saline-alkali soil by X-Ray fluorescence spectrometry. *Spectrosc. Spectr. Anal.* **2020**, *40*, 1467–1472.
31. Page, A.L. Methods of Soil Analysis, Part 2. In *Chemical and Microbiological Properties*, 2nd ed.; American Society of Agronomy, Soil Science Society of America: Madison, WI, USA, 1982; pp. 1035–1049.
32. Pansu, M.; Gautheyrou, J. *Handbook of Soil Analysis: Mineralogical, Organic and Inorganic Methods*; Springer: Berlin/Heidelberg, Germany, 2006; pp. 605–635.
33. Lu, R.K. *Chemical Analysis of Agricultural Soils*; China Agricultural Science and Technology Press: Beijing, China, 2000; pp. 107–108.
34. Xu, Z.Q.; Chen, Y.; Mao, X.M. Influences of salt adsorption ratio and salt concentration on the physical properties of typical sandy loam in Xinjiang. *Trans. Chin. Soc. Agric. Eng.* **2022**, *38*, 86–95.
35. Sun, Z.J. Research on Effects and the Mechanism of Desulfurization Gypsum and Humic Acid on Coastal Saline-Alkali Soil Improvement. Ph.D. Thesis, China University of Mining & Technology, Beijing, China, 2013.
36. Yan, S.L.; Liu, S.F.; Zhu, J.J.; Fang, Z.G.; Liu, J. TOPSIS decision-making method with three-parameter interval number based on entropy measure. *Chin. J. Manag. Sci.* **2013**, *21*, 145–151.
37. Lei, X.P.; Robin, Q.; Liu, Y. Evaluation of regional land use performance based on entropy TOPSIS model and diagnosis of its obstacle factors. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 243–253.
38. Wang, M.W.; Chen, G.Y.; Jin, J.L. Entropy-based of set pair analysis model for optimization of land consolidation plans. *Trans. Chin. Soc. Agric. Eng.* **2010**, *26*, 322–325.
39. Liang, J.F.; Chen, S.L. Evaluation and grey correlational analysis of land use performance in Fujian Province based on entropy-weight TOPSIS model. *J. Fujian Norm. Univ. Nat. Sci.* **2019**, *35*, 80–87.
40. Zhang, Q.Q.; Liao, H.P.; Yang, W.; Zhang, Y.F.; Long, H. Evaluation of rural land use transformation based on the entropy weight TOPSIS model——A case study of Yubei District, Chongqing. *J. Southwest Univ. Nat. Sci.* **2018**, *40*, 135–144.
41. Shen, S.M. *Soil Fertility in China*; China Agriculture Press: Beijing, China, 1998; pp. 111–335.
42. Zhao, Y.; Wang, S.; Li, Y.; Liu, J.; Zhuo, Y.; Chen, H.; Wang, J.; Xu, L.; Sun, Z. Extensive reclamation of saline-sodic soils with flue gas desulfurization gypsum on the Songnen Plain, Northeast China. *Geoderma* **2018**, *321*, 52–60. [CrossRef]
43. Mahmoodabadi, M.; Yazdanpanah, N.; Rodriguez Sinobas, L.; Pazira, E.; Neshat, A. Reclamation of calcareous saline sodic soil with different amendments (I): Redistribution of soluble cations within the soil profile. *Agric. Water Manag.* **2013**, *120*, 30–38. [CrossRef]

44. Nan, J.; Chen, X.; Chen, C.; Lashari, M.S.; Deng, J.; Du, Z. Impact of flue gas desulfurization gypsum and lignite humic acid application on soil organic matter and physical properties of a saline-sodic farmland soil in Eastern China. *J. Soils Sediments* **2016**, *16*, 2175–2185. [CrossRef]
45. Tokova, L.; Igaz, D.; Horak, J.; Aydin, E. Can application of biochar improve the soil water characteristics of silty loam soil. *J. Soils Sediments* **2023**, *23*, 2832–2847. [CrossRef]
46. Sakai, Y.; Ren, S.; Wang, C.; Sadakata, M. Salt-affected soil amelioration with flue gas desulfurization by-products and waste gypsum board in Tianjin, China. *J. Chem. Eng. Jpn.* **2011**, *44*, 750–756. [CrossRef]
47. Mandal, S.; Thangarajan, R.; Bolan, N.S.; Sarkar, B.; Khan, N.; Ok, Y.S.; Naidu, R. Biochar-induced concomitant decrease in ammonia volatilization and increase in nitrogen use efficiency by wheat. *Chemosphere* **2016**, *142*, 120–127. [CrossRef]
48. Esfandbod, M.; Phillips, I.R.; Miller, B.; Rashti, M.R.; Lan, Z.M.; Srivastava, P.; Singh, B.; Chen, C.R. Aged acidic biochar increases nitrogen retention and decreases ammonia volatilization in alkaline bauxite residue sand. *Ecol. Eng.* **2017**, *98*, 157–165. [CrossRef]
49. Tubail, K.; Chen, L.; Michel, F.C., Jr.; Keener, H.M.; Rigot, J.F.; Klingman, M.; Kost, D.; Dick, W.A. Gypsum additions reduce ammonia nitrogen losses during composting of dairy manure and biosolids. *Compost Sci. Util.* **2008**, *16*, 285–293. [CrossRef]
50. Qu, J.; Zhang, L.; Zhang, X.; Gao, L.; Tian, Y. Biochar combined with gypsum reduces both nitrogen and carbon losses during agricultural waste composting and enhances overall compost quality by regulating microbial activities and functions. *Bioresour. Technol.* **2020**, *314*, 123781. [CrossRef] [PubMed]
51. Mishra, A.; Cabrera, M.L.; Kissel, D.E.; Rema, J.A. Gypsum effect on nitrogen mineralization and ammonia volatilization from broiler litter. *Soil Sci. Soc. Am. J.* **2013**, *77*, 2045–2049. [CrossRef]
52. He, K.; Li, X.P.; Zhang, X.Y.; Zhang, Y.B. Effect of flue gas desulfurization gypsum (FGD-gypsum) on physical and chemical properties of soil and growth of upland rice in Chongming coastal saline soils. *Southwest China J. Agric. Sci.* **2016**, *29*, 1381–1386.
53. Naidu, R.; Syers, J.K.; Tillman, R.W.; Kirkman, J.H. Assessment of plant-available phosphate in limed, acid soils using several soil-testing procedures. *Fert. Res.* **1991**, *30*, 47–53. [CrossRef]
54. Lashari, M.S.; Ye, Y.; Ji, H.; Li, L.; Kibue, G.W.; Lu, H.; Zheng, J.; 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.* **2015**, *95*, 1321–1327. [CrossRef]
55. Lashari, M.S.; Liu, Y.; Li, L.; Pan, W.; Fu, J.; Pan, G.; Zheng, J.; Zheng, J.; Zhang, X.; Yu, X. Effects of amendment of biochar-manure compost in conjunction with pyroligneous solution on soil quality and wheat yield of a salt-stressed cropland from Central China Great Plain. *Field Crops Res.* **2013**, *144*, 113–118. [CrossRef]
56. Renforth, P.; Mayes, W.M.; Jarvis, A.P.; Burke, I.T.; Manning, D.A.C.; Gruiz, K. Contaminant mobility and carbon sequestration downstream of the Ajka (Hungary) red mud spill: The effects of gypsum dosing. *Sci. Total Environ.* **2012**, *421*, 253–259. [CrossRef]
57. Khan, N.; Clark, I.; Sanchez-Monedero, M.A.; Shea, S.; Meier, S.; Bolan, N. Maturity indices in co-composting of chicken manure and sawdust with biochar. *Bioresour. Technol.* **2014**, *168*, 245–251. [CrossRef] [PubMed]
58. Maathuis, F.J.M. Sodium in plants: Perception, signalling, and regulation of sodium fluxes. *J. Exp. Bot.* **2014**, *65*, 849–858. [CrossRef] [PubMed]
59. Bello, S.K.; Alayafi, A.H.; Al-Solaimani, S.G.; Abo-Elyousr, K.A.M. Mitigating soil salinity stress with gypsum and bio-organic amendments: A review. *Agronomy* **2021**, *11*, 1735. [CrossRef]
60. Aboelsoud, H.; Engel, B.; Gad, K. Effect of planting methods and gypsum application on yield and water productivity of wheat under salinity conditions in North Nile Delta. *Agronomy* **2020**, *10*, 853. [CrossRef]
61. Cramer, G.R. Kinetics of maize leaf elongation: III. Silver thiosulfate increases the yield threshold of salt-stressed plants, but ethylene is not involved. *Plant Physiol.* **1992**, *100*, 1044–1047. [CrossRef]