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Study on the Use of Soda Saline–Alkali Soil as a Rice-Seedling-Raising Soil After Short-Term Improvement

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Abstract: In western Jilin Province, China, the presence of soda saline–alkali soil poses a significant threat to the raising of rice seedlings due to its harsh soil properties. The scarcity of suitable seedling-raising soil resources has become increasingly pronounced. A short-term soil-improvement experiment was conducted using the original saline–alkali soil sourced from the rice-growing region of Jilin Province, followed by the rice-seedling-raising test in the improved soil to identify an effective soil-improvement strategy. Four distinct treatments were established: no amendment (JCK); gypsum and straw (JCW); gypsum, straw, and sulfuric acid (JCWH); and gypsum, straw, and chemical fertilizer (JCWF). The effects of these amendment treatments on the soil physicochemical properties (pH, electrical conductivity, exchangeable sodium, total alkalinity) were evaluated, as well as the effects on soil organic carbon (SOC) and its components including humic acid carbon (HAC), and fulvic acid carbon (FAC). The results indicated that, compared to the control group, all amendment treatments effectively reduced the average soil pH by 0.53 to 0.79 units and decreased exchangeable sodium by 56.7% to 74.8%. Furthermore, the average SOC, HAC, and FAC increased by 48.3%, 89.4%, and 56.0%, respectively. Among the treatments, JCWH proved to be the most effective. After two years of improvement, the rice seedlings in the JCWH-treated soil exhibited the highest dry weight and plant height, surpassing those grown in the farmer's seedling-raising soil. The scheme of utilizing soda saline–alkali soil for rice-seedling raising, following a short-term improvement treatment with corn straw, gypsum, and sulfuric acid (JCWH), provides technical support and an effective solution to the soil scarcity issue faced by seedling farmers in saline–alkali regions.

Keywords: saline–sodic soil; rice-seedling-bed soil; short-term improvement; organic fertilization; physicochemical properties

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Academic Editor: Tiago Filipe da Silva Miranda

Received: 23 March 2025
Revised: 19 April 2025
Accepted: 19 April 2025
Published: 22 April 2025

Citation: Nie, Y.; Jiang, L.; Liu, X.; Feng, L.; Li, Z. Study on the Use of Soda Saline–Alkali Soil as a Rice-Seedling-Raising Soil After Short-Term Improvement. *Appl. Sci.* **2025**, *15*, 4638. https://doi.org/10.3390/app15094638

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1. Introduction

Currently, the area of soda saline–alkali soil in the Songnen Plain of China exceeds 4.97×10^6 ha. This region is recognized as one of the three major global concentrations of soda saline–alkali soil [1], primarily located in the provinces of Jilin, Inner Mongolia, and Heilongjiang. The western region of Jilin Province is a crucial base for commodity grain production; however, it is significantly affected by saline–alkali soil. Rice is one of the primary crops cultivated in this area. The presence of saline–alkali soil not only adversely impacts the growth of local rice but also contributes to a shortage of soil suitable for rice-seedling raising.

The key components contributing to soil salinization in saline–alkali soils are sodium carbonate (Na_2CO_3) and sodium bicarbonate ($NaHCO_3$). The elevated salinity and al-

kalinity adversely affect soil properties, including aeration and permeability. When the soil-to-water ratio is 5:1, the pH of the surface soil (0–20 cm) can reach 10.16, and the sodium adsorption ratio (SAR) can attain 196.64 (mmol $L^{-1})^{1}/^{2}$ [2]. The significant adsorption of sodium ions (Na^+) by the soil enhances the hydrophilicity of soil colloids, leading to soil dispersion and structural deterioration. This process limits nutrient availability and reduces soil fertility [3]. The high degree of sodification and low fertility of these soils are major drawbacks that impede their use in rice-seedling raising and other agricultural practices [4].

Farmers in areas with soda saline–alkali soils often utilize mildly saline–alkali soil for simple acid-adjustment treatments as seedbed soil due to a scarcity of suitable soil resources. However, this practice leads to the depletion of soil resources and degradation of the soil environment. Inadequate improvement measures can also harm seedlings and potentially reduce crop yields. Therefore, addressing the issue of soil for rice-seedling raising has become an urgent task. The application of rapidly improved soda saline–alkali soil for rice-seedling raising can enhance the availability of quality seedling-raising soil resources, providing an effective solution to this challenge.

Gypsum is one of the most significant and widely utilized amendments for the improvement of saline–alkali soils. It enhances the soil bulk density, hydraulic conductivity, and microporosity [5]. Gypsum ameliorates soda saline–alkali soils by supplying calcium ions (Ca^{2+}), which replace excessive monovalent sodium ions (Na^+) at cation exchange sites within the soil [6]. Soil colloids exhibit a strong affinity for divalent Ca^{2+}, rendering them more stable than monovalent Na^+ [7]. The displaced Na^+ is subsequently leached away with irrigation water. However, gypsum has a low solubility, and in the absence of irrigation or rainfall, there is a risk of insufficient hydraulic conductivity. The combined application of straw organic matter can mitigate this issue. The macromolecular organic acids generated during straw decomposition readily bind with Ca^{2+} ions, facilitating the dissolution of gypsum [8]. Additionally, returning straw to the soil releases a substantial amount of nutrients. Nie et al. [9] observed that long-term straw return increased the soil organic carbon and total nitrogen by 8.85% to 15.01%, effectively enhancing soil fertility. The application of straw can also modify the soil carbon-to-nitrogen ratio and promote nutrient cycling, thereby benefiting crop growth [10,11].

Soda saline–alkali soil typically leads to the fixation of essential nutrients, such as phosphorus and calcium, under conditions of high salinity and alkalinity [12]. Additionally, it hinders the absorption of nutrients, thereby inhibiting plant growth [13]. Soil salinization also negatively impacts the accumulation of organic matter and the soil carbon cycle, which are key processes for maintaining soil health [14]. The application of sulfuric acid has been shown to significantly lower the pH of saline–alkali soil, promoting the dissolution of Ca^{2+} and enhancing the Na–Ca exchange process, as well as Na leaching in such soils [15]. Furthermore, sulfuric acid improves nutrient availability and increases both the nutrient utilization and absorption rates of crops [16]. The use of chemical fertilizers supplies essential nutrient elements to the soil, thereby improving nutrient availability and mitigating the detrimental effects of salinity on plants [17]. The combined application of inorganic and organic fertilizers has been found to reduce the soil salinity and pH value [18]. Moreover, studies have shown that the application of chemical fertilizers combined with straw in saline–alkali soil can alter soil aggregates, enhance the soil carbon sequestration capacity [19], and increase nutrient absorption, plant vitality, and crop yield [20]. Currently, the co-application of gypsum, straw, and sulfuric acid or inorganic fertilizers for the amelioration of saline–alkali soils is relatively uncommon. This study aims to evaluate the effects of applying gypsum and straw, along with the addition of sulfuric acid and fertilizers, on saline–alkali soil. Specifically, our objectives are as follows: (1) to investigate

the response of soil salinity and fertility following various treatments; and (2) to reflect the impact of different improvement treatments on the growth of rice seedlings in saline–alkali soil.

2. Materials and Methods

2.1. Site Description

The pot experiment was conducted at the experimental station of Jilin Agricultural University (43°48′40″ N, 125°23′38″ E), Changchun City, Jilin Province, Northeast China, from 2021 to 2022. This study aimed to enhance the quality of soda saline–alkali soil in the western region of Jilin Province to facilitate its application in rice-seedling cultivation. The soda saline–alkali soil utilized in the experiment was sourced from the top 20 cm of a field with the original saline–alkali soil in Qian'an County, Songyuan City, Jilin Province (44°52′49″ N, 124°02′32″ E), which was located within the Songnen Plain and was classified as a typical meadow alkali soil. The location of the soil sampling point is shown in Figure 1. The soil was sieved through 2 mm mesh to thoroughly homogenize and remove plant residues and stones. The soil had a pH value of 9.19, an organic carbon content of 8.57 g·kg^{-1}, an electrical conductivity of 0.288 ms·cm^{-1}, an exchangeable sodium content of 5.59 cmol·kg^{-1}, a cation exchange capacity (CEC) of 9.32 cmol·kg^{-1}, and a total alkalinity of 1.22 cmol·kg^{-1}. All testing data were derived from the test results of the Jilin Agricultural University experimental station.

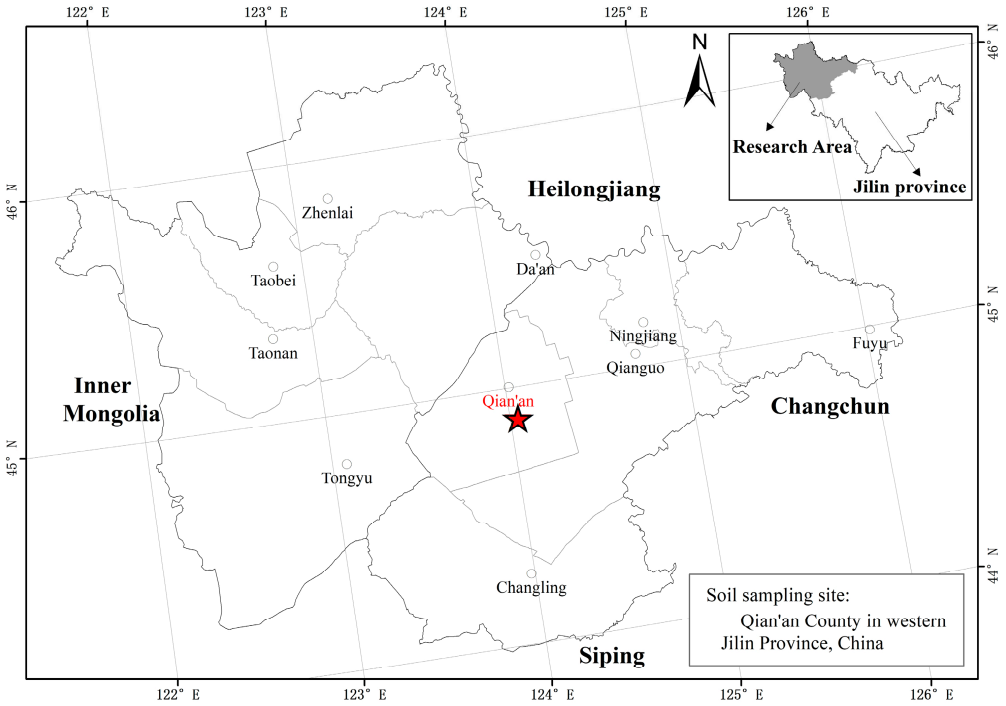


Figure 1. Research area and soil sampling site.

The corn straw used in this experiment was sourced from the teaching experimental field of Jilin Agricultural University. After crushing, the corn straw measured approximately 1 cm in length and was mixed evenly. The organic carbon content was measured at 396.7 g·kg^{-1}, while the total nitrogen, total phosphorus, and total potassium contents were 6.59 g·kg^{-1}, 2.20 g·kg^{-1}, and 7.32 g·kg^{-1}, respectively.

In the rice-seedling experiment, the control group utilized the farmer's seedling-raising soil (ZCK) alongside JCK. This soil was sourced from the seedling-raising area at Taohe Farm, situated in Linhai Town, Taobei District, Baicheng City, Jilin Province,

where agricultural seedling-conditioning agents had been incorporated by farmers. The soil was sieved through 2 mm mesh to thoroughly homogenize and remove plant residues and stones. The soil exhibited a pH value of 6.27, an organic carbon content of 18.01 $g \cdot kg^{-1}$, an electrical conductivity of 2.69 $ms \cdot cm^{-1}$, alkali-hydrolyzable nitrogen of 156.5 $mg \cdot kg^{-1}$, available phosphorus of 42.48 $mg \cdot kg^{-1}$, available potassium of 175.2 $mg \cdot kg^{-1}$, exchangeable sodium of 0.53 $cmol \cdot kg^{-1}$, and a total alkalinity of 0.23 $cmol \cdot kg^{-1}$.

2.2. Experimental Design and Soil Sampling

In the improvement experiment of soda saline–alkali soil, four treatments were established: JCK (control, no amendment), JCW (straw + gypsum treatment), JCWH (straw + gypsum + sulfuric acid treatment), and JCWF (straw + gypsum + chemical fertilizer treatment). The amendments were applied in proportion to the soil weight, with the specific addition rates detailed in Table 1. All treatments were replicated three times.

Table 1. Addition status of amendments for each treatment.

Treatment	Gypsum	Straw	Sulfuric Acid	Chemical Fertilizer
JCK	-	-	-	-
JCW	2%	6%	-	-
JCWH	2%	6%	40 mL of a (1 + 1) sulfuric acid solution per kilogram of soil	-
JCWF	2%	6%	-	4 g of urea, 8 g of diammonium hydrogen phosphate, and 4 g of potassium sulfate per kilogram of soil

The following steps were adopted to improve the soil samples: A total of 3 kg of soda saline–alkali soil was uniformly mixed with the amendment and subsequently placed into a 5 L plastic bucket. The bottom of the bucket was evenly perforated to ensure proper drainage. Initially, a substantial volume of water was utilized for leaching, with a total of 10 L of water applied over a period of 8 days. Following this, the mixture was maintained at field capacity and room temperature, with regular turning and mixing. After 8 months, the cultivation process concluded, and samples were collected. In both 2021 and 2022, the soil was treated with the same amendment following identical procedures once a year. After air-drying, the soil samples obtained each year were passed through a 2 mm sieve to separate undecomposed straw, after which the soil physical and chemical indicators were determined.

Rice-seedling raising adopted the following steps: The treated soils from the improvement experiments of the years 2021 and 2022 were utilized as seedling-bed soils for seedling-raising pot experiments, with the farmer's seedling-raising soil (ZCK) included as a control. The seeding rate was 3 g of dry seeds per 100 g of soil. After 30 days of seedling cultivation, the representative seedlings were selected, cleaned to remove root attachments, and subsequently assessed for quality indicators. Following the seedling cultivation, soil samples were collected, air-dried, passed through a 2 mm sieve to ensure thorough homogenization and the removal of plant residues, and then analyzed for their soil-organic-carbon-component content.

2.3. Soil Analysis and Rice-Seedling Determination

The pH and conductivity of the soil were measured using the electrode method at a soil-to-water (w/v) ratio of 1:5. Soil exchangeable sodium was determined through ammonium acetate and ammonium hydroxide exchange, followed by flame photometry.

The total alkalinity of the soil was calculated as the sum of the soluble carbonates and bicarbonates, which were determined by extracting the soil with a solution at a soil-to-water (w/v) ratio of 1:5 and titrating with a 0.1 M hydrochloric acid solution.

The separation of soil humus components was conducted following the modified method of soil humus composition as described by Zhang et al. [21]. Soil samples were extracted using a mixed solution of sodium hydroxide (0.1 M) and sodium pyrophosphate (0.1 M), followed by centrifugation and filtration. The remaining soil residue was identified as humin (HU), while the filtrate constituted the extracted humus extract (HE). Subsequently, the filtrate was acidified to a pH of 1 to facilitate the separation of humic acid (HA) and fulvic acid (FA) from HE.

The contents of soil organic carbon (SOC), humic acid carbon (HAC), and fulvic acid carbon (FAC) were determined using the $K_2Cr_2O_7$ oxidation method followed by $FeSO_4$ titration. The PQ value, calculated as PQ = HAC/(HAC + FAC), serves as an indicator of the degree of soil humification. Both HA and FA solutions were appropriately diluted, and their absorbances at 400 nm and 600 nm (A_{400} and A_{600}) were measured. The value of Δlog K was computed as $\Delta \log K = \log A_{400} - \log A_{600}$. This Δlog K value reflects the complexity of the soil humus molecular structure [22]. A larger Δlog K indicates a lower degree of aromaticity and condensation in the molecular structure, suggesting a simpler structure of humic substances.

The determination of leaf age, plant height, root length, and dry weight of rice seedlings was conducted using the following methods: The roots of the seedlings were washed with water, and surface moisture was removed using absorbent paper. Subsequently, the leaf age, plant height, and root length of the seedlings were measured. The seedlings were then placed in an oven at 105 °C for 30 min for blanching, followed by drying in an oven at 70 °C to 80 °C until a constant weight was achieved, at which point they were weighed.

2.4. Statistical Analysis

Statistical analyses were conducted using SPSS software (IBM SPSS Statistics 22.0). The differences between treatment means were assessed using one-way analysis of variance (ANOVA), followed by Duncan's new multiple range test to evaluate significance at the 5% level. The results of these tests were plotted, and Pearson correlation analysis was performed using Origin Pro 2018 software.

3. Results

3.1. Soil Physical and Chemical Properties

Two years of experimental data indicated that, overall, with the increase in years, the soil pH and exchangeable sodium across all amendment treatments significantly decreased (Figure 2a,c), while soil electrical conductivity (EC) significantly increased (Figure 2b). The total alkalinity of the soil exhibited a trend of initially decreasing, followed by an increase (Figure 2d). Compared to the JCK treatment, the average pH values for the JCW, JCWH, and JCWF treatments were significantly reduced by 0.53 to 0.79 units. Meanwhile, the soil EC value significantly increased by 3.05 to 7.20 times, with the JCWH treatment exhibiting the highest EC value. The soil exchangeable sodium for the JCW, JCWH, and JCWF treatments significantly decreased, from an average of 1.93 mmol·kg^{-1} in JCK to 0.43, 0.38, and 0.31 mmol·kg^{-1} in 2022 ($p < 0.05$), respectively. For total alkalinity, the average reduction in each treatment in 2021 was greater than that in 2022.

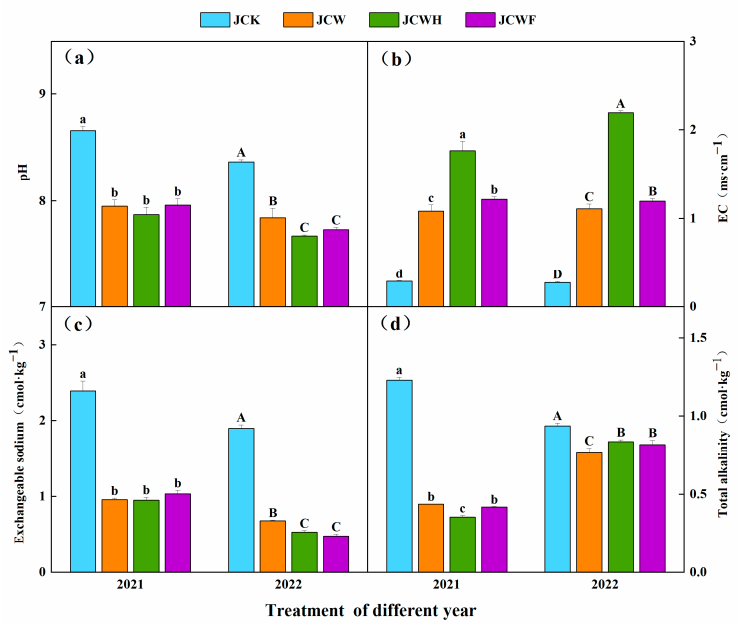


Figure 2. Effects of different improvement treatments on soil pH (**a**), EC (**b**), exchangeable sodium (**c**), and total alkalinity (**d**). Control (JCK): with no amendments; straw + gypsum treatment (JCW); straw + gypsum + sulfuric acid treatment (JCWH); straw + gypsum + chemical fertilizer treatment (JCWF). The different lowercase and uppercase letters above the column indicate the significant differences among different treatments in 2021 and 2022, respectively ($p < 0.05$). Bars are means, with standard errors (n = 3).

3.2. Soil Organic Carbon Components and Humification Degree

In this study, we applied the improved soil obtained over two years to rice-seedling raising. We investigated the organic carbon content and the degree of humification of the seedling-raising soil, comparing it with the farmer's seedling-raising soil (ZCK). The average soil organic carbon (SOC) of the seedling-raising soil across all improved treatments ranged from 10.42 to 19.39 g·kg^{-1} (Figure 3). Overall, the average SOC for each treatment in 2022 was 24.4% to 31.4% higher than that in 2021. Compared to JCK, the amendment treatments significantly increased the SOC by 23.3% to 78.9% ($p < 0.05$). Among all of the amendment treatments, the JCWH treatment, which included additional sulfuric acid, exhibited the highest SOC levels over the two years, measuring 14.76 and 19.39 g·kg^{-1}, respectively. Notably, we found no significant difference in the SOC content between the JCWH-treated soil over the two years and the ZCK soil.

All amendment treatments resulted in a year-on-year increase in both humic acid carbon (HAC) and fulvic acid carbon (FAC) in the soil (Figures 4 and 5). Compared to the control group (JCK), the HAC increased by 46.3%, reaching 137.2%, while the FAC rose by 26.4% to 86.0%. As is shown in Figure 4, the increases in HAC for JCW and JCWH were more pronounced than that of JCWF over the two-year period. However, despite these improvements, a notable disparity remained when comparing the HAC of the farmer's seedling-raising soil (ZCK), which was 3.38 g·kg^{-1}, with that of the amendment treatments. In 2022, the HAC/SOC ratios for both JCW and JCWH increased compared to 2021, while that of JCWF experienced a slight decrease. Figure 5 illustrates that among the various improved treatments, the increases in FAC for JCWH and JCWF were more significant than that of JCW. Nevertheless, the FAC/SOC ratio for JCWH exhibited a downward trend, decreasing by 7.7% over the two years, whereas the FAC/SOC ratios for JCW and JCWF showed upward trends, increasing by 5.8% and 8.2%, respectively. Importantly, after two years, the FAC of all amendment treatments significantly exceeded that of the ZCK soil.

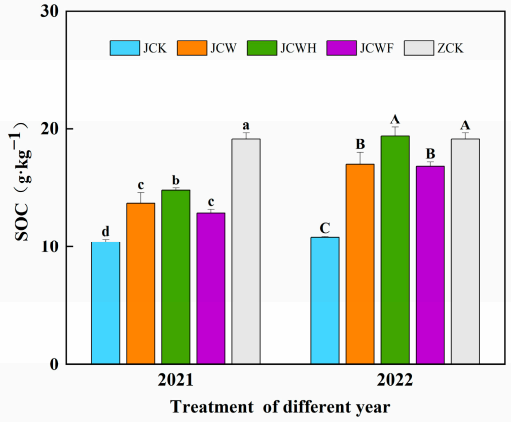


Figure 3. The effect of different improvement treatments on soil organic carbon content. Control (JCK): with no amendments; straw + gypsum treatment (JCW); straw + gypsum + sulfuric acid treatment (JCWH); straw + gypsum + chemical fertilizer treatment (JCWF); the farmer's seedling-raising soil (ZCK). The symbol notation is the same as in Figure 2.

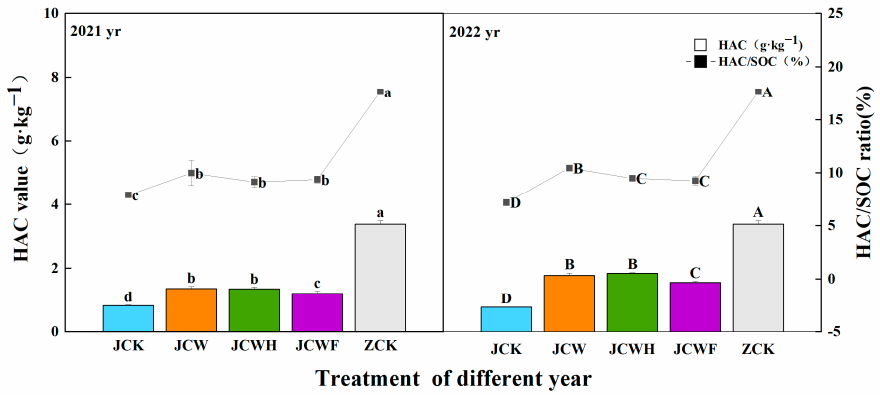


Figure 4. Effects of different improvement treatments on soil HAC content and HAC/SOC ratio. Control (JCK): with no amendments; straw + gypsum treatment (JCW); straw + gypsum + sulfuric acid treatment (JCWH); straw + gypsum + chemical fertilizer treatment (JCWF); the farmer's seedling-raising soil (ZCK). The symbol notation is the same as in Figure 2.

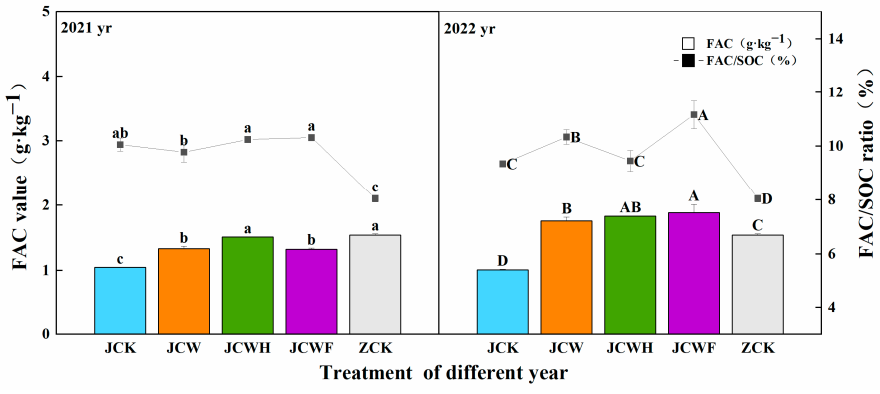


Figure 5. Effects of different improvement treatments on soil FAC content and FAC/SOC ratio. Control (JCK): with no amendments; straw + gypsum treatment (JCW); straw + gypsum + sulfuric acid treatment (JCWH); straw + gypsum + chemical fertilizer treatment (JCWF); the farmer's seedling-raising soil (ZCK). The symbol notation is the same as in Figure 2.

In comparison to JCK, the PQ values of all amendment treatments exhibited an increase over the two-year period (Table 2). The JCW treatment recorded the highest PQ value, with measurements of 50.46% and 50.30% in the respective years, followed by JCWH. Notably,

the JCWH treatment showed an upward trend across the two years, whereas the JCWF treatment showed a downward trend. Compared with JCK, the HA⊿lgK values for the JCW, JCWH, and JCWF treatments significantly increased, ranging from 11.4% to 35.9%, with a consistent year-on-year rise. Among these, the JCWH treatment displayed the highest HA⊿lgK value. Conversely, for FA⊿lgK, the values for each amendment treatment were lower than those of JCK over the two years, reflecting a decrease of 2.3% to 12.9%, which also declined year by year.

Table 2. The effects of different treatments on seedling-soil PQ value and ⊿lgK value.

Treatment	PQ (%)	HA⊿lgK	FA⊿lgK
(a) 2021 yr			
JCK	44.04 ± 0.54 c	0.59 ± 0.01 d	0.96 ± 0.01 a
JCW	50.46 ± 2.04 a	0.71 ± 0.02 b	0.94 ± 0.02 ab
JCWH	47.16 ± 1.14 b	0.74 ± 0.01 a	0.92 ± 0.02 b
JCWF	47.64 ± 1.18 b	0.66 ± 0.00 c	0.91 ± 0.00 b
(b) 2022 yr			
JCK	43.44 ± 0.13 b	0.58 ± 0.01 c	0.96 ± 0.01 a
JCW	50.30 ± 0.30 a	0.73 ± 0.01 b	0.93 ± 0.06 a
JCWH	50.18 ± 0.35 a	0.79 ± 0.00 a	0.85 ± 0.01 b
JCWF	45.38 ± 2.22 b	0.72 ± 0.01 b	0.83 ± 0.01 b

Figures sharing similar small letters in columns in a year are not statistically different at $p = 5\%$.

3.3. Growth Status of Rice Seedlings

Two years of experimental data indicate that, overall, as the years progressed, the dry weight, plant height, and root length of seedlings treated with JCW exhibited a decreasing trend (Figure 6). In contrast, the dry weight and plant height of seedlings treated with JCWH and JCWF showed significant increases. Notably, the root length of seedlings under the JCWF treatment was longer in 2022. The variation in leaf age across all amendment treatments was minimal. Compared to the control group (JCK), all amendment treatments significantly enhanced the dry weight of seedlings by 67.31% to 149.21%, increased root length by 15.38% to 62.26%, and elevated plant height by 71.7% to 133.5%. After two years, seedlings treated with JCWH reached a height of 20.91 cm and a weight of 24.83 mg, demonstrating no significant difference when compared to the farmer's seedling-raising soil ZCK ($p > 0.05$).

A correlation analysis can further elucidate the relationship between the physical and chemical properties of amended soils, the soil organic carbon and its components, and the growth parameters of rice seedlings (Figure 7). All amendment treatments, including the application of straw, gypsum, sulfuric acid, and chemical fertilizers in soda saline–alkali soil, have demonstrated significant effects in improving the soil physical and chemical properties, enhancing soil fertility, and promoting seedling growth. The seedling growth parameters, such as seedling height (SH), leaf age (LA), and seedling dry weight (SDW), exhibited a negative correlation with the physical and chemical properties of soils, including total alkalinity (TA), exchangeable sodium (ES), and pH, while showing a significantly positive correlation with soil EC. Furthermore, the seedling growth parameters (SH, root length (RL), LA, and SDW) displayed a positive correlation with soil-fertility-related parameters, including SOC, HAC, FAC, HA⊿lgK, and PQ values, while demonstrating a negative correlation with FA⊿lgK.

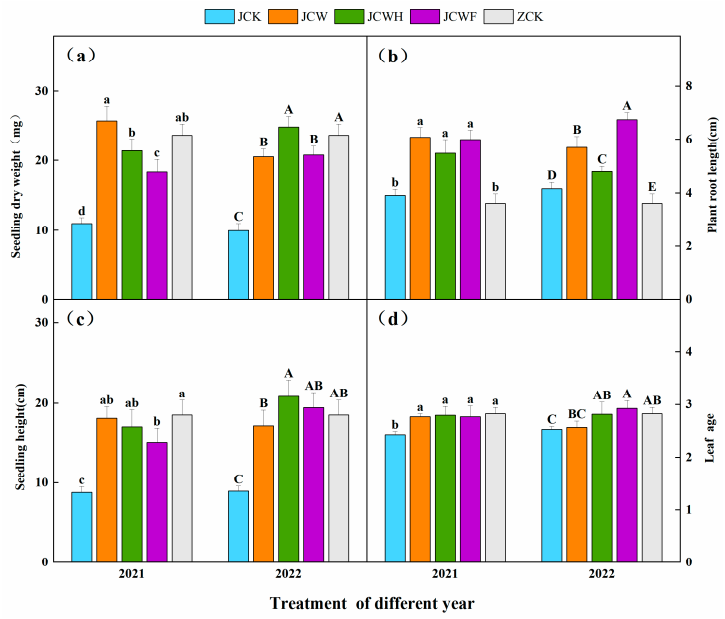


Figure 6. Effects of different improvement treatments on seedling dry weight (**a**), plant root length (**b**), seedling height (**c**), and leaf age (**d**). Control (JCK): with no amendments; straw + gypsum treatment (JCW); straw + gypsum + sulfuric acid treatment (JCWH); straw + gypsum + chemical fertilizer treatment (JCWF); the farmer's seedling-raising soil (ZCK). The symbol notation is the same as in Figure 2.

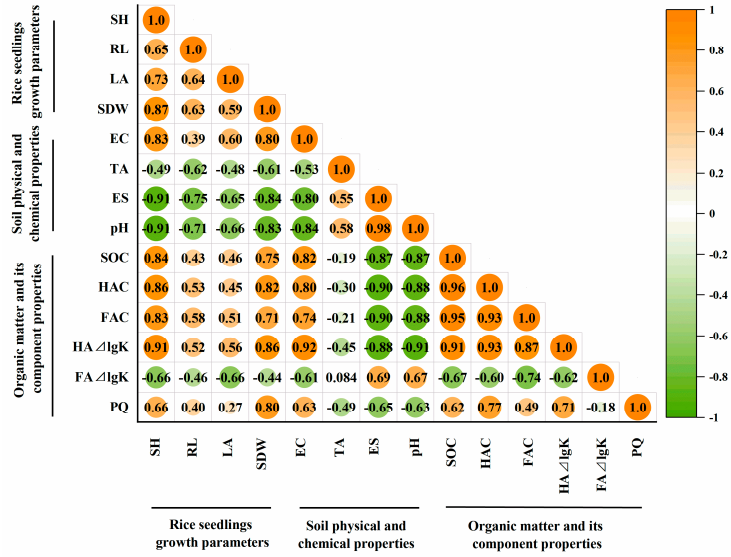


Figure 7. Pearson correlation analysis of seedling quality parameters with indicators relative to soil salinity, alkalinity, and fertility under different improvement treatments. SH, seedling height; RL, root length; LA, leaf age; SDW, seedling dry weight; EC, electrical conductivity; TA, total alkalinity; ES, exchangeable sodium; SOC, soil organic carbon; HAC, humic acid carbon; FAC, fulvic acid carbon; HA⊿lgK, color tone coefficient of humic acid; FA ⊿lgK, color tone coefficient of fulvic acid; PQ, humification coefficient.

4. Discussion

4.1. Short-Term Improvement Enhances the Physicochemical Properties of Saline–Alkali Soil

Under the 2-year short-term soil improvement involving gypsum, straw, and other amendments, notable changes occurred in the physical and chemical properties of the soil. Specifically, the soil pH and exchangeable sodium decreased significantly over the years, while the electrical conductivity (EC) value exhibited an annual increase. The total alkalinity

displayed a trend of initially decreasing and then increasing (Figure 2). In alignment with the experimental findings of Abdel-Fattah [23] and Ghafoor [24], this study also observed a significant reduction in the soil pH and exchangeable sodium. The observed decrease in pH could be attributed to the presence of acidic substances and acidifications generated due to the amendments [6,15], as well as the macromolecular carboxyl groups formed through the humification of straw [25,26], which exerted neutralizing effects on alkaline ions. The reduction in exchangeable sodium primarily resulted from the enhancement of the Ca–Na exchange process facilitated by gypsum [27]. Moreover, Ca^{2+} ions reduced the electrokinetic potential of the soil colloid surfaces, promoting colloid coagulation, which subsequently increased soil hydraulic conductivity and enhanced the leaching of sodium [28,29]. The extent of the decrease in pH and exchangeable sodium across treatments was ranked as follows: JCWH > JCWF > JCW (Figure 2a,c), with JCWH demonstrating the most effective results. While sulfuric acid lowered the pH of saline–alkali soil, it also facilitated the dissolution of deposited calcium in the soil, thereby enhancing Ca–Na replacement [15].

Similar to the research trends observed by Zhao [30], El Hasini [31], and others, this study found that the EC values of all amendment treatments were higher than those of the control group (Figure 2b). This phenomenon can be attributed to the extended cultivation time of the soil, which facilitates a more complete dissolution of soluble salts [32]. Zhao et al. [30] also reported that the application of gypsum and straw to saline–alkali soil resulted in decreases in the soil pH and exchangeable sodium percentage (ESP), while the EC increased by 31.79% compared to the control group. Furthermore, the concentrations of ions detrimental to plant growth, such as Na^+ and Cl^-, were significantly reduced, whereas the levels of beneficial ions, such as Ca^{2+} and SO_4^{2-}, were significantly increased. These outcomes resulted from the effective improvement process.

In this study, the total alkalinity of all amendment treatments in 2021 was significantly reduced. However, an upward trend was observed in 2022 (Figure 2d). The total input of straw carbon was identified as a key driving factor [33]. In carbon-rich and alkaline soils, the continuous application of substantial amounts of straw promoted the mineralization of soil organic carbon (SOC) and resulted in the accumulation of calcium bicarbonate, thereby increasing total alkalinity. This impact can be mitigated by reducing the quantity of straw applied.

4.2. Short-Term Improvement Promotes Soil Fertility Enhancement

Organic matter is widely recognized as a crucial component of soil fertility. In a rice-seedling-raising experiment utilizing short-term improvement, the organic carbon (SOC) in the seedling-raising soil exhibited significant enhancement (Figure 3). In alkaline soils, gypsum, which serves as an exogenous source of calcium, exerts a strong bridging effect that facilitates the connection between organic carbon and minerals, thereby promoting soil clay flocculation [34]. This function enhances the stability and accumulation of SOC [35,36]. Furthermore, decomposed substances from straw can act as a cementing agent [37], contributing to the formation of microstructures, such as calcium-bonded organic carbon [38]. Research has demonstrated a positive correlation between exchangeable calcium (ECa) and SOC [39]. Our findings indicated that after two years of improvement, the SOC of the JCWH-treated soil was the highest and did not show significant differences compared to that of the ZCK soil.

The composition of soil organic matter profoundly influences soil properties and the multifunctionality of ecosystems. Humic acid (HA) and fulvic acid (FA) are the primary active components of organic matter. HA significantly impacts soil fertility and structural stability [40]. The aromatic compounds in HA, including carboxyl and hydroxyl groups, can form organic–inorganic complexes with polyvalent cations at the active sites of min-

eral colloids, thereby enhancing the formation of microaggregates [41]. In this study, all amendment treatments significantly increased the amounts of HAC and FAC in the soils (Figures 4 and 5). In accordance with the findings of Li et al. [42], the FAC/SOC ratio in 2022 decreased in the JCWH treatment, while the HAC/SOC ratio increased, indicating a transformation trend from FA to HA. From the perspective of humic acid accumulation, the JCWH treatment demonstrates distinct advantages.

In this study, after two years of short-term improvement, the PQ values and ΔlgK values of HA in all amendment treatments were found to be higher than those of the control group, whereas the ΔlgK values of FA were lower than those of the control group (Table 2). The addition of straw organic materials promotes the renewal and activation of soil organic matter, thereby enhancing the degree of humification in the soil [43]. Notably, the PQ value of the JCWH treatment increased progressively over the years, while that of the JCWF treatment exhibited a year-on-year decline. This indicates that the application of sulfuric acid significantly enhances the quality of soil humus. The HA ΔlgK value of the JCWH-treated soil was the highest, suggesting that the addition of sulfuric acid effectively reduces both the oxidation and aromatization degrees of HA, increases the aliphatic carbon content, and simplifies its structure [44].

4.3. Short-Term Improvement Enhances the Growth Status of Seedlings

The salt and alkali stress associated with soda saline–alkali soil poses significant threats to plant growth [45], as it impedes the absorption and transportation of essential nutrient ions. This study conducted short-term improvement aimed at rapidly improving soda saline–alkali soil, thereby ameliorating the saline–alkali stress environment and enhancing the utilization efficiency of carbon, nitrogen, and phosphorus, which in turn promotes nutrient absorption by plants [46]. Following the soil amendment treatments, marked increases were observed in the dry weight, root length, and height of rice seedlings (Figure 6). The addition of exogenous calcium is crucial for alleviating saline–alkali stress, a mechanism corroborated by the findings of Cao [47] and Rahman [45]. Supplementing seedlings with exogenous calcium enhances the selective absorption and stability of potassium by rice roots, while simultaneously reducing sodium absorption and improving plants' salt tolerance [48,49]. This study corroborated these findings: under the gypsum application method, rice-seedling growth was notably improved. The dry weight and height of seedlings in the JCWH-treated soil surpassed those of seedlings in the farmer's seedling-raising soil, ZCK. This can be attributed to the increased dissolution of calcium in the soil due to sulfuric acid, as well as the ability of sulfuric acid to neutralize soil alkalinity and reduce alkaline stress. Notably, in 2022, the root length of seedlings in the JCWH-treated soil was shorter than that in 2021 (Figure 6b), potentially due to increased soil EC and total alkalinity that year, which inhibited root growth [50]. This impact may be mitigated by reducing the dosage and frequency of the modifier application.

This study demonstrates a significant correlation between the quality of rice seedlings and the parameters of soil salinity and alkalinity, as well as the amount of organic carbon and its components. The findings suggest that short-term improvements to saline–alkali soil can be achieved by applying straw, gypsum, sulfuric acid, and fertilizers. These amendments can reduce salt–alkali stress and enhance nutrient absorption by lowering soil pH and exchangeable sodium, while also increasing the amount of soil organic carbon and its components, ultimately promoting seedling growth (Figure 7).

5. Conclusions

In this study, the short-term improvement treatments of applying corn stover, gypsum, sulfuric acid, and chemical fertilizers for two consecutive years all played a positive role in

improving the soil physicochemical properties and enhancing soil fertility. Firstly, these treatments significantly reduced soil pH and alkalinity. The application of exogenous calcium facilitated Ca–Na exchange, thereby decreasing soil alkalinity. The decomposition of corn straw contributed nutrients and acidic substances, such as humic acid. The acidification effects of sulfuric acid and chemical fertilizers further neutralized soil alkalinity. These actions enhanced the solubility and mobility of nutrients, effectively alleviating the ecological barriers posed by saline–alkali soil. Moreover, the short-term improvement treatments increased the contents of soil organic matter and humic acid, and the degree of soil humification, ultimately enhancing soil fertility. The increase in the number of calcium ions promoted the fixation of organic carbon, thereby improving the nutrient content and availability in the soil, which meets the growth requirements of crops. Among all the treatments, the JCWH treatment exhibited a more comprehensive effect compared to JCW and JCWF, proving to be more beneficial for enhancing both the quantity and quality of organic matter.

The short-term improvement treatment was applied to soil in rice-seedling cultivation experiments, resulting in significant increases in the dry weight of plants, root length, and plant height. Exogenous calcium helped plants to alleviate growth pressure under salt stress, thereby increasing nutrient utilization and crop productivity. Compared to the farmer's seedling-raising soil, the JCWH-treated soil significantly enhanced seedling growth, demonstrating superior performance in the seedling-cultivation indicators. The combined application of corn straw, gypsum, and sulfuric acid (JCWH) served as an effective improvement scheme for soda saline–alkali soil, making the improved soil meet the growth requirements of rice seedlings. This study provides a theoretical foundation and technical support for the comprehensive improvement and application of soda saline–alkali soil.

Author Contributions: Conceptualization, Y.N.; Methodology, Y.N. and Z.L.; Software, X.L. and L.F.; Validation, Y.N. and Z.L.; Formal analysis, Y.N. and L.J.; Investigation, Y.N. and X.L.; Resources, Z.L.; Data curation, Y.N. and L.J.; Writing—original draft, Y.N.; Writing—review and editing, Y.N. and Z.L.; Visualization, Y.N. and L.F.; Supervision, Y.N. and Z.L.; Project administration, Z.L.; Funding acquisition, Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China, grant number [2018YFD0300208].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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