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Improving Soil Properties by Sand Application in the Saline-Alkali Area of the Middle and Lower Reaches of the Yellow River, China

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Abstract: Excessive soil salinity is a problem that makes soil unusable for agriculture, and most current research focuses on either chemical supplements or water conservation measures. Nevertheless, more information is needed about how sand treatment affects soil quality. In this study, a field experiment assessed the effect of sand application and cropping year on soil properties in an arid and semi-arid saline-sodic agricultural ecosystem. We found that sand application significantly improved the saline–alkali soil's physical (i.e., pH, EC, TSC, BD), chemical (i.e., OC, AN, AP), and enzyme activity (i.e., Amy, Ure, Alp, Cat) properties, and that soil AN, AP, as well as TSC, were the crucial factors affecting soil properties. Simultaneously, soil properties gradually improved along with increasing cropping years, although these increases gradually became small. Our findings highlight the potential of sand as a soil supplement to enhance soil quality and structure in semi-arid agricultural ecosystems, especially when considering the cost.

Keywords: sand application; soil physicochemical properties; soil enzyme; saline-alkali soil

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1. Introduction

Salinization has been an issue globally as anthropogenic activity and climate change intensify, drastically lowering soil quality and the amount of cultivated land [1,2]. According to statistics, excessive soil salinization has decreased crop output on up to one-fourth of the world's arable land [3,4]. There were 340,000 km^2 of saline-sodic land in China in 2015, according to the Chinese Ministry of Agriculture, with roughly 33% of that area having the ability to support crop growth with fairly good remediation [5].

Wang et al. [5] found that the application of FGD gypsum significantly reduced soil salinity, improved soil structure, and increased crop yield. The researchers found that FGD gypsum application reduced soil exchangeable sodium percentage (ESP) and increased soil organic matter content, available phosphorus, and available potassium. The study also found that the effects of FGD gypsum on soil amelioration were more pronounced in the surface soil layer compared to the subsoil layer.

The unfortunate increase in saline-sodic soil in China requires different management practices. Researchers have expended great effort over the last twenty years, including human and financial or material resources, to improve saline-alkali soil [6–9]. The study by [9] found that the addition of organic amendments significantly increased soil pH, total organic carbon, and microbial biomass. Furthermore, the amendments improved the soil's ability to retain water and nutrients, which can be beneficial for plant growth. The results suggest that the addition of organic amendments can be an effective strategy for improving the quality of sodic clay subsoil.

For instance, gypsum could provide abundant Ca^{2+} to replace exchangeable Na+ in saline-sodic soils, a benefit for which gypsum has been widely used to deal with these issues [10]. In addition, biological and organic amendments have also been used to remediate the saline-sodic land [11]. Li et al. [11] found that the addition of both organic and inorganic amendments improved soil properties, including increasing pH, electrical conductivity, organic carbon content, and enzyme activity. The combination of organic and inorganic amendments was found to be more effective than using either amendment alone. The study suggests that the use of organic and inorganic amendments can be an effective strategy for the remediation of saline-sodic soils. However, organic amendments and inorganic improvements both have some drawbacks, such as high cost, instability, and easy degradation, especially the high cost for engineering use; therefore, when implementing an established saline-alkali land project, the actual effect and specific costs should be considered. The increase in saline-sodic soils in China has been caused by a combination of natural and human-induced factors. Natural factors include high evaporation rates, low precipitation, and poor drainage conditions in arid and semi-arid regions. Human-induced factors include excessive irrigation, inappropriate agricultural practices such as excessive use of chemical fertilizers and pesticides, and industrial activities that produce and release salts into the environment. Climate change and soil erosion also contribute to the problem.

The saline-alkali area of the middle and lower reaches of the Yellow River, with an area of about 1.2×10^4 km^2, is one of the five largest saline-alkali regions in China, which severely restricts the development of local agriculture husbandry [12]. What is not expected is that another discordant ecosystem, namely Mu Us Sandy Land, surrounds the saline-sodic land. Soil salinization or desertification is a massive challenge for agricultural production [13,14]. The study by [14] found that the soil in the desert was generally alkaline and deficient in nitrogen and phosphorus. The paper concluded that soil amendment and fertilization were necessary for agricultural development. Amazingly, crop growth has been significantly improved after mixing sand into the saline-sodic soil by the local population. Accordingly, numerous studies have been conducted to assess the impact of sand-covering on saline-alkali soil cultivation. It has been demonstrated that it can improve plant stress resistance under salt stress. Zhou (2011) reported that sand-covering significantly increased the production of *Zea mays* L., a crucial coarse grain crop, for local farmers [15]. Similarly, sand application alleviates salt stress leading to improved quality and yield of *Lolium perenne* L. in saline arable land [16]. However, few studies have examined its impact on saline-sodic soil properties.

In this study, the researchers aimed to investigate the effectiveness of sand application for improving soil properties in the saline-alkali area of the middle and lower reaches of the Yellow River in China. A field experiment was conducted, and the results indicated that sand application significantly improved the soil's physical, chemical, and enzyme activity properties. The study also found that soil AN, AP, and TSC were the crucial factors affecting soil properties. The researchers suggested that sand application could be an effective soil supplement for enhancing soil quality and structure in semi-arid agricultural ecosystems. This study provides valuable insights into soil amelioration techniques and has practical implications for sustainable agriculture in saline-alkali areas.

Considering low pH, low salt content and loose structure [17,18], we predicted that sand application would significantly affect saline-sodic soil's physical, chemical, and enzyme-activity properties. A field experiment was designed to enable the improvement of saline-sodic soil property to be mapped and to answer the following issues: (1) How does the saline-sodic soil property respond to the sand application? (2) Which coefficient plays a more significant role in shaping the saline-sodic soil property? (3) How does the saline-sodic soil property change along with cultivation years?

2. Materials and Methods

2.1. Experimental Site

A long-term sand addition field experiment started implementation in 2015 at the pilot site (108°20′ E, 37°54′ N) of the Key Laboratory of Degraded and Unused Land Consolidation Engineering, the Ministry of Nature and Resource, China, which is an area that has a representative continental arid and semi-arid climate (Figure 1a). In addition, this region's average annual temperature, sunshine hours, and rainfall are 7.9 °C, 2700 h, and 397 mm, respectively. The soil at this location, which is silty loam, has a bulk density of 1.61 g cm^{-3} and is composed of 25% silt, 68% sand, and 7% clay. Before the experiment started, the original saline-sodic soil was characterized by high salinity and a lack of soil nutrients. The fundamental soil characteristics are listed in Table 1.

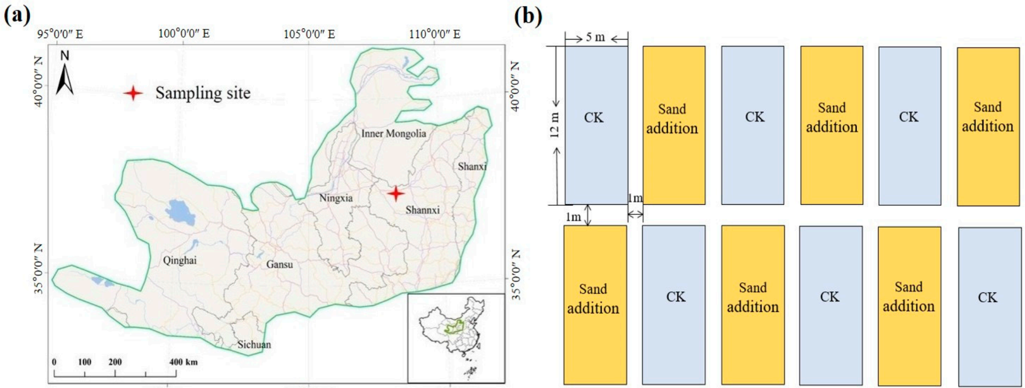

Figure 1. Geographic location (**a**) and floor plan (**b**) in this study.

Table 1. Basic properties of the soil at the test site (n = 6).

Characteristic	Value
PH $_{1:5}$	8.77
EC $_{1:2.5}$/(mS cm^{-1})	4.28
Total salt content/(%)	8.82
Bulk density/(g cm^{-3})	1.62
Organic matter/(g kg^{-1})	3.32
Available nitrogen/(mg kg^{-1})	32.11
Available phosphorus/(mg kg^{-1})	10.14
Amylase activities/(mg g^{-1} 24 h^{-1})	0.96
Urease activity/(mg g^{-1} 24 h^{-1})	0.08
Alkaline phosphatase activity/(mg g^{-1} 24 h^{-1})	0.13
Catalase activity/(mL g^{-1} h^{-1})	2.51

2.2. Experimental Design

The soil's physical, chemical, and enzyme-activity properties respond to sand addition in the saline-sodic soil; experimental plots based on a maize (*Zea mays* L.) single-cropping system were established in April 2017 in six sand-addition saline-sodic farmlands (Sand addition, +), namely, covering sand with a thickness of about 30 cm over the surface of saline-alkali soil and then mixing well, as well as six sand-free saline-sodic farmlands (sand free, CK(−)) alternately arranged in two rows, with a 1 m isolated area (Figure 1b).

The experimental crop was Zhengdan 958, corn varieties, with a planting density of 6.7×10^6 plants/km^2. The identical chemical fertilizer rate of 75 kg N (urea), 24.6 kg P (P_2O_5), and 46.7 kg K (K_2O) per ha was applied to all plots. Before planting, each fertilizer (which made up half of the nitrogen) was administered to the soil once. The remaining half of the nitrogen was used as a top dressing during the maize growing season. The local agricultural sector decided upon these dosages.

The sand used in the experiment was taken from the Mu Us Sandy Land, adjacent to the experimental area, with a low pH (7.1), low salt content (0.07%), loose structure as well as exceedingly low soil physicochemical properties. Thanks to the convergence of the Mu Us Sandy Land and the saline-alkali area in the middle and lower reaches of the Yellow River, it is possible to improve the saline-alkali land from a cost standpoint.

2.3. Soil Sampling and Assays

After the harvest of maize in 2017, 2018, 2019, and 2020, a composite sample was created by combining six randomly selected cores (3.8 cm in diameter, 25 cm in depth). The microscopic structure of samples was characterized by FEI Q45 SEM [11]. One-third of the soil (about 200 g) samples were stored at 4 °C to determine soil enzyme-activity properties. In addition, to measure bulk density (BD), undisturbed soil was collected using stainless steel rings (5 cm in height, 5 cm in diameter). The leftover soil was air-dried naturally, crushed, and put through a 2 mm mesh sieve for physical and chemical property analysis.

The process of determining soil physicochemical properties (including pH, soil organic carbon (SOC), available nitrogen (AN) and available phosphorus (AP), electrical conductivity (EC) and bulk density (BD) was conducted using the same methods described by Zheng [19].

A reaction mixture (4 mL) consisting of 1 mL of enzyme solution and 2 mL of soluble starch in phosphate buffer (pH 6.5) was used to assay the soil amylase activity. The mixture was incubated for 10 min at 30 °C. The level of reducing sugars was determined using the dinitrosalicylate method and is expressed in units.

Urease (Ure) activity was assessed using the indophenol blue colorimetric method. First, a 5 g soil sample was added to a 50 mL triangular flask with 1 ml toluene, shaken evenly. Second, 10 mL of 10% urea solution and 20 mL of pH 6.7 citrate buffer solution as the substrate were added and mixed thoroughly after 15 min. The mixture was incubated in the dark at 37 °C for 24 h and then diluted with distilled water to 50 mL. After filtration, 1 ml of filtrate was added to a 50 mL volumetric flask, followed by 4 mL of sodium phenol solution and 3 mL of sodium hypochlorite solution. After 20 min, the color was developed, and the volume was fixed, followed by colorimetric colorimetry at 578 nm using a spectrophotometer within 1 h.

Alkaline phosphatase (Alp) activity was measured following the disodium phenyl phosphate colorimetric method. First, 2.5 mL toluene was added to a 200 mL volumetric flask containing 5g soil samples, shaken gently for 15 min. Then, 20 mL of 0.5% disodium benzene phosphate as the substrate was added and mixed thoroughly. The mixture was incubated in the dark at 37 °C for 24 h. Second, 100 mL of 0.3% $Al_2(SO_4)_3$ solution was added to the mixture, and then 3 mL filtrate was added into a 50 mL volumetric flask. When using a boric acid buffer, it appears blue and is colorimetric at 660 nm on a spectrophotometer.

Catalase (Cat) activity was quantified according to the permanganimetric method. First, 0.5mL of toluene was added to a 50 mL volumetric flask containing 5 g soil samples, shaken well, and placed in a refrigerator at 4 °C for 30 min. Second, 25 mL of 3% H_2O_2 solution stored in the refrigerator was added to the mixture at 4 °C for 60 min. Third, 25 mL of 2 mol/L H_2SO_4 solution stored in the refrigerator was added to the mixture quickly, and then shaken well. Fourth, 1 mL of filtrate was placed in a triangular flask containing 5 mL of distilled water and 5 mL of 2 mol/L H_2SO_4 solution, and then titrated with 0.02 mol/L $KMnO_4$ solution. Based on the titration difference of the control and the sample, the amount of $KMnO_4$ consumed was calculated for the amount equivalent to the decomposed H_2O_2. Catalase activity is expressed as the volume of 0.1 mol/L $KMnO_4$ consumed per g of dry soil within 1 h.

All these soil enzyme activity detection methods were carried out according to Guan [20].

2.4. Statistical Analyses

The statistical significance of physicochemical characteristics and enzyme activity between various treatments was assessed using a two-way analysis of variance (ANOVA) followed by Fisher's least significant difference (LSD). Simultaneously, the relationship between soil physicochemical characteristics and soil enzyme activity was estimated using Pearson correlation analysis. The dissimilarities of the soil's physical, chemical, and enzyme-activity properties among treatments were elucidated using principal component analysis (PCA) [21]. All statistical analyses were performed using R (v.3.3.2; https://www.r-project.org/, accessed on 28 March 2023) [22] and Microsoft Excel v. 2016 (Microsoft Corp., Redmond, WA, USA).

3. Results

3.1. Effects of Sand Addition on Physical Properties of Soil in the Field

Sand addition reduced soil pH ($F = 123.30$, $p < 0.001$) and soil EC ($F = 1371.44$, $p < 0.001$), increased soil TSC ($F = 538.44$, $p < 0.001$) and soil BD ($F = 16.36$, $p < 0.001$), although the number of years of cultivation had no significant impact on the soil's physical properties involved in pH ($F = 3.36$, $p = 0.06$), EC ($F = 2.33$, $p > 0.05$), TSC ($F = 4.32$, $p > 0.05$), BD ($F = 0.15$, $p > 0.05$). After sand addition, soil pH and EC reduced with the increase of farming years, and the lowest soil pH with a value of 7.79 appeared in 2017, but there was no significant difference among the other years. Similarly, the lowest soil EC with a value of 1.11 appeared in 2017; no significant difference was found among the other years. Furthermore, there was no significant interaction between the sand addition and the farming years according to the ANOVA results (Table 2). Increased soil aperture due to sand application was discovered from the typical SEM images of the sample from 2018 (Figure 2).

Table 2. Physical properties of the soil for the sand addition treatments (+) and sand-free treatments (−) in different years in the field (mean ± SE, n = 6) and the significance of year effect on each variable. Significant diferences of each variable among treatments are indicated by dissimilar lowercase letters.

Year	Sand (+/−)	pH	EC/(mS cm^{-1})	TSC/(%)	BD/(g cm^{-3})
2017	−	8.77 ± 0.15	4.28 ± 0.45	8.67 ± 0.45	1.62 ± 0.14
2018	−	8.67 ± 0.23	4.31 ± 0.22	8.62 ± 0.55	1.67 ± 0.11
2019	−	8.75 ± 0.19	4.26 ± 0.15	8.53 ± 0.42	1.56 ± 0.15
2020	−	8.74 ± 0.11	4.28 ± 0.21	8.62 ± 0.33	1.61 ± 0.17
2017	+	7.79 ± 0.13 ^{b}	1.11 ± 0.15 ^{b}	3.27 ± 0.45	1.47 ± 0.11
2018	+	8.35 ± 0.10 ^{a}	1.32 ± 0.21 ^{a}	3.76 ± 0.75	1.42 ± 0.12
2019	+	8.21 ± 0.09 ^{a}	1.26 ± 0.07 ^{a}	3.45 ± 0.23	1.43 ± 0.13
2020	+	8.24 ± 0.11 ^{a}	1.32 ± 0.13 ^{a}	3.23 ± 0.34	1.46 ± 0.15
Summary of treatment effects					
Year (Y)	*F*-value	3.36	2.33	4.32	0.15
	p-value	0.06	ns	ns	ns
Sand addition (S)	*F*-value	123.30	1371.44	538.44	16.36
	p-value	<0.001	<0.001	<0.001	<0.001
Y × S	*F*-value	2.74	0.18	0.20	0.01
	p-value	ns	ns	ns	ns

3.2. Effects of Sand Addition on the Soil's Chemical Properties in the Field

Sand addition leads to a significant increase in OC ($F = 5.66$, $p = 0.02$), AN ($F = 75.06$, $p < 0.001$), in AP ($F = 111.15$, $p < 0.001$). In addition, OC ($F = 106.90$, $p < 0.001$), AN ($F = 237.67$, $p < 0.001$), and AP ($F = 271.30$, $p < 0.001$) were also affected significantly by cultivation years. Furthermore, a strong interaction (Sand addition × cultivation years) impact on AN ($F = 41.87$, $p < 0.001$) and AP ($F = 30.86$, $p < 0.001$) was detected in the experiment. Compared to the sand addition treatment, irregular chemical properties of the soil can be found in the sand-free treatment (CK), except for the AP, which increased with cultivation years. However, for the sand addition treatment, the lowest OC was recorded in 2017 (35.57 mg kg^{-1}) and the highest in 2020 (49.36 mg kg^{-1}), showing a strong regularity, namely, OC increased with cultivation years. Similar to OC, the contents of AN and AP of each year treatment were ordered as follows: 2020yr > 2019yr > 2018yr > 2017yr (Table 3).

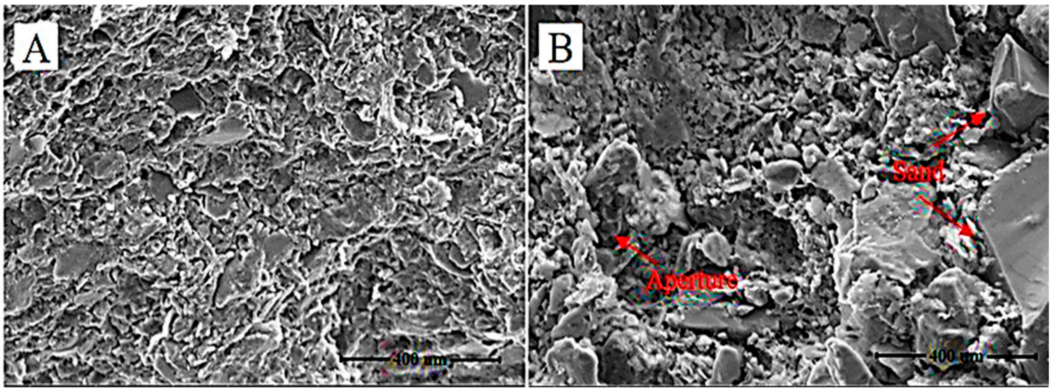

Figure 2. The SEM images of soil sampling from sand-free (CK) treatment (**A**) and sand application treatment (**B**), respectively (150×). Picture by wangjian.

Table 3. The soil's chemical properties for the sand addition treatments (+) and sand-free treatments (−) in different years in the field (mean ± SE, n = 6) and the significance of year effect on each variable. Significant diferences of each variable among treatments are indicated by dissimilar lowercase letters.

Year	**Sand (+/−)**	**OC/(g kg^{-1})**	**AN/(mg kg^{-1})**	**AP/(mg kg^{-1})**
2017	−	3.19 ± 0.12^{b}	32.82 ± 1.67^{a}	9.51 ± 0.90^{b}
2018	−	3.64 ± 0.21^{a}	30.21 ± 2.28^{b}	10.40 ± 0.74^{b}
2019	−	3.32 ± 0.25^{b}	32.92 ± 2.14^{a}	10.42 ± 1.30^{b}
2020	−	3.38 ± 0.24^{ab}	34.15 ± 1.06^{a}	12.51 ± 0.46^{a}
2017	+	3.82 ± 0.10^{c}	35.57 ± 3.08^{d}	12.17 ± 1.16^{d}
2018	+	3.97 ± 0.14^{b}	41.23 ± 1.71^{c}	15.11 ± 0.93^{c}
2019	+	4.03 ± 0.11^{ab}	46.10 ± 3.61^{b}	17.68 ± 1.06^{b}
2020	+	4.14 ± 0.14^{a}	49.36 ± 1.12^{a}	19.02 ± 0.85^{a}
Summary of treatment effects				
Year (Y)	*F*-value	5.66	75.06	111.15
	p-value	0.02	<0.001	<0.001
Sand addition (S)	*F*-value	106.90	237.67	271.30
	p-value	<0.001	<0.001	<0.001
Y × S	*F*-value	2.07	41.87	30.86
	p-value	ns	<0.001	<0.001

3.3. Effects of Sand Addition on the Soil's Enzyme-Activity Properties in the Field

Table 4 shows that the soil's enzyme-activity properties were affected not only by sand addition but also by cultivation years (all $p < 0.05$), except for the Alp-activity properties, for which the discrepancy shows that it is not sensitive to cultivation years ($p > 0.05$). Sand addition increased the soil's Amy-activity properties ($F = 183.08$, $p < 0.001$), Ure-activity properties ($F = 101.22$, $p < 0.001$), Alp-activity properties ($F = 324.91$, $p < 0.001$), and Cat-activity properties ($F = 802.0$, $p < 0.001$), respectively. Furthermore, all soil enzyme-activity properties rose gradually across the cultivation years under the sand addition treatment. The Amy activity under sand addition was significantly higher in 2018 (1.43 mg g^{-1} 24 h^{-1}), 2019 (1.46 mg g^{-1} 24 h^{-1}), and 2020 (1.51 mg g^{-1} 24 h^{-1}) than that in 2017 (1.21 mg g^{-1} 24 h^{-1}). Ure activity was highest in 2020 (0.16 mg g^{-1} 24 h^{-1}) and lowest in 2017 (0.11 mg g^{-1} 24 h^{-1}). In addition, Alp activity increased by 15% in the last two years compared to the first two years. Similarly, the lowest Cat activity was recorded in 2017 (2.74 mL g^{-1} h^{-1}) and the highest in 2020 (3.61 mL g^{-1} h^{-1}).

Table 4. Soil enzyme activity for the sand addition treatments (+) and sand-free treatments (−) in different years in the field (mean ± SE, n = 6) and the significance of year effect on each variable. Significant diferences of each variable among treatments are indicated by dissimilar lowercase letters.

Year	Sand (+/−)	Amy /(mg g^{-1} 24 h^{-1})	Ure /(mg g^{-1} 24 h^{-1})	Alp /(mg g^{-1} 24 h^{-1})	Cat /(mL g^{-1} h^{-1})
2017	−	0.94 ± 0.125	0.08 ± 0.007	0.13 ± 0.010 ^{a}	2.51 ± 0.013 ^{b}
2018	−	1.01 ± 0.045	0.07 ± 0.005	0.11 ± 0.009 ^{bc}	2.44 ± 0.010 ^{b}
2019	−	0.98 ± 0.048	0.07 ± 0.009	0.09 ± 0.010 ^{c}	2.67 ± 0.005 ^{a}
2020	−	0.97 ± 0.017	0.08 ± 0.012	0.11 ± 0.010 ^{ab}	2.66 ± 0.007 ^{a}
2017	+	1.21 ± 0.058 ^{b}	0.11 ± 0.013 ^{b}	0.20 ± 0.007 ^{b}	2.74 ± 0.019 ^{c}
2018	+	1.43 ± 0.137 ^{a}	0.11 ± 0.007 ^{b}	0.20 ± 0.007 ^{b}	3.13 ± 0.012 ^{b}
2019	+	1.46 ± 0.216 ^{a}	0.16 ± 0.025 ^{a}	0.23 ± 0.031 ^{a}	3.55 ± 0.026 ^{a}
2020	+	1.51 ± 0.044 ^{a}	0.16 ± 0.032 ^{a}	0.24 ± 0.030 ^{a}	3.61 ± 0.028 ^{a}
Summary of treatment effects					
Year (Y)	*F*-value	13.07	10.09	3.03	298.6
	p-value	<0.001	0.002	0.088	<0.001
Sand addition (S)	*F*-value	183.08	101.22	324.91	802.0
	p-value	<0.001	<0.001	<0.001	<0.001
Y × S	*F*-value	9.94	7.36	19.80	118.0
	p-value	0.003	0.009	<0.001	<0.001

3.4. Correlation between the Enzyme Activities and Physicochemical Properties of the Soil

The correlation analysis between the soil's physicochemical properties (pH, EC, TSC, BD, OC, available N, P) and the soil's enzyme activities (Amy, Ure, Alp, Cat) is shown in Figure 3. The data were based on sand-free treatments (Figure 3a) and sand-addition treatments (Figure 3b). As for the sand-free treatment (CK), impressive positive correlations were detected between the soil's Amy and Cat activities and soil AN (r = 0.51, $p < 0.05$; r = 0.51, $p < 0.05$, respectively); moreover, Cat activities were remarkably positively correlated with soil AP (r = 0.46, $p < 0.05$), while, surprisingly, there was no real relationship between soil AP and Alp (r = −0.10, $p > 0.05$). Nevertheless, for the sand-addition treatment, Alp enzyme activity, including all activity, any activity, Ure activity, and Cat activity, were significantly correlated with soil OC (all $p < 0.05$).

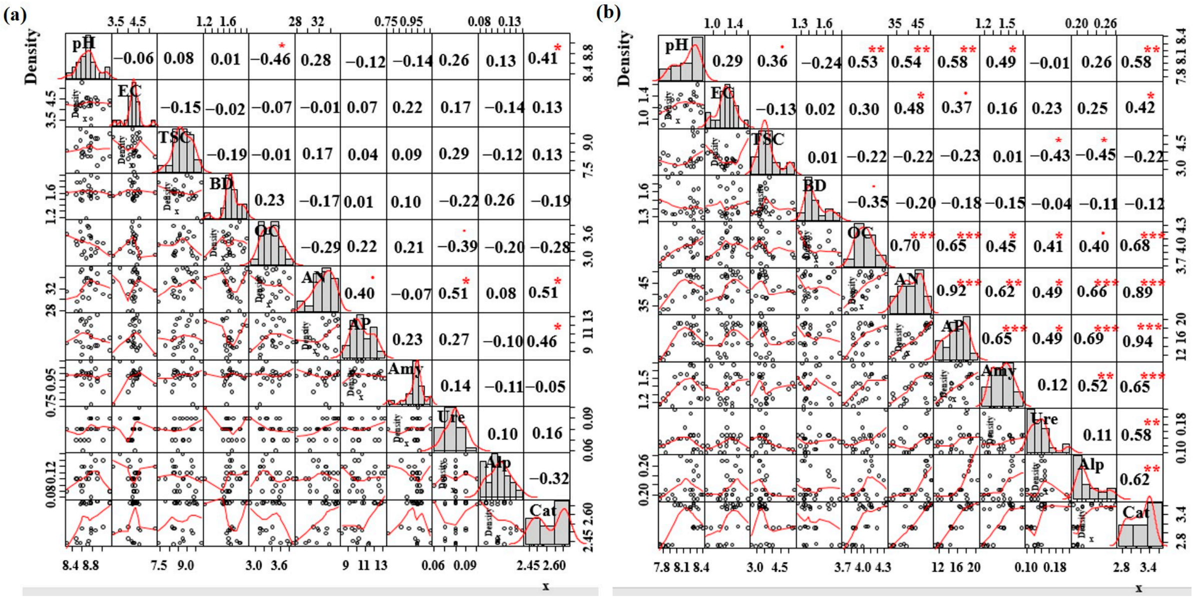

Figure 3. Correlation analysis of the soil's physical, chemical, and enzyme-activity properties before (**a**) and after (**b**) remediation in a saline-sodic soil. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; figures without * indicate $p > 0.05$.

Moreover, soil pH was discovered to correlate with soil OC ($r = 0.53$, $p < 0.01$), soil AN ($r = 0.54$, $p < 0.01$), soil AP ($r = 0.58$, $p < 0.01$) and soil Cat activity ($r = 0.58$, $p < 0.01$). Furthermore, the research also showed that the correlation between different enzyme activities became gradually correlated with each other; for instance, the soil's Cat activity was remarkably positively correlated with Alp ($r = 0.62$, $p < 0.01$), Ure activity ($r = 0.58$, $p < 0.01$), and Amy activity ($r = 0.65$, $p < 0.01$), respectively.

3.5. Principal Component Analysis of the Properties of Saline-Sodic Soil

As shown on the PCA plots, the soil's properties were quite distinct, including the physicochemical and enzyme activities of saline-sodic soil, between the sand-addition treatment and the sand-free treatment. It demonstrates that sand addition leads to a noticeable difference between the two treatments (Figure 4). The first two principal components (PCs) explained 97.756% of the variance (Table 5), which shows that these two principal components represent most of the information on saline-sodic soil. The larger the absolute value of factor-loading scores, the more strongly correlated to the relevant PC variables. Among them, the proportion explained by the first principal component (PC1) to the total variance has the most significant proportion, up to 92.78%, wherein a considerable absolute value corresponding to the magnitude of the eigenvector is AN, AP. Furthermore, PC2, a proportion explained by 4.98%, had a significant positive correlation with soil TSC (Table 6).

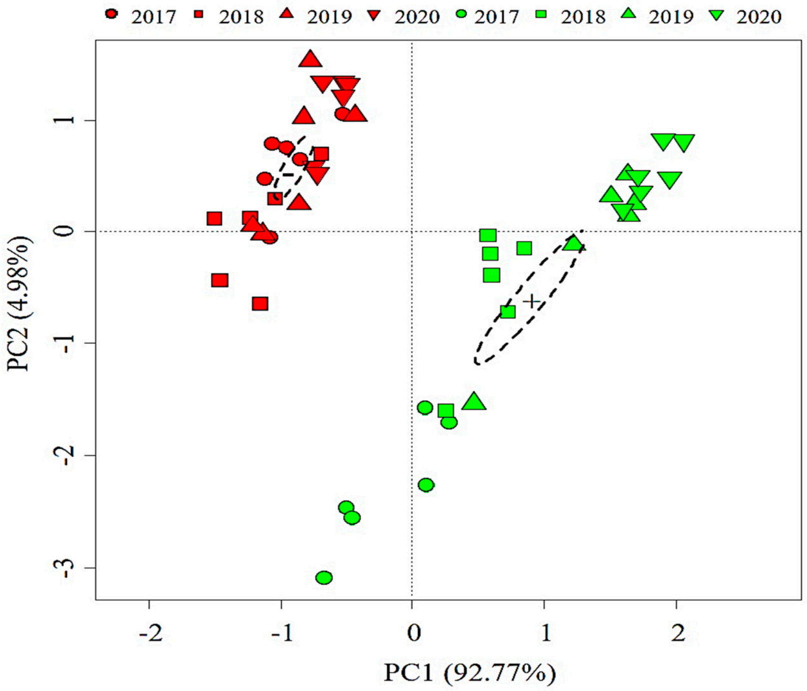

Figure 4. The principal component analysis (PCA) of soil properties includes the soil's physicochemical properties and enzyme activity between different treatments in the field experiment years. Red and green represent sand-addition treatment (−) and sand-free treatment (+). Ellipses indicate 95% confidence intervals for each treatment.

Table 5. Principal component eigenvalue, proportion explained, and cumulative proportion.

Principal Component	Eigenvalue	Proportion Explained /(%)	Cumulative Proportion /(%)
1	64.514	92.777	92.777
2	3.466	4.984	97.756
3	1.261	1.814	99.571
4	0.185	0.267	99.838

Table 5. *Cont.*

Principal Component	Eigenvalue	Proportion Explained /(%)	Cumulative Proportion /(%)
5	0.042	0.060	99.898
6	0.027	0.039	99.938
7	0.019	0.028	99.967
8	0.012	0.018	99.985
9	0.009	0.013	100
10	0.000	0.000	100
11	0.000	0.000	100

Table 6. Principal component analysis matrix.

Trait	PCA1	PCA2	PCA3
pH	−0.193	0.228	−0.009
EC (mS cm^{-1})	−1.113	0.791	−0.087
TSC (%)	−1.966	1.347	−0.121
BD (g/cm^3)	−0.077	0.020	−0.013
OC (g kg^{-1})	0.263	−0.115	−0.045
AN (mg kg^{-1})	6.213	0.581	0.397
AP (mg kg^{-1})	3.005	0.002	−0.925
Amy (mg g^{-1} 24 h^{-1})	0.196	−0.052	−0.018
Ure (mg g^{-1} 24 h^{-1})	0.027	−0.007	0.000
Alp (mg g^{-1} 24 h^{-1})	0.046	−0.018	0.001
Cat (mL g^{-1} 24 h^{-1})	0.377	−0.008	−0.042

4. Discussion

Generally, engineering effectiveness or low economic cost should be considered when dealing with the issue of saline-alkali soil. The clipping effect, chemical amendments, and microbial application for amelioration are undoubtedly good choices [8,23,24]. However, both of them have become expensive for potential users, especially with the increase in use by industry. Contrary to the method described above, planting plants and using agricultural resource waste are usually used to remediate saline-alkali soil when necessary to balance benefits and effectiveness [13,25,26]. In our case, sand is familiar, convenient, and inexpensive to transport.

Furthermore, considering its porous structure, sand is usually thought to block soil capillaries, preventing underground salinity's upward movement to a certain degree. In addition, low pH is also a crucial reason [17]. Consequently, this research chose sand as the soil amendment, corresponding to a local proverb, 'Sand cover alkali, can match gold'.

Although prior research has shown that sand amendment is an effective method in improving the structure of saline-alkali soil in the Horqin Sandy Land and Songliao plain intersection area, which is located in the northeast of China [15], the application of sand in the saline-alkali soil in the ridge of Mu Us Sandy Land has received relatively little attention. Our results showed that sand application significantly decreased the physical properties (i.e., pH, EC, TSC, and BD) in the saline-alkali soil compared to CK (Table 2). The following factors may be responsible for the deterioration of the soil's physical characteristics. On the one hand, a porous structure weakened the capillary action of the soil capillary [8,27], thus efficiently inhibiting the upward movement of salt from the subsoil, thereby resulting in a low EC and TSC. On the other hand, mixing sand into saline-alkaline soil can lower the pH of the soil, which is a credit to its low pH [17]. Additionally, compared to the first year, the pH and EC of soil increased in the next three years in the sand addition treatment even though no significant differences were observed, indicating that the sand application was possibly a repetitive process.

Soil salinity is a major problem in many agricultural areas around the world [28,29] including the middle and lower reaches of the Yellow River in China. High soil salinity can make the soil unsuitable for agriculture, reduce crop yields, and even lead to land degradation. In recent years, there has been growing interest in finding cost-effective and sustainable methods to improve the soil's properties in these areas. One such method is the application of sand to the soil. Sand application has been shown to improve soil structure, increase water infiltration and retention, and reduce soil salinity. However, the effectiveness of sand application in the saline-alkali area of the middle and lower reaches of the Yellow River has not been extensively studied.

Soil salinization adversely affects the cycle of soil C, N, and P, which are generally factors restricting plant growth [30,31]. Correspondingly, extensive research, including through biological and chemical means, has been performed to confirm soil nutrients' response to the remediation of saline-sodic soil [32–36]. For example, biochar amendment significantly increased soil OC, AN, and AP by 475.22%, 128.57%, and 100.01%, respectively [20]. Consistent with previous research, our findings also confirmed this phenomenon: the soil's chemical properties (i.e., OC, AN, AP) were significantly increased after sand application. We also discovered that the increased saline-alkaline soil enzyme activity caused by applying sand was likely responsible for the improved chemical properties of the soil, which can be confirmed by the robust correlation between the soil's chemical properties and soil enzyme activity (Figure 3). Furthermore, the soil's chemical properties increased with cultivation years in sand-addition treatment. It suggests that sand application is an effective method for improving chemical properties in saline-alkali soil.

Soil enzyme activity is commonly considered a biological indicator of soil health. [37,38]. Amylase can catalyze polysaccharide hydrolysis and provide labile carbon sources for microorganisms. Urease can hydrolyze nitrogen-containing organic matter, whereas alkaline phosphatase is the primary enzyme in the P cycle, and catalase can break down the metabolically generated hydrogen peroxide [39,40]. Furthermore, our findings demonstrated that sand application to the saline-alkali soil significantly increases the soil's enzyme-activity properties (i.e., Amy, Ure, Alp, Cat). It is generally recognized that the predominate soil structure enables it to sufficiently nourish soil microorganisms, thus significantly alleviating the secretion of soil enzymes [41,42]. Surprisingly, we detected that the soil's Amy and Cat correlated significantly with the soil's pH, inconsistent with previous research [43]. Considering that the type of saline-alkali soil in this research belongs to the chloride type, the sand addition-induced increase in the soil's enzyme activity might be more associated with increasing plant root exudates, which benefited from the improved soil structure [44,45].

Findings from our study showed that that soil's properties were noticeably different between sand-addition treatment and CK, suggesting that our sand application effectively improved the properties of saline-alkaline soil (Figure 4). Furthermore, the properties of saline-alkali soil are gradually becoming significantly related (Figure 3). These findings indirectly provide evidence of the properties of soil improving and highlight the positive influence of sand application on saline-alkali soil in the newly reclaimed inland land in northwest Shanxi province, China. The overall finding of the experiment is illustrated graphically in Figure 5.

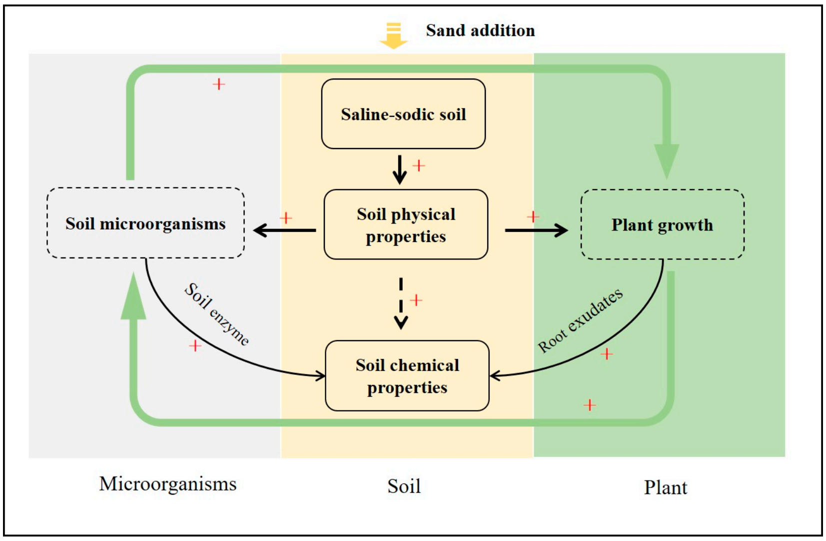

Figure 5. A conceptual framework of a sand addition-induced virtuous circle. Solid and dashed frames represent the researched and the part to be researched, respectively. Red '+' represent a positive effect.

5. Practical Implication of the Study

Although the results are valuable and persuasive, our understanding of the response of soil properties to sand application in four consecutive years of trials still needs to be completed. Considering the increasing trend of soil properties (i.e., Amy, Ure, Alp, Cat, pH, EC) to slow down gradually with the increasing years of continuous cropping after sand application, future research is needed to assess the aftereffect stability at more considerable timescales. Furthermore, more studies are needed to address how and to what extent either soil microbes or root exudates could indirectly affect the soil's physical, chemical, and enzyme-activity properties, especially in a saline-alkali land ecosystem that is experiencing remediation using the sand amendment, which has been proven to be an effective method here.

6. Conclusions and Recommendations

This study comprehensively investigates the change of both physicochemical and enzyme-activity properties of soil induced by sand application in a saline-alkali land ecosystem, which is located in the northwest Shanxi province, China. By studying multiple metrics, we were able to carry out a comprehensive evaluation of the effects of the sand aspect on the properties of saline-alkali soil. We have demonstrated that sand application significantly improves the saline-alkali soil's physical (i.e., pH, EC, TSC, BD), chemical (i.e., OC, AN, AP), and enzyme-activity (i.e., Amy, Ure, Alp, Cat) properties, and that soil AN, AP, and TSC were the crucial factors affecting the soil's properties. Simultaneously, soil properties gradually improved along with increasing cropping years, although these increases gradually became small. Furthermore, the soil's microbial community composition and plant root exudates should be measured in further research to identify how and to what extent they could affect saline-alkaline soil properties. These studies will continue to deepen our understanding of the irreplaceable role of sand in remediating saline-alkaline land in the northwest Shanxi province, China. Based on the findings of the study, the following recommendations can be made:

1. Sand application can be considered as a cost-effective method to improve soil quality and structure in arid and semi-arid saline-sodic agricultural ecosystems. It is recommended that further research be conducted to investigate the optimal amount and frequency of sand application for different soil types and cropping systems.

2. The soil's AN, AP, and TSC were identified as the crucial factors affecting the soil's properties. Therefore, it is recommended that these soil parameters be monitored regularly and managed appropriately to maintain or improve soil quality.
3. Cropping year was found to have a positive effect on the soil's properties. Therefore, it is recommended that crop rotation and other sustainable farming practices be implemented to improve soil quality over time.
4. This study was conducted in an arid and semi-arid saline-sodic agricultural ecosystem, and further research is needed to determine whether similar results can be achieved for other soil types and in other climatic conditions.

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