Effects of different soil amendments on physicochemical property of soda saline-alkali soil and crop yield in Northeast China

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Abstract: Soil amendment is one of the most effective methods to improve saline-alkali soil. In this study, laboratory experiments were conducted to verify the effect of 13 kinds of amendments and their combinations (Citric acid (NM), Phosphogypsum (LS), Aluminum sulfate+citric acid (AL+NM), Aluminum sulfate+phosphogypsum (AL+LS), Aluminum sulfate+citric acid+phosphogypsum (HH), Zeolite (Z), Acidified zeolite (ZH), Aluminum sulfate (AL), Aluminum sulfate+zeolite (AL+Z), Aluminum sulfate+acidified zeolite (AL+ZH), Poly Aluminum chloride (ALCL), Polyaluminium chloride+zeolite (ALCL+Z), Polyaluminium chloride+acidified zeolite (ALCL+ZH)) on soil pH, metal cations content, exchangeable Na^+, exchangeable sodium percentage (ESP) in the lab. And then the five most effective amendments (Z, ZH, AL, AL+Z, and AL+ZH) were chosen applying both in dry field (maize field) and paddy field to evaluate their improvement on soda saline-alkali soil and crop yield in the northeast Songnen Plain, China. The lab results showed that AL, AL+Z and AL+ZH treatments could significantly reduce the pH in soil solution and increase the content of metal cations. Z and ZH treatments could adsorb metal cations in soil. Both in dry and paddy fields, all five treatments could increase the soil saturated hydraulic conductivity (*Ks*), increased from 9.63 to 60.02 mm/d and 0.18 to 33.25 mm/d, respectively, of which the AL treatment was the best; all five treatments could reduce the content of exchangeable Na^+ in soil, and decrease by 38.62%-61.33% and 25.24%-71.53%, respectively, of which the AL+ZH treatment was the best; all treatments could reduce soil exchangeable sodium percentage, and decrease by 0.14-0.22 and 0.14-0.41, respectively, of which the AL+ZH treatment was the best; AL, AL+Z and AL+ZH treatments could improve soil organic matter content; all treatments could effectively improve the yield of crops, and increase 23.98%-60.75% and 52.51%-260.21%, respectively, of which the AL treatment was the best in dry field and the AL+ZH treatment was the best in paddy field. The effect of AL treatment was the best in dry field and AL+ZH treatment was the best in paddy field of soda saline-alkali soil. This study could provide instructive information for the chemical improvement and agricultural utilization of soda saline-alkali soils in the world.

Keywords: soil amendments, soda saline-alkali soil, aluminum sulfate, zeolite, maize, rice
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1 Introduction

In arid and semi-arid climate areas, soil salination is one of the main reasons for soil degradation, which seriously affects the sustainable development of agriculture[1,2]. It was reported that about 7% of the earth's surface area has been affected by soil salinization[3,4]. Salinization and alkalinization of soil were the process of salt accumulation in surface soil, which is the main cause of soil quality degradation and plant growth restriction[5,6], as well as reducing farmland productivity. Songnen Plain, located in the northeast of China (43°30'N-48°40'N; 121°30'E-127°00'E), with an annual precipitation from 300 to 600 mm[5], is one of the three largest soda alkali lands in the world[7]. There are more than 3.2×10^6 hm^2 of soda saline-alkali land in Songnen Plain, which is still increasing by 2.0×10^4 hm^2 soda alkali land every year[4]. The properties of local soil, such as poor structure, high bulk density, ease to harden and low permeability, have seriously affected the normal growth and development of local plants. The reclamation practices of saline-sodic soils have been extensively investigated, including physical, chemical, and biological amelioration[8-13]. The government and researchers have conducted kinds of methods to solve these problems, of which the most effective and practical method is chemical methods.

Presently, there are several Salinity chemical amendments, such as gypsum, phosphogypsum, calcium chloride, sulfuric acid, and aluminum sulfate, etc.[14-17] Among these amendments, gypsum is one of the most popular chemical amendments which have been proved to improve rice yield. But the dissolution rate of gypsum is very low which will affect the improvement effect greatly. The dissolution rate of Aluminum sulfate is faster than that of gypsum, and the sedimentation capacity of soil colloidal particles is stronger than that of gypsum, so Aluminum sulfate can achieve rapid

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flocculation and sedimentation of colloidal particles in water. Furthermore, aluminum ions could produce H^+ ions by hydrolysis dissolving $CaCO_3$ in soil to provide Ca^{2+} ions for improving saline-sodic soils[4]. Recently, zeolite has been widely applied in agriculture production and environmental protection because of its high absorption capacity and cation exchanging capacity.

In Songnen Plain, rice cultivation could help with improvement of the soda alkali land. However, under single irrigated rice cropping without additional soil amelioration, rice yields are still very low within the first four years[18]. Thus in the study, the objectives were to: 1) verify the effect of 13 kinds of amendments and their combination on soda saline-alkali soil in the lab; 2) choose the most five effective amendments both applying in both dry and paddy fields to evaluate their improvements on soda saline-alkali soil and crop yield.

2 Materials and methods

2.1 Experimental site

The experimental site is at Changchun Ling Town, Fuyu City, Jilin Province (45°23'33"N, 125°26'54"E, altitude 132 m), located in the center of northeast Songnen Plain, which is a typical area of moderate and severe soda alkali land. The area has an eastern temperate continental monsoon climate, with an annual average rainfall of 422 mm, and little rainfall in spring. Most of the rainfall is concentrated in summer, accounting for about 60% of the total annual rainfall. The annual illumination is sufficient, of which the sunlight could be more than 3000 h and the frost-free period is 145 d. The annual average evaporation is 1733 mm, and the annual average temperature is 4.4°C. The basic characteristics of the local are listed in Table 1.

Table 1 Basic characteristics of tested soil

Types of cultivated land	pH	EC/dS·m^{-1}	Organic matter/g·kg^{-1}	$CaCO_3$/%	Exchangeable Na^+/cmol·kg^{-1}	Exchangeable sodium percentage/%
Dry field	9.06	1.05	16.06	6.37	3.62	34.81
Paddy filed	10.62	2.58	10.52	9.56	7.61	56.79

2.2 Experimental design

The experiments were conducted both in lab and in field. In the lab, the effects of 6 amendments (Citric acid, phosphogypsum, zeolite, acidified zeolite, aluminum sulfate and polyaluminium chloride) were evaluated and their combinations amendments (7 treatments) on the sedimentation in soda saline-alkali soil. Together with one control treatment, 14 treatments were set up as follows: 1) Control, no amendments (CK); 2) Citric acid (NM); 3) Phosphogypsum (LS); 4) Aluminum sulfate+citric acid (AL+NM); 5) Aluminum sulfate+phosphogypsum (AL+LS); 6) Aluminum sulfate+citric acid + phosphogypsum (HH); 7) Zeolite (Z); 8) Acidified zeolite (ZH); 9) Aluminum sulfate (AL); 10) Aluminum sulfate+zeolite (AL+Z); 11) Aluminum sulfate+acidified zeolite (AL+ZH); 12) Poly Aluminum chloride (ALCL); 13) Polyaluminium chloride+zeolite (ALCL+Z); 14) Polyaluminium chloride+acidified zeolite (ALCL+ZH). Each treatment included three replications.

2.2.1 Sedimentation experiment

In each treatment, 200 g air-dried soil samples were sieved to 2 mm and then were put into a glass beaker of 2000 mL. Each glass beaker added 0.2%, 0.4%, 0.6% and 0.8% in mass amendments (equal to 0.4 g, 0.8 g, 1.2 g and 1.6 g), respectively. Then 1000 mL of distilled water was added into the glass beaker Stir the soil-water mixture quickly with a magnetic stirrer for 2 min and then stir slowly for 4 min. Finally, the mixture was put into a measuring cylinder of 1500 mL. After 24 h standing, the sedimentation rate was measured. In order to simulate the rice soaking process, the ion composition was measured after 7 d standing.

2.2.2 Field experiments

After the experiments in the lab were finished, five soil amendments were chosen as the best amendments, which were applied to the dry field and paddy field.

In the dry field experiment, six treatments were set up, including control without amendment (CK), zeolite (Z), acidified zeolite (ZH), aluminum sulfate (AL), aluminum sulfate and zeolite (AL+Z), aluminum sulfate and acidified zeolite (AL+ZH). Each treatment had three replicates.

The amendments were all spread on the surface of the soil, and then were all ploughed into the ground by mechanical ploughing. The maize variety is Jingke 968. The application amount of fertilizer (N-P_2O_5-K_2O: 27-14-14) was 750 kg/hm^2 and the application amount of amendments was 1.5 t/hm^2, which was equivalent to 0.6% of the soil quality. The experiment was performed from April 2017 to October 2018, which had 2 consecutive growing seasons. Soil samples from 0-20 cm were collected and measured, together with the yield every year. Amendments were applied in the paddy field during rice soaking. The application rate was the same as that in dry field. The rice variety was Jihong-6, and all farming practices and field management were performed according to the local cultivation in the study area.

2.3 Experimental methods

In sedimentation test, soil equilibrium solution was centrifuged and pH was measured by PHS-3C pH meter potential method; electrical conductivity (EC) was measured by DDB-303A portable electrical conductivity machine of Shanghai Leici; Na^+ was measured by flame photometry; Ca^{2+} and Mg^{2+} were measured by atomic absorption flame photometry. Calculate the sodium adsorption ratio.

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}} \tag{1}$$

The soil micro-aggregates were obtained by ultrasound-sedimentation method[19]. Weighed 10 g of air-dried soil that has passed through a 1 mm sieve into a beaker and added distilled water to soak overnight, dispersed it by ultrasonic wave for 15 min, then passed through 0.25 mm sieve and washed it into a 1000 mL beaker with distilled water, absorbed each particle size by Stokes law, dried and weighed it. The exchangeable Na^+ content was determined by ammonium acetate ammonium hydroxide exchange flame photometry, and the cation exchange capacity (CEC) was determined by sodium acetate flame photometry. The potassium dichromate oxidation method is used to determine the organic content.

The soil saturated hydraulic conductivity (K_s) of soil was determined using a downward flow experiment with constant-water head. The test soil was air-dried and then passed through a 2 mm sieve. Put 1060 g soil respectively in a polyvinyl cylinder (diameter: 10 cm; height: 25 cm) to a depth of 10 cm and packed to a bulk density of 1.35 g/cm^3. The bottom of the cylinder was fixed with a nylon sieve and filter paper was put on the sieve. Soil in the cylinder was saturated by submerging it into distilled water for 24 h. Take the soil columns out from water after the soil columns were fully saturated. When there was no leachate out from the bottom, distilled water was continuously added onto the soil surface in each cylinder with Markov bottles. 3 cm water head was maintained. The leachate was collected and its quantity was then measured at a certain time. The K_s was calculated according to Darcy's law:

$$K_s = \frac{\Delta Q \times L}{A \times \Delta t \times (L + H)} \tag{2}$$

where, K_s is the soil saturated hydraulic conductivity, mm/d; ΔQ is the volume of leachate collected from the bottom of cylinder during a given time period, mm^3; L is the depth of soil sample, mm; A is the cross-sectional area of the soil columns, mm^2; Δt is the given time period, d; H is the height of constant water head, mm.

2.4 Statistical analysis

Data were analyzed by DPS 7.5. Average values in each subplot were subjected to one-way analysis of variance. The least significant differences were calculated for multiple comparisons among all treatments.

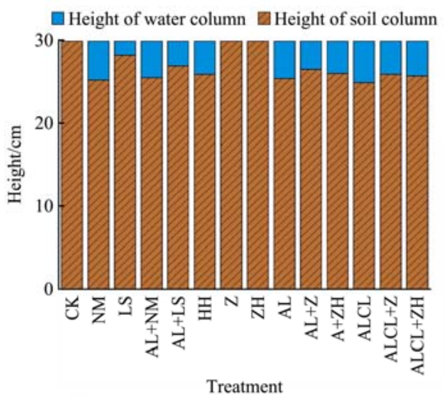
3 Results and discussion

3.1 Effect of different amendments on physical and chemical properties of soda saline-alkali soil

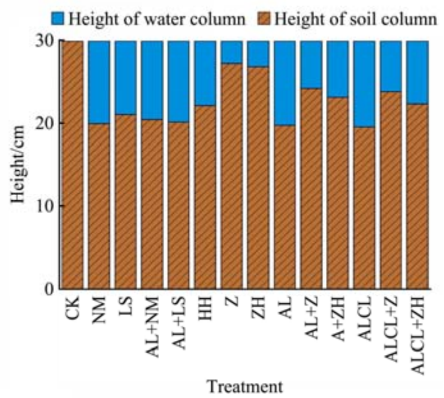
3.1.1 Effect of different amendments on settling properties of suspension in soda saline-alkali soil

The settlement test could reflect the improvement of different amendments on soda saline-alkali soil, and then the suitable amendments would be selected for field application. At the initiative of the experiment, the water and soil in the settling bottle were mixed well and observed in the static state. After the application of NM, AL and ALCL, the suspension immediately began to settle down. However, the settling speed of AL+NM, AL+LS, HH, AL+Z, AL+ZH, ALCL+Z and ALCL+ZH was significantly slower than that with NM, AL and ALCL. The hydrolysis of aluminum ions promotes the dissolution of metal carbonate and the formation of polyaluminum ions or monomer aluminum, promotes the aggregation of soil colloids and the formation of micro aggregates, and increases the porosity, water holding capacity and permeability[20]. There was no significant change in the treatment of LS, Z and ZH in a short time. After 24 h of static state, the settlement phenomena were observed. The soil suspension with LS and ZH treatment became clear, but there was no difference was found in the CK and treatment with Z. Moreover, soil suspension with other treatments has completely settled down, and the water column is clear and transparent.

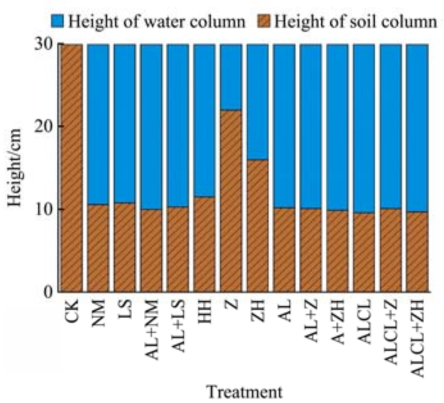
In order to further evaluate the effect of different amendments dosage on soda saline-alkali soil, the average height of soil column and water column of each treatment after one week's standing was shown in Figure 1. With the increase of the added amount, the settling velocity of the soil column became faster and the effect became better (Figure 1). It could be found in Figure 1 that CK had no sedimentation and the solution was still a suspension; Z and ZH had a certain degree of colloidal flocculation effect but Z and ZH were not as good as those with other amendments; the rest of the treatment has already been settled. The results showed that all treatments could promote soil colloid flocculation.



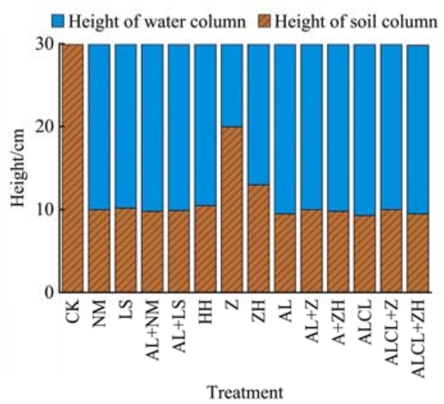
a. Amendment dosage 0.2%



b. Amendment dosage 0.4%



c. Amendment dosage 0.6%



d. Amendment dosage 0.8%

Note: CK: Control, no amendments; NM: Citric acid; LS: Phosphogypsum; AL+NM: Aluminum sulfate+citric acid; AL+LS: Aluminum sulfate+phosphogypsum; HH: Aluminum sulfate+citric acid+ phosphogypsum; Z: Zeolite; ZZ: Acidified zeolite; AL: Aluminum sulfate; AL+Z: Aluminum sulfate+zeolite; AL+ZH: Aluminum sulfate+acidified zeolite ALCL: Poly Aluminum chloride; ALCL+Z: Polyaluminium chloride+zeolite; ALCL+ZH: Polyaluminium chloride+acidified zeolite. The following is the same.

Figure 1 Effects of different amendments and dosage on soil colloid flocculation

3.1.2 Effect of different amendments on chemical properties of equilibrium solution of soda saline-alkali soil

In order to know the effect of different amendments on chemical properties of soda saline-alkali soil, pH, EC, Na^+, Ca^{2+}, Mg^{2+} and sodium adsorption ratio (SAR) of soil balance solution were all determined and the results were shown in Table 2. From Table 2, it can be seen that all treatments with NM, LS and AL could significantly reduce the pH of soil equilibrium solution (p<0.05) and the highest pH value of 9.15 was in CK[7], but the lowest pH value of 7.53 was in AL+LS treatment. The EC can reflect the soluble salt content of soda saline-alkali soil. Except Z and ZH treatment, other treatments increased the EC of soil equilibrium solution compared to CK, the increased range was 0.58-1.80, and there was significant difference with CK (p<0.05), and the lowest EC of Z treatment was 0.89 dS/m, the highest EC of ALCL treatment was 2.85 dS/m. Sodium content reflects soda saline-alkali soil content of sodium salt. All treatments except Z and ZH increased Na^+ in soil equilibrium solution, and there was a significant difference between them and CK (p<0.05). The content of Na^+ in soil equilibrium solution of Z treatment was the lowest, with the value of 177 mg/L, and the AL was the highest, with the value of 677.65 mg/L. Except for all treatments in which Z and ZH were involved, all treatments could significantly increase the content of Ca^{2+} in soil equilibrium solution (p<0.05). The content of Ca^{2+} was the lowest in Z and ZH treatments; Z and ZH treatments were also the treatment with the lowest Mg^{2+} content. Except for AL+Z treatment, all the treatments that AL participated in significantly increased the content of Mg^{2+} in soil equilibrium solution (p<0.05); Z and ZH treatment reduced the SAR of soil equilibrium solution, and the other treatments increased the SAR of soil equilibrium solution except HH treatment. The smaller the SAR value is, the improvement will be better. The main reason is that the settlement test was conducted in a semi-sealed environment without iron exchange, and the main components of the soda saline-alkali soil in the Northeast Songnen Plain are Na_2CO_3 and $NaHCO_3$. Then SAR value rises, which is equivalent to a process of leaching with irrigated water in the field production. In this experiment, the higher SAR of the equilibrium solution means more salt was washed away. The same is true for EC. The increase of EC value is caused by the increase of the content of various ions in the equilibrium solution. The higher the EC value of the equilibrium solution, the better the salt was washed away. With the application of chemical amendment, the pH of Soil equilibrium solution decreased, but the EC, metal cation and SAR increased due to the H^+ produced by hydrolysis of aluminum ions amendments, which will result in the dissolution of the soil metal carbonate and the entry of cations into the equilibrium solution[17].

The results in Table 2 also showed that all chemical amendments have excellent improvement effects on soda saline-alkali soil. But considering the practicability, the high price of NM and ALCL will limit the application. Moreover, the dissolution rate of LS was too slow at room temperature. So three amendments, Z, ZH, AL, and two combinations, AL+Z and AL+ZH, were selected for field experiment.

Table 2 Effect of different amendments on pH, Electrical conductivity, Na^+, Ca^{2+}, Mg^{2+} and sodium adsorption ratio of soil equilibrium solution

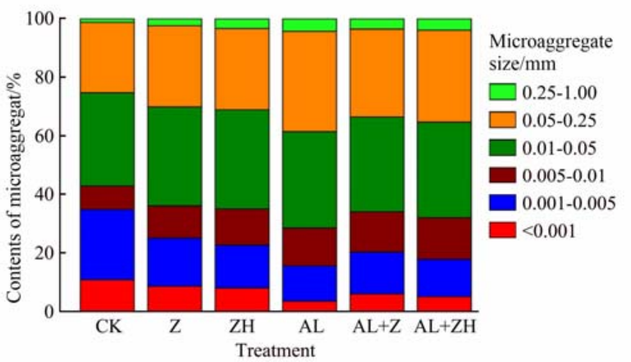
Treatment	pH	EC/dS·m^{-1}	Na^+/mg·L^{-1}	Ca^{2+}/mg·L^{-1}	Mg^{2+}/mg·L^{-1}	SAR/mmol·L^{-1}
CK	9.15±0.05^a	1.05^h	334.59±9.06^f	28.70±1.14^f	10.43±0.38^f	19.17
NM	7.73±0.07^k	2.54^b	585.83±9.70^c	44.44±1.04^c	41.18±0.55^{ab}	21.42
LS	7.93±0.10^i	1.81^f	470.35±12.23^d	49.41±1.60^b	15.82±0.55^e	21.01
AL+NM	7.72±0.09^k	2.28^c	581.85±10.57^c	40.63±1.58^d	40.06±0.63^b	21.83
AL+LS	7.53±0.07^l	2.41^b	587.36±7.81^c	66.17±1.56^a	39.97±1.31^b	19.82
HH	8.13±0.06^g	2.2^c	484.52±12.35^d	49.58±0.39^b	35.78±1.19^c	18.03
Z	9.04±0.02^b	0.89^i	177.00±7.33^g	21.44±2.09^g	4.88±0.16^j	12.66
ZH	8.78±0.02^c	0.94^i	185.90±4.60^g	21.74±1.36^g	5.95±0.07^i	12.85
AL	8.17±0.09^f	2.12^d	677.65±11.53^a	65.99±0.68^a	42.48±1.65^a	22.53
AL+Z	8.51±0.09^d	1.63^g	480.52±16.35^d	25.92±1.89^f	8.96±0.08^g	29.23
AL+ZH	8.35±0.08^e	1.69^g	478.52±6.03^d	26.74±2.32^f	11.24±0.50^f	27.59
ALCL	7.97±0.08^i	2.85^a	632.10±11.87^b	64.89±1.48^a	36.27±0.48^c	21.96
ALCL+Z	8.23±0.06^f	2.04^e	468.01±4.66^d	25.63±0.91^f	9.10±0.07^g	28.50
ALCL+ZH	8.11±0.02^{gh}	2.09^d	491.72±9.81^d	25.83±0.55^f	7.13±0.17^h	31.14

Note: The data in the table are average±standard deviation. Different lower letters indicate significant differences at p<0.05. EC: Electrical Conductibity; SAR: Sodium Adsorption Ratio; CK: Control, no amendments; NM: Citric acid; LS: Phosphogypsum; AL+NM: Aluminum sulfate+citric acid; AL+LS: Aluminum sulfate+phosphogypsum; HH: Aluminum sulfate+citric acid+ phosphogypsum; Z: Zeolite; ZZ: Acidified zeolite; AL: Aluminum sulfate; AL+Z: Aluminum sulfate+zeolite; AL+ZH: Aluminum sulfate+acidified zeolite ALCL: Poly Aluminum chloride; ALCL+Z: Polyaluminium chloride+zeolite; ALCL+ZH: Polyaluminium chloride+acidified zeolite. The following is the same.

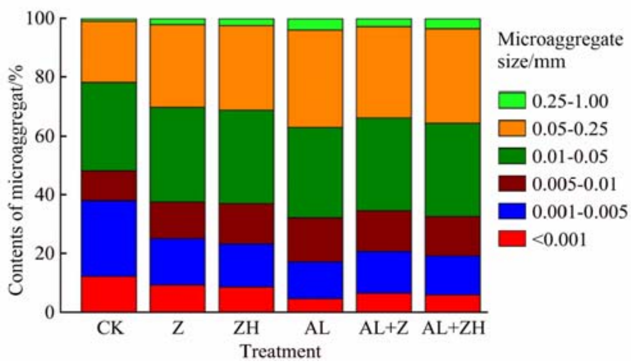
3.2 Effects of different amendments on soil properties and crop yield

3.2.1 Effects of different amendments on soil microaggregates and soil saturated hydraulic conductivity (K_s)

The composition of soil microaggregate affects the ability of soil water and nutrient supply, which is an important indicator for soil fertility. The effect of different amendments on soil microaggregates was illustrated in Figure 2. As shown in Figure 2, the microaggregates contents with the size less than 0.001 mm and 0.010-0.005 mm decreased, but the microaggregates of 0.05-0.25 mm and 0.25-1.00 mm increased. For dry field, comparing to CK, the contents of microaggregate with the size of less than 0.005 mm in each treatment decreased by 28.16%, 35.06%, 55.46%, 41.67% and 48.85%, respectively. The application of different amendments significantly reduced the proportion of microaggregate that less than 0.001 mm and 0.001-0.005 mm particles (p<0.05); the proportion aggregate with the size of 0.05-0.25 mm and 0.25-1.00 mm increased significantly (p<0.05), and aggregate size of 0.05-0.25 mm has a whopping percentage, the contents of microaggregate with the size of 0.05-0.25 mm in each treatment increased by 19.05%, 19.05%, 52.78%, 32.94% and 39.68%, respectively. AL treatment had the highest proportion of 0.05-0.25 mm aggregate size, which indicated that under dry farming conditions, AL treatment has the strongest ability to promote the aggregation of small aggregates to large aggregates. As shown in Figure 2, the effect of different amendments on paddy soil microaggregates was consistent with that of dry field. For paddy field, the application of different amendments significantly reduced the proportion of microaggregate of less than 0.001 mm and 0.001-0.005 mm particles (p<0.05), comparing to CK, the content of microaggregate with the size of less than 0.005 mm in each treatment decreased by 34.21%, 38.95%, 55.00%, 45.53% and 49.74%, respectively; However, the proportion of 0.05-0.25 mm and 0.25-1.00 mm aggregates increased significantly (p<0.05), the content of microaggregate with the size of 0.05-0.25 mm and 0.25-1.00 mm in each treatment increased by 37.61%, 42.20%, 69.21%, 54.59% and 62.84%, respectively; the proportion of 0.05-0.25 mm particle microaggregate increased the most.



a. Dry field



b. Paddy field

Figure 2 Effects of different amendments on soil microaggregates

Saturated hydraulic conductivity (K_s) is a useful index to evaluate the ameliorative effects of amendments on soil physical properties. So the effect of different amendments on soil K_s was illustrated in Table 3. As shown in Table 3, all treatments can significantly increase the K_s. The highest K_s in dry field was 60.02 mm/d, and the highest K_s in paddy land was 33.25 mm/d. The highest treatment of K_s was AL treatment. The remarkable change of K_s was mainly attributed to the increase of soil micro-aggregates and the formation of a fine soil pore system.

Table 3 Effects of different amendments on soil saturated hydraulic conductivity measured with soil columns

Types of cultivated land	Soil K_s /mm·d^{-1}					
	CK	Z	ZH	AL	AL+Z	AL+ZH
Dry field	9.63±1.22^d	15.45±1.63^c	15.29±2.58^c	60.02±5.32^a	42.12±4.22^b	43.22±3.69^b
Paddy field	0.18±0.02^d	3.68±0.42^c	3.81±0.37^c	33.25±3.51^a	26.96±1.56^b	27.68±2.01^b

Aluminum or polymer aluminum ions are produced after hydrolysis of aluminum sulfate[21], which promotes the formation of soil colloid agglomerates and microaggregates; Zeolite adsorbs colloidal clay particles to form aggregates to increase the number of large particle size aggregates[22], then improve the soil structure and increased saturated hydraulic conductivity.

3.2.2 Effect of different amendments on exchangeable Na^+, CEC and ESP in soil

Exchangeable Na^+ and ESP are both important indexes to measure soda saline-alkali soil, ESP is the percentage of exchangeable Na^+ in CEC, which reflects the alkalization degree of soda saline-alkali soil. The effects of different amendments on exchangeable Na^+, CEC and ESP in soil are listed in Table 4. As listed in Table 4, all treatments have significantly reduced the content of exchangeable Na^+ and ESP in dry field and paddy field and increased CEC slightly.

The contents of soil exchangeable Na^+ in dry field were reduced by 38.6%, 42.5%, 52.2%, 57.7% and 61.3%, respectively; there was no significant difference between the treatments with Z and ZH (p>0.05) and there was also no significant difference among the treatments with AL, AL+Z and AL+ZH (p>0.05), but significant difference were found in treatment with Z and ZH (p<0.05) where CEC has been increased slightly and ESP decreased significantly of which each treatment could reduce 14.24%, 15.85%, 19.21%, 20.89%, and 22.23%, respectively. Each treatment could significantly reduce the content of soil exchangeable Na^+ (p<0.05) in paddy field and decreased by 25.2%, 29.7%, 50.2%, 62.7% and 71.5%, respectively; ESP decreased significantly, each treatment could reduce 14.43, 16.65, 29.90, 35.95, and 40.92 percentage points, respectively. AL+ZH treatment had the best effect.

Reduced exchangeable Na^+ and ESP is probably due to strong ion exchange and adsorption capacity of zeolite, which adsorbs Na^+[23]. By producing H^+ through hydrolysis, aluminum sulfate rapidly reduced soil pH and promoted the dissolution of metal carbonate to provide Ca^{2+} and Mg^{2+} for replacing exchangeable Na^+ in soda saline-alkali soil[7,24].

Table 4 Effects of different amendments on exchangeable Na^+, CEC and ESP in soils

Types of cultivated land	Treatment	Exchangeable Na^+/cmol·kg^{-1}	CEC /cmol·kg^{-1}	ESP/%
Dry field	CK	3.62±0.36^a	10.40±0.30^b	34.81
	Z	2.22±0.52^b	10.79±0.15^b	20.57
	ZH	2.08±0.19^b	10.97±0.25^{ab}	18.96
	AL	1.73±0.06^c	11.09±0.13^{ab}	15.60
	AL+Z	1.53±0.29^c	10.99±0.64^{ab}	13.92
	AL+ZH	1.40±0.38^c	11.22±0.22^a	12.48
Paddy field	CK	7.61±0.76^a	13.40±0.50^b	56.79
	Z	5.69±0.62^b	13.43±0.40^b	42.36
	ZH	5.35±0.33^b	13.33±0.25^b	40.14
	AL	3.79±0.56^c	14.09±0.17^a	26.89
	AL+Z	2.84±0.49^{cd}	13.63±1.22^{ab}	20.84
	AL+ZH	2.17±0.28^d	13.67±1.40^{ab}	15.87

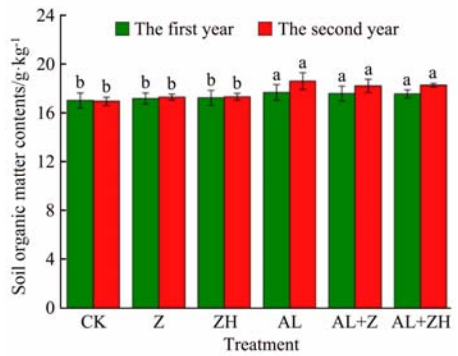
Note: The data in the table are mean±standard deviation. There is no significant difference at 0.05 level in the same column of data with the same letters (Duncan's method).

3.2.3 Effects of different amendments on soil organic matter content

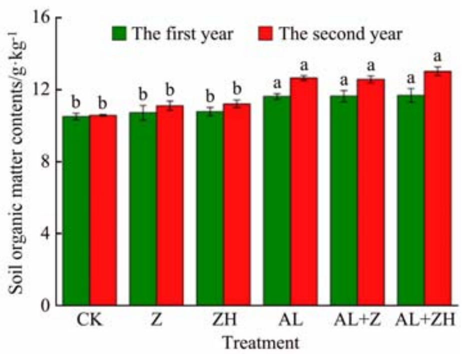
Soil organic matter is a complex mixture of organic compounds such as plant residues, microbial products and rhizosphere inputs in various stages of decomposition[25,26], which will influence physical, chemical and biological activities and processes in the soil[26,27]. The increase of soil organic matter content improved soil structure and aggregation, and increased soil hydraulic conductivity and cation exchange capacity[29]. Besides, organic matter has the potential influence to crop yields via any of these processes above[30].

The effect of different amendments on soil organic matter content is illustrated in Figure 3. Compared to CK, treatments with Z and ZH could increase the organic matter content slightly. AL, AL+Z, and AL+ZH could significantly increase the organic matter content and the results were consistent in dry field and paddy field which showed that the application of aluminum sulfate could improve the content of soil organic matter.

The increase of organic matter content is mainly because the application of aluminum sulfate and zeolite has improved the poor physical and chemical properties of the soil and promoted the growth of crops as well as the development of root system. The developed roots could further excrete organic acids and produce more organic matter[20]. Moreover, a large amount of straw remained during harvest is straw returning to the field, which is also the reason for the increased of organic matter content[21].



a. Dry field



b. Paddy field

Figure 3 Effects of different amendments on soil organic matter content

3.2.4 Effects of different amendments on yield components and yield of crops

Crop yield components and yield can reflect the growth of crops and directly reflect the improvement effect. The effects of different amendments on maize yield components and yield were presented in Table 5, rice yield components and yield in Table 6. As shown in Table 5, compared to CK, all treatments significantly improved yield components and significantly increased yield in maize. In the first year, AL treatment had the highest spike number, spike grain number and 1000 grain weight, all treatments had a significant difference to that of CK in maize yield (p<0.05). The spike number of AL treatment was the best, with an average of 48500/hm^2, and there was no significant difference among other treatments compared to CK (p>0.05); No significant difference was found between treatments of AL, AL+Z and AL+ZH (p>0.05), but there was a significant difference between treatments of ZH and Z (p<0.05). The 1000 grain weight of AL treatment was the best, with an average of 295.0g, which was significantly different from other treatments (p<0.05). All treatments could significantly increase maize yield, AL treatment had the highest yield, with an average yield of 10 394 kg/hm^2 and was increased by 60.75%. The best treatment for dry field improvement was AL.

Table 5 Effects of different amendments on yield components and yield of maize

Time	Treatment	Spike number/ 10^4 hm^2	Spike grain number	1000 grain weight/g	Yield /kg·hm^{-2}
First-year	CK	4.13±0.06^c	617.22±14.93^c	261.2±3.8^d	6613.2±459.3^e
	Z	4.40±0.10^b	698.72±7.65^b	271.3±2.3^c	7844.9±199.1^d
	ZH	4.50±0.10^b	699.48±14.60^b	273.1±5.1^c	8300.5±172.4^c
	AL	4.77±0.12^a	738.00±21.08^a	298.0±4.3^a	10341.5±592.0^a
	AL+Z	4.53±0.15^b	726.88±13.59^{ab}	281.3±1.9^b	9001.2±383.3^b
	AL+ZH	4.57±0.06^b	721.60±20.88^{ab}	282.0±2.0^b	8958.0±463.0^b
Second-year	CK	4.00±0.00^c	594.08±23.45^c	259.3±3.3^d	6319.0±421.2^d
	Z	4.37±0.06^b	696.96±10.63^b	273.1±5.3^c	8188.7±345.9^c
	ZH	4.47±0.15^b	701.76±5.22^b	272.4±6.7^c	8563.1±94.2^c
	AL	4.93±0.25^a	729.80±9.21^a	292.0±2.2^a	10447.1±596.4^a
	AL+Z	4.47±0.29^b	709.92±9.88^b	283.3±3.1^b	8773.2+182.8^{bc}
	AL+ZH	4.53±0.15^b	716.00±15.17^{ab}	285.0±4.0^b	9033.3±302.2^b

As listed in Table 6, in the first year, spike number and 1000 grain weight of rice with AL+ZH treatment were the highest. There was a significant difference between all treatments and CK treatment (p<0.05). AL treatment had the highest spike grain number, there was no significant difference between Z and ZH treatment with CK treatment (p>0.05), the results showed that treatments with Z and ZH had no significant effect on the spike grain number; the spike number, spike grain number and 1000 grain weight of AL+ZH treatments were the best in the second year. Treatment with AL+ZH was the best in rice yield and the average yield is 7971.5 kg/hm^2. The rice yield was increased by 260.21%. The effect of AL treatment was the best in dry field, the effect of AL+ZH treatment was the best in paddy field.

On the whole, due to the improvement of soil physical and chemical properties and the increased organic matter content[31], different amendments could have a positive effect on crop yield components and significantly increased crop yields and the yield increased significantly.

Table 6 Effects of different amendments on yield components and yield of rice

Time	Treatment	Spike number /10^4 hm^2	Spike grain number	1000 grain weight/g	Yield /kg·hm^{-2}
First year	CK	185±8.67^d	92±2.08^c	13.6±0.35^c	2315.2±158.3^f
	Z	242±7.64^c	90±1.73^c	15.0±0.46^{bc}	3268.4±266.6^e
	ZH	275±12.22^{bc}	91±2.52^c	15.4±0.62^b	3855.5±277.3^d
	AL	280±16.62^b	122±6.00^a	17.8±1.27^a	6083.7±347.5^c
	AL+Z	339±18.08^a	110±3.79^b	18.5±0.61^a	6902.1±56.6^b
	AL+ZH	348±2.31^a	112±3.79^b	19.4±0.15^a	7565.3±236.4^a
Second year	CK	179±3.45^d	90±1.35^c	13.1±0.75^e	2111.2±196.3^f
	Z	250±8.75^c	91±3.78^c	15.3±0.33^d	3482.5±300.4^e
	ZH	286±15.24^b	93±2.22^c	16.0±0.66^c	4108.6±298.4^d
	AL	297±10.98^b	120±4.39^a	18.2±1.35^b	6489.7±463.9^c
	AL+Z	345±11.65^a	116±5.12^{ab}	18.3±0.89^b	7327.4±477.9^b
	AL+ZH	352±6.64^a	122±7.79^a	19.5±0.28^a	8378.9±386.1^a

4 Conclusions

According to the settlement experiment, aluminum ion amendments could significantly reduce the pH value of soil equilibrium solution, significantly improve EC, metal cation content and SAR of soil equilibrium solution; zeolite and acidified zeolite could significantly reduce EC, metal cation content and SAR of soil equilibrium solution. It can be seen from the field experiments that the application of aluminum sulfate and zeolite could reduce the number of small and medium-sized aggregates, increase large aggregates, increase saturated hydraulic conductivity, improve the permeability of soil, and significantly reduce the exchangeable Na^+ and ESP of soil. The improvement of soil structure is conducive to the leaching of salt; the application of aluminum sulfate could improve the soil organic matter content; the application of aluminum sulfate and zeolite could improve the yield of maize and rice. It was concluded that among all treatments, the most effective way to improve soda alkali soil was to apply aluminum sulfate alone in dry fields, and for paddy fields, it is the combination of aluminum sulfate and acidified zeolite.

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