

Study on the effect of hydrothermal charcoal source modifier on saline-alkaline soil improvement

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Abstract

Land salinization has become a global issue. To mitigate this issue, the modifiers and water-soluble fertilizers have emerged as a promising strategy to enhance soil nutrient content and promote crop production in saline soils. In this study, based on the hydrothermal method for preparing corn stalks derived biochar prepared modifiers and water-soluble fertilizers for using in soda saline-alkali soil. Through field microplot experiments, the separate and interactive effects of different concentrations of them were studied, as well as their influence on the growth of alfalfa and *Leymus chinensis* on saline-alkali soil. The combined application of modifiers and water-soluble fertilizers can effectively increase soil nutrient content and enzyme activity, significantly reducing soil pH and alkalinity. It was found that the optimal application rate of 20 g/kg of improver resulted in a 4.99% decrease in pH of soil and 11.23% decrease in alkalinity. Additionally, organic matter, available P₂O₅, NH₄⁺-N, and NO₃⁻-N contents increased by 25.74%, 28.48%, 19.87%, and 32.90%, respectively. Soil enzyme activities generally peaked at 20 g/kg of modifiers and water-soluble fertilizers, with sucrase showing the most significant increases, with 31.14% for alfalfa and 25.52% for *L. chinensis*. Two-way ANOVA results demonstrated significant interaction effects between the modifiers and water-soluble fertilizer on pH, Ca²⁺ and Mg²⁺ content, quick-acting potassium content, soil sucrase and urease activity, biomass of soil and alfalfa leaf width. Moreover, planting alfalfa and *L. chinensis* indicated that combined use of modifiers and fertilizer had a significant effect on promoting crop cultivation in saline-alkali soil. Our findings provided a robust theoretical groundwork for improving the management of saline soils and optimizing crop production in such challenging environments.

Keywords: alfalfa; enzyme; *Leymus chinensis*; modifier; saline-alkaline soil; water-soluble fertilizer

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Introduction

Land salinization poses a significant threat to agricultural productivity and ecological stability globally (Ren *et al.*, 2022). The estimated area of saline-alkali land covers over 1 billion hectares in more than 100 countries globally, accounting for approximately 7% of the total land area worldwide. Moreover, the affected land area is expanding at a yearly rate of 0.1 - 0.15 million hm² (Darwish *et al.*, 2005). The Songnen Plain of China is one of the world's three main saline areas, accounting for approximately 15.24% of the total saline area. Salinization affects the physicochemical properties of soil, such as water retention capacity and fertility (Yuan *et al.*, 2023), reducing the abundance and diversity of soil microbial communities (Canfora *et al.*, 2014). Furthermore, salinity stress decreases crop germination rates, inhibiting crop growth and causing economic losses of at least \$27.3 billion in global agricultural production (Xie *et al.*, 2017). Saline-alkali land plays a crucial role in ensuring national food security and serves as an important reserve of land resources (Zhao *et al.*, 2020).

The improvement of saline and alkaline land can be mainly achieved through physical, chemical, and biological means. Among these, the physical method is characterized by its speed but also higher costs (Wang *et al.*, 2014), biological improvement methods are typically associated with lower investment, but they need a long improvement cycle (Gao *et al.*, 2022). Saline soils, in general, suffer from nutrient deficiency, chemical harshness, and toxic levels of harmful elements. Hence, the aforementioned methods are inadequate for directly enhancing soil nutrient levels and replenishing the necessary elements for crop growth. Therefore, there is an urgent need for a method that can compensate for the limitations of both physical and biological modification approaches. Chemical improvement methods have become a common approach for the restoration of saline-alkali land due to their simplicity and speed (Jaiswal *et al.*, 2022). Application of modifiers and water-soluble fertilizers containing essential elements are effective chemical pathways for saline soil improvement which promotes stable particle structure and the formation of soil-amine complexes, thereby enhancing soil fertility and increasing crop yields (Wang *et al.*, 2017). Ca²⁺ and Mg²⁺ in water-soluble fertilizers can be replaced with Na⁺ in saline and alkaline soils reducing its harmful effect and efficiently utilized by vegetation upon absorption. In recent years, more and more studies found that the application of biochar into saline-alkaline soil can improve soil fertility (Hou *et al.*, 2023), enhances soil enzyme activity and promotes crop growth (Li *et al.*, 2020; He *et al.*, 2020). Straw returning helps to slow down the accumulation of salt in the surface soil and enhances microbial activity (Xie *et al.*, 2017; Song *et al.*, 2018). The production and application of biochar extracted from straw can address the limitations of incorporating straw in the field while improving the effectiveness of soil improvement (Liang *et al.*, 2021). Hydrochar is prepared via high temperature methods with lower preparation temperature and energy consumption, resulting in products with abundant organic functional groups and organic acids (Bian *et al.*, 2024; Dimitrios *et al.*, 2024). Therefore, hydrochar has a dual effect of reducing resource waste and being more conducive to improving saline-alkali soil (Wang *et al.*, 2024; Liu *et al.*, 2024). At present, limited research existed on converting hydrochar products into modifiers and water-soluble fertilizers, as well as on their combined application.

In this study, hydrochar of corn stalks was mixed with mushroom chaff, humic acid and fine sand to prepare soil modifiers. The acidic mixed solution (liquid product of hydrochar) and inorganic salt were used to prepare water-soluble fertilizer of medium elements. They were applied in combination to explore the effect of soda saline soil on nutrient content, salt content, crop growth, and soil enzyme activity in saline soils. The research findings provided a theoretical basis and technical support for effectively improving alkaline soil and promoting the utilization of straw resources.

Materials and Methods

Materials

The soda saline soil samples were collected from Erlong Village, Erlong Township, Taonan City, Jilin Province, China and was conducted in July 2020 at a 0-20 cm depth. The soda saline soil was thoroughly mixed, air-dried, and passed through a 2 mm sieve. The basic physical and chemical characteristics of the soil samples were presented in Table 1.

Corn stalks were sourced from the corn production field at the Agricultural Science Experiment Station of Jilin Agricultural University. They were naturally air-dried, crushed and passed through a 60-mesh sieve. Cu, Zn, Fe and Mn contents in straw were 19.12 mg/kg, 13.10 mg/kg, 39 mg/kg and 323.11 mg/kg, respectively. Discarded black fungus chaff was collected from Dapu Chaihe Town, Dunhua City, Jilin Province. The initial composition of the black fungus chaff included 85% wood chips, 10% wheat bran, 3% soybean cake powder, 1% gypsum, and 1% quicklime. The harvested fungus chaff was air-dried, crushed to remove impurities, and utilized in the formulation of soil conditioners. The pH value of the chaff was 7.13. The nutrient analysis of the two aforementioned materials was showed in Table 2 (Li *et al.*, 2022; Shao *et al.*, 2023).

Humic acid was obtained from Harbin Yisida Ecological Science and Technology Development Limited Liability Company. The content of effective humic acid was 71.85% with pH value 4.42. Alfalfa seeds were sourced from Ningxia, China, and *Leymus chinensis* seeds were sourced from Taonan, Jilin Province, China. Two types forage seeds were carefully selected and their germination rates were evaluated in a controlled environment of a constant temperature and light incubator.

Table 1. The basic physical and chemical properties of soda saline-alkali soil

Organic matter (g/kg)	Available N (mg/kg)	Available P ₂ O ₅ (mg/kg)	Available K ₂ O (mg/kg)	pH (1:2.5; 20 °C water leaching)	
7.7	36.28	14.16	161.69	8.73	
Alkalinity (%)	Volume weight (g/cm ³)	Total porosity (%)	Na ⁺ (mg/kg)	Ca ²⁺ (mg/kg)	Mg ²⁺ (mg/kg)
6.51	1.52	36.94	109.5	42.92	237.16

Table 2. The nutrient content of the corn stalk and the waste fungus chaff

Experimental material	Organic matter (%)	Total nitrogen (%)	Total phosphorus (%)	Total potassium (%)
Corn stalk	71.72	1.07	0.13	2.07
Waste fungus chaff	57.31	0.43	0.35	0.03

Soil modifiers and water-soluble fertilizer preparation methods

Hydrochar was prepared via corn stalks and water. The mixture was stirred for 30 min at room temperature and transferred into a 1000 ml Teflon-lined stainless-steel autoclave which was placed into oven and reacted at 240 °C for 24 hours (Zhang *et al.*, 2021). It was withdrawn and cooled down to room temperature. The product was filtered and separated into solid and liquid fractions. The solid portion and the liquid portion were utilized in the soil modifiers and water-soluble fertilizer, respectively. The yield of corn stalks hydrochar was 30.21% with a C/N atomic ratio of 29.59. The pH value of the liquid portion was 4.52 including glucose and organic acids.

The soil modifier was prepared by solid biochar, fungal chaff, humic acid, fine sand and acidic mixed solution with the mass ratio of 0.5:4.5:2:1:2, and then a certain amount of acidic mixed solution (liquid portion and dilute hydrochloric acid) was added into, and adjusted pH value to 6.5 with dilute hydrochloric acid. The moisture content of the modifier is approximately 20%, with an organic matter content of 48.80 g/kg.

The water-soluble fertilizer was prepared by mixing acidic solution obtained from preparing hydrochar with a certain amount of calcium nitrate tetrahydrate (60 g/L) and magnesium nitrate hexahydrate (40g/L). The pH value of it was 2.47. When it was sprayed onto the surface of leaves, the water-soluble fertilizer was diluted ($V_{\text{water-soluble fertilizer}}:V_{\text{water}} = 1:1500$) with pH value of 6.97.

Field micro-area experiments and test analysis

Field micro-area experiments

The field micro-area experiment was conducted from May 10 to September 20, 2022 in Erlong Village, Erlong Town. The land was divided into 138 test plots in the form of 1.00 m × 1.00 m. The top layer of tillage soil (above 20.00 cm) was removed to mix with modifiers and then refilled it to its original position, ensuring that the physicochemical properties remain essentially unchanged. The 100 seeds were sown uniformly in each subdistrict, which was denoted as M0, M10, M20, M30, M40, M50 with modifier dosage of 0-5%, respectively. The plants were sprayed with 100 ml water-soluble fertilizer for the first time when they grew the three-leaf stage, and then sprayed every 10 days with spraying being carried out three times, denoting by MF (modifier dosage of 1-5%, denoted as MF10, MF20, MF30, MF40, MF50). After 50 days of growth, the roots of alfalfa and *L. chinensis* were taken out from the soil, cleaned, and then determined various of the indicators. The second batch experiment was conducted in original soil and only sprayed water-soluble fertilizer without modifiers. At harvest time, the pasture grasses were removed from the soil, placed on a sieve, cleaned with water. The forages were carried out an oven at 105 °C for 24 h to measure biomass. Errors bars represent standard errors. Different lowercase letters above the bars indicate significant differences among treatments at $P < 0.05$ with applied different amounts of modifier, which applied all the figures.

Test analysis

Soil pH was measured by PHS-3C acidimeter ($V_{\text{soil}}:V_{\text{water}} = 1:2.5$). the soil EC was determined by conductivity meter. The content of water-soluble salt was determined by mass method. The calcium and magnesium ions were conducted by atomic absorption, respectively. Using flame photometry to measure potassium and sodium ions. carbonate and bicarbonate ions were carried out by combined titration with double indicator. Cl⁻ and sulfate ion was determined by silver nitrate titration and indirect complexation titration with EDTA, respectively. alkalinity = exchangeable sodium/cation exchange capacity (CEC). The content organic matter was determined by $K_2Cr_2O_7-H_2SO_4$ plus heat capacity method. $NaHCO_3$ leaching-molybdenum antimony colorimetric method was used to perform effective phosphorus and NH_4OAC leaching-flame photometric method was to measure fast-acting potassium. Ammonium nitrogen and nitrate nitrogen content were determined by AA3 continuous flow injection analyzer.

The soil catalase activity, alkaline phosphatase activity, enzyme activity of soil alkaline phosphatase and soil polyphenol oxidase activity were performed using a biochemical method kit. The colorimetric method of 3,5-dinitrosalicylic acid was used to measure soil sucrose activity. And soil urease activity was determined by the colorimetric method of sodium phenol-sodium hypochlorite.

Statistical analysis

Excel 2013 was used for data organization and Origin 2018 was applied for charting. SPSS Statistics 20.0 was performed for two-way ANOVA, R software corrplot package and psych package were used for single-matrix county inertia analysis and two-matrix linear analysis, respectively.

Results

Effect of modifiers and water-soluble fertilizers on saline soils

Acidity, alkalinity and nutrient

The pH value of saline soil exhibited a decreasing trend after the application of ameliorator (Figure 1a), and 10 g/kg of modifier can significantly reduce pH value to 2.51% ($P < 0.05$). The lowest of soil pH value was in M50 treatment group, which was lower than that of in M0 treatment group by 7.15% ($P < 0.05$), and the water-soluble fertilizer further reduced the pH to 0.37% ($P < 0.05$).

The addition of modifiers led to an increase in soil conductivity (Figure 1b). However, there was no significant the effect at dosages up to 30 g/kg ($P < 0.05$).

Soil alkalinity showed a decreasing at first and then increasing trend with the increase of modifier dosage (Figure 1c). The soil alkalinity reached the lowest in M10 treatment group, being lower than that of M0 and M20 treatment group by 19.72% and 11.23%, respectively. The water-soluble fertilizer did not exhibit an obvious significance on soil alkalinity.

The effects of modifiers and water-soluble fertilizers on the organic matter of saline-alkaline soils were displayed in Figure 1d. With the increase of modifiers, the organic matter content in the saline-alkali soil showed an upward trend, and the differences among treatment groups were significant ($P < 0.05$). Among them, the M50 treatment reached the maximum value, showing an increase of 59.18% compared to the M0 treatment group. The addition of water-soluble fertilizer led to a decrease in organic matter content, with the MF0 treatment group decreasing by 0.88% compared to the M0 treatment group, and the difference between the two treatment groups was not significant.

The content of available phosphorus and available potassium in the soil showed an increasing trend with the increase modifier dosage (Figure 1 e- f). Furthermore, under the M50 treatment, the content of phosphorus and potassium obtained the maximum values, being 33.77% ($P < 0.05$) and 694.80% ($P < 0.05$) higher, respectively, compared to the M0 treatment groups.

The effects of modifier and water-soluble fertilizer on soil ammonium content of nitrogen and nitrate nitrogen were observed in Figure 1 g-h. With the increase of modifier dosage, content of soil ammonium nitrogen and nitrate nitrogen showed an upward trend, and content of ammonium nitrogen and nitrate nitrogen with M50 treatment group got the maximum, which were higher than that of the M0 treatment group by 55.77% ($P < 0.05$) and 93.55% ($P < 0.05$), respectively. Moreover, the application of water-soluble fertilizer further enhanced the contents of ammonium nitrogen and nitrate nitrogen, but the effect was not significant.

Water-soluble salts and salt-based ions

The content of the water-soluble salt tended to increase with the increase in the amount of modifier (Figure 2a), and content of the water-soluble salt was the maximum value in the M50 treatment group. However, the effect of the water-soluble fertilizer on content of the soil water-soluble salt was not significant.

The content of water-soluble calcium ion was increased with the addition in the amount of modifier (Figure 2b). And prominent impact was observed on content of the calcium ion with each increasing of 10 g/kg modifier. The calcium ion content was significantly affected by the addition of 10 g/kg of modifier. The M50 treatment group had a 436.67% higher calcium ion content compared to the M0 treatment group ($P < 0.05$).

The trend on content of magnesium ion after the application of modifier was similar with that of content of magnesium ions (Figure 2c), and the content of magnesium ion with the M50 treatment group reached the maximum value, which was higher than that of the M0 treatment group to 518.72% ($P < 0.05$). The water-soluble fertilizer further increased content of the magnesium ion to 8.79% ($P < 0.05$).

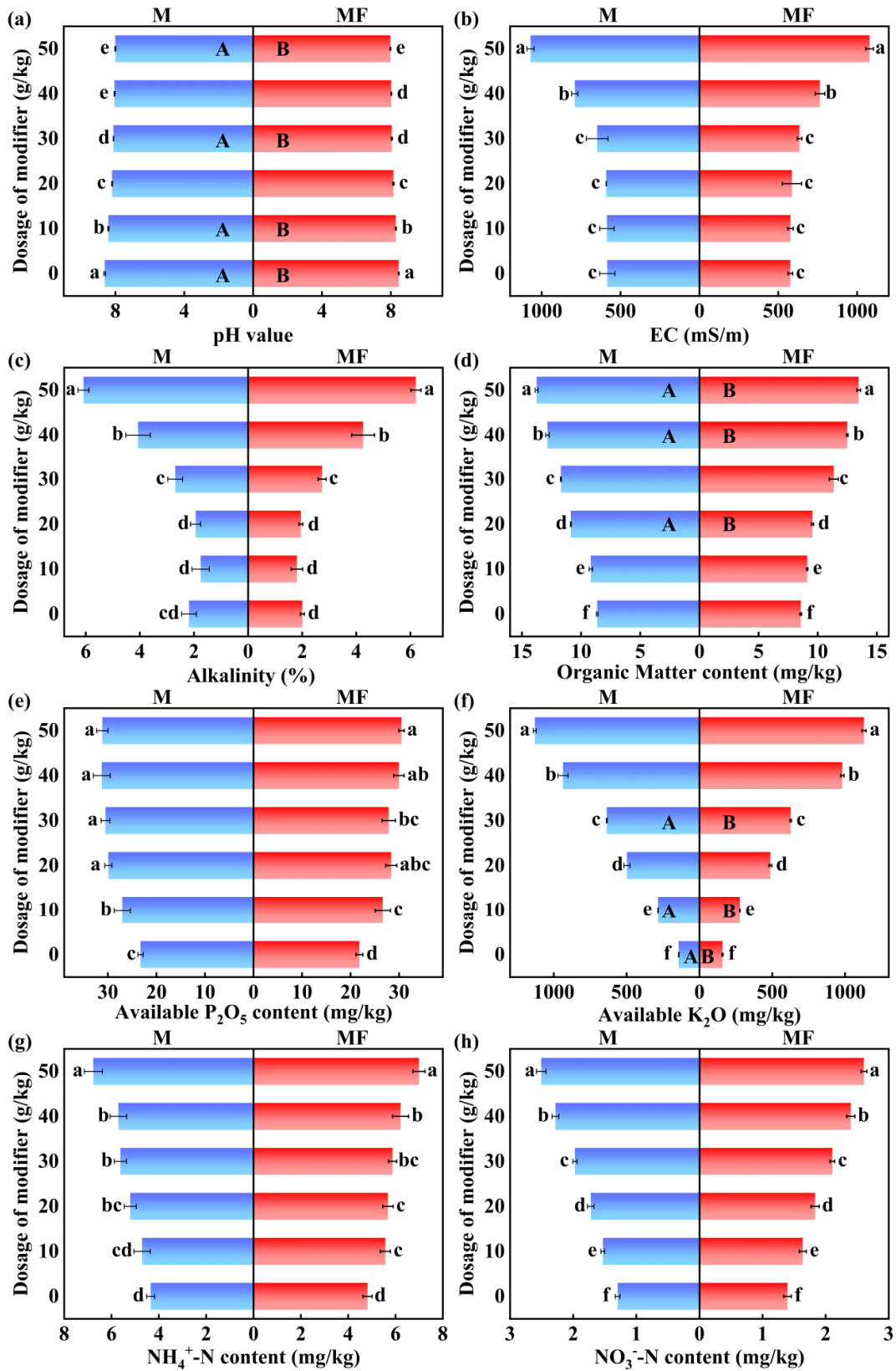


Figure 1. Effect of modifiers and water-soluble fertilizers on acidity, alkalinity and nutrient in saline soil

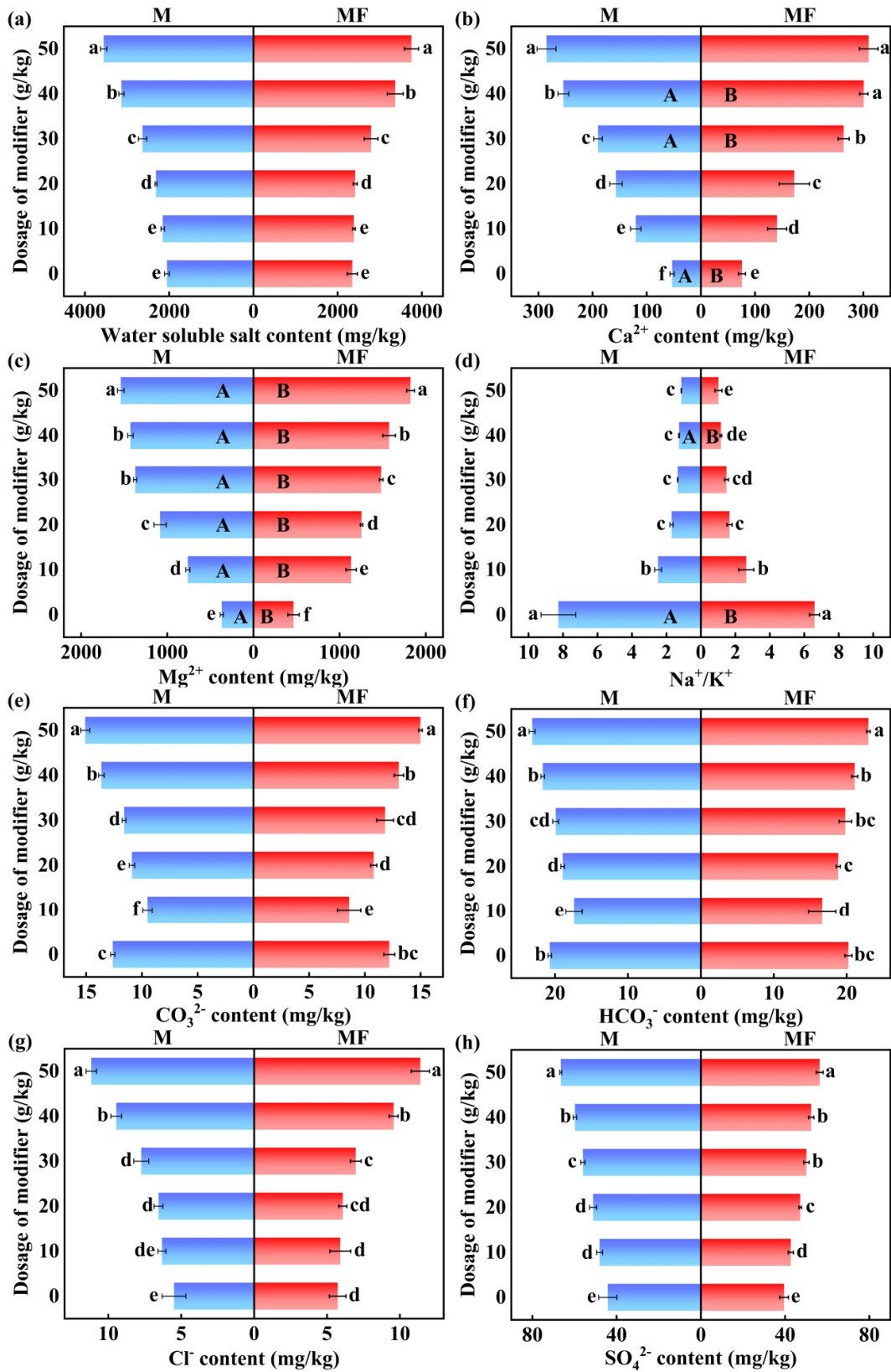


Figure 2. Effect of modifiers and water-soluble fertilizers water-soluble on salts and salt-based ions in saline soil

The application of modifiers resulted in a decrease on Na^+/K^+ (Figure 2d) in the M10 treatment group, showing the most dramatic reduction to 69.97% ($P < 0.05$). Compared with the M0 treatment group, the M20 treatment group further reduced Na^+/K^+ by 31.60% ($P < 0.05$). There was no significant difference in the soil Na^+/K^+ ratio with the continuous increase of modifier dosage compared to the M10 treatment group.

Figure 2e and Figure 2f displayed the distinct effects applied modifier and water-soluble fertilizer on CO_3^{2-} and HCO_3^- . The application of the modifier significantly reduced the content of these two ions. At a modifier dosage of 10 g/kg, the content of the two ions decreased by 24.68% ($P < 0.05$) and 16.06% ($P < 0.05$) respectively, compared to when no modifier was added. Conversely, further increasing the modifier dosage led to an increase in the content of these two ions.

The concentration of SO_4^{2-} and Cl^- increased with the increase of modifier dosage. The addition of modifiers led to an increase in content of SO_4^{2-} with Cl^- . However, no remarkable impact was observed on Cl^- at a dosage of 10 g/kg.

Effects of modifiers and water-soluble fertilizers on alfalfa

Growth

As can be seen from Figure 3a, the biomass of the two batches of alfalfa showed a tendency of first increasing and then decreasing with the increase in the amount of modifier, and the M20 treatment significantly increased the biomass of the two batch of alfalfa, which were higher than that of the M0 treatment by 81.67% ($P < 0.05$) and 15.32% ($P < 0.05$), respectively.

With the increase in modifier dosage, the biomass of both batches of alfalfa showed a trend of initially increasing and then decreasing in Figure 3a. They were increased 81.67% ($P < 0.05$) and 15.32% ($P < 0.05$) in the M20 treatment group, respectively, compared to the M0 treatment group. The addition of water-soluble fertilizers further improved the biomass of the M20 treatment on the first planting of alfalfa by 23.68% ($P < 0.05$) and had no significant effect on the second planting of alfalfa.

Figure 3b exhibited the effects of modifier and water-soluble fertilizers on alfalfa leaf length. The leaf length of alfalfa in first planting with M20 treatment group significantly increased to 43.84% ($P < 0.05$) compared to M0. And the leaf length of alfalfa with water-soluble fertilizers was further increased to 8.89% ($P < 0.05$) in the M20 treatment group. The modifier and water-soluble fertilizers did not appear marked effect on the leaf length of the second planting of alfalfa.

The effect of modifier and water-soluble fertilizer on leaf width of alfalfa were showed in Figure 3c. The leaf width of two batches of alfalfa significantly increased in M20 treatment group, which were higher 40.71% ($P < 0.05$), and 8.72% ($P < 0.05$) than that of M0 treatment group, respectively. The addition of water-soluble fertilizer further increased the leaf width of the first planting of alfalfa treated with M20 by 17.77% ($P < 0.05$). However, that of on the second planting did not present significant effect.

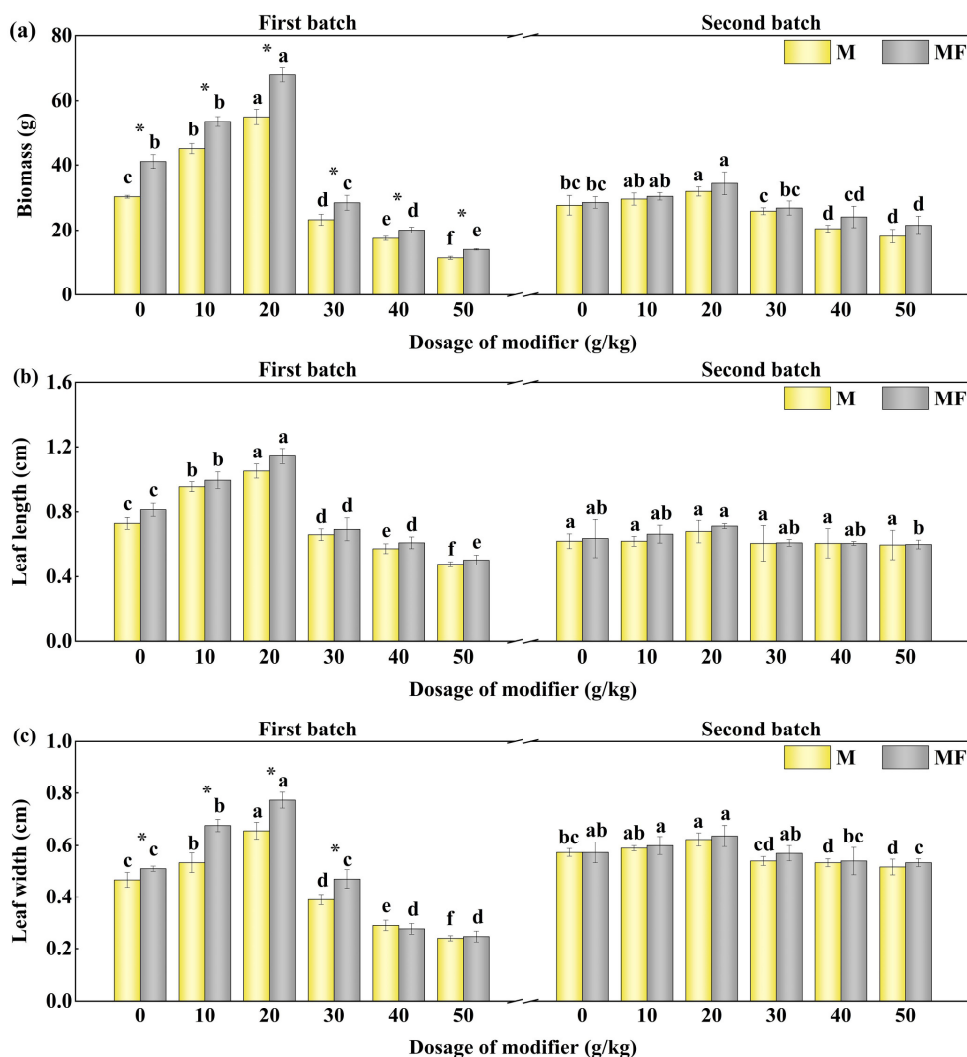


Figure 3. Effect of modifiers and water-soluble fertilizers on alfalfa growth in saline soil

Soil enzyme activity

The effects of modifiers and water-soluble fertilizers on soil enzyme activities were shown in Figure 4a-e. The addition of modifiers enhanced the activity of several soil enzymes, but the effects vary. With increasing doses of the modifier, the alkaline phosphatase, sucrase, and urease activities of the two batches soil showed a trend of initially increasing and then decreasing. Among these enzyme activities, the activities of several enzymes in the M20 treatment reached maximum levels, with alkaline phosphatase activity being 50.95% higher ($P < 0.05$) and 28.22% higher ($P < 0.05$) compared to the M0 treatment, respectively.

The sucrase activity of M20 treatment group with water-soluble fertilizer further were increased 16.56% ($P < 0.05$) and 9.05% ($P < 0.05$), respectively. Soil polyphenol oxidase activity gradually increased with the adding of modifier dosage, and appeared the highest value in M40 treatment group, increasing to 47.74% ($P < 0.05$) and 41.39% ($P < 0.05$) in the two batches alfalfa, respectively, compared with M0 treatment group. There was no significant difference between the M50 treatment group and the M40 treatment group. In addition, water-soluble fertilizers did not present a significant effect on soil polyphenol oxidase activity. The effect of modifier and water-soluble fertilizer on soil catalase activity was less, only that of the M20 treatment group of the first planting alfalfa increased by 32.70% ($P < 0.05$) compared with that of no modifier application.

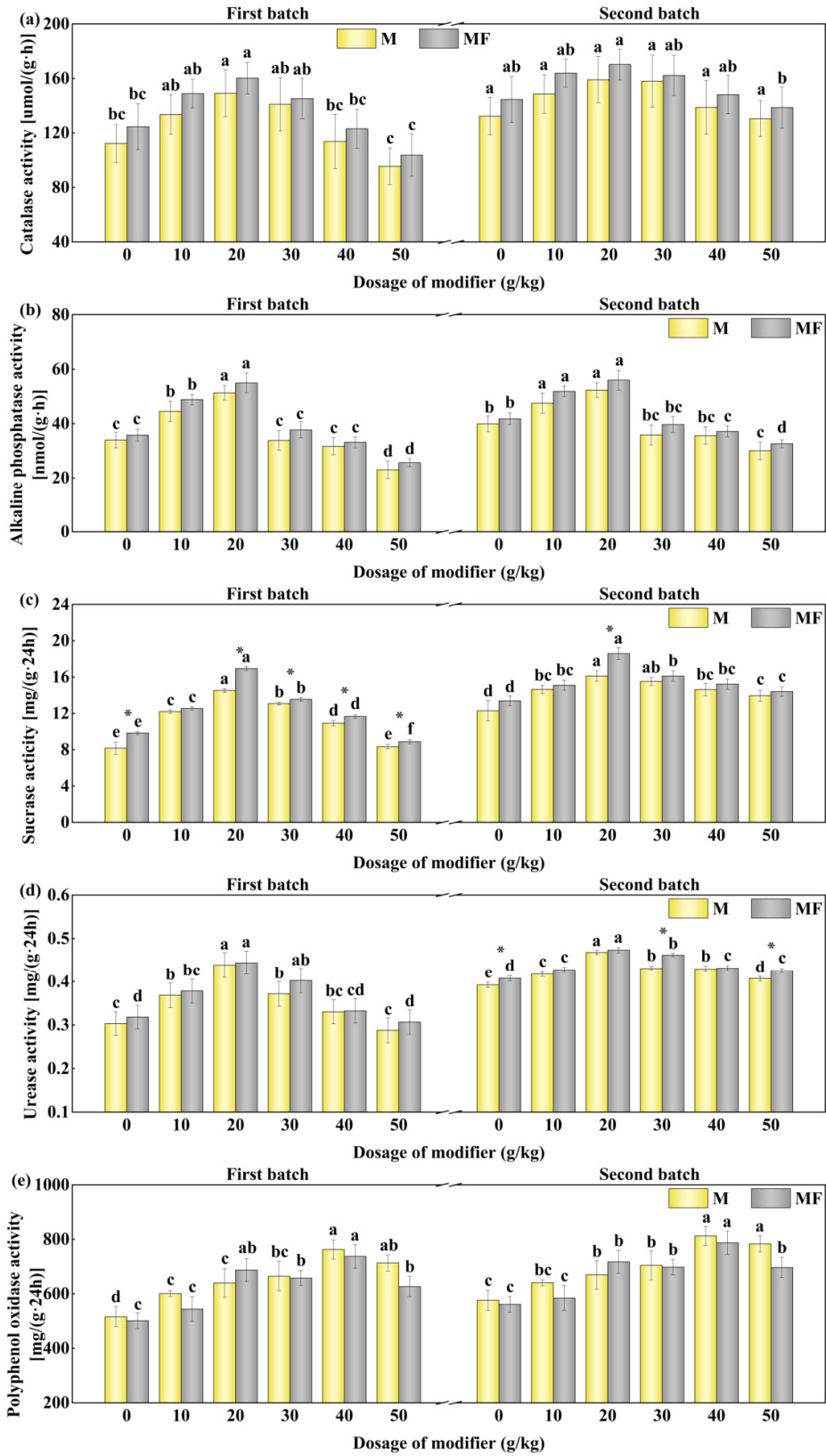


Figure 4. Effect of modifiers and water-soluble fertilizers on soil enzyme activity of planting alfalfa in saline soil

Effects of modifiers and water-soluble fertilizers on L. chinensis

Growth

As can be seen from Figure 5a, the biomass of the two batches of *L. chinensis* exhibited a tendency of first increasing and then decreasing with the increase in the amount of modifier. The biomass of the two batches of *L. chinensis* was significantly increased under the M20 treatment group, which was higher than that of the M0 treatment group by 28.64% ($P < 0.05$) and 8.71% ($P < 0.05$), respectively. The addition of water-soluble fertilizers further improved the biomass of the first batch of *L. chinensis* in the M20 treatment group by 16.95% ($P < 0.05$) and had no significant effect on the second batch of *L. chinensis* in this experiment.

The leaf length of *L. chinensis* were displayed in Figure 5b after applied modifier and water-soluble fertilizer. Compared with that of M0 treatment group, leaf length of the first batch of *L. chinensis* in M20 treatment group distinctly increased to 51.58% ($P < 0.05$), and the water-soluble fertilizer did not make the leaf length pronounced increased again. The effect of modifier and water-soluble fertilizer on leaf length of the second batch of *L. chinensis* hardly appeared.

The impact of modifier and water-soluble fertilizer on leaf width of *L. chinensis* can be seen in Figure 5c. The leaf width of the first batch of *L. chinensis* significantly increased 23.38% ($P < 0.05$) in M20 treatment group, and the same effect did not happen in the second batch.

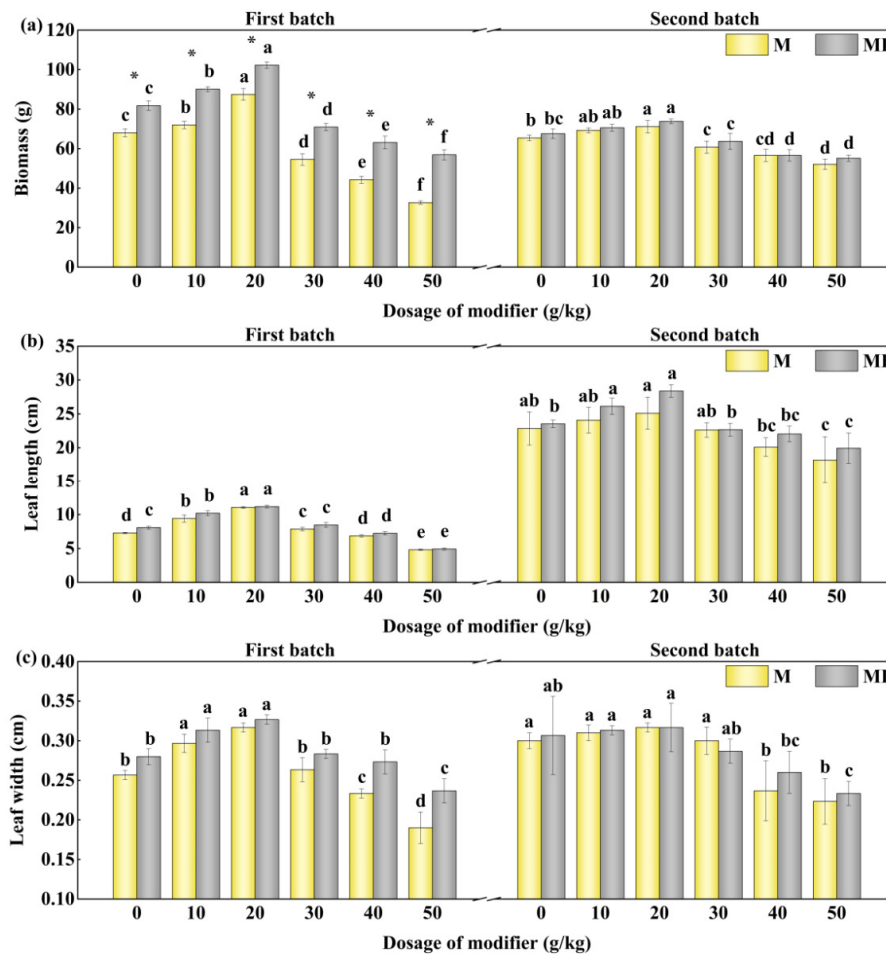


Figure 5. Effect of modifiers and water-soluble fertilizers on *L. chinensis* growth in saline soil

Soil enzyme activity

With the increase in the dosage of modifiers, the trend of soil enzyme activities in *L. chinensis* was similar to that of in alfalfa (Figure 6 a-e). With the increase of modifier dosage, soil catalase, alkaline phosphatase, sucrase, and urease activities presented a trend of first increasing and then decreasing, and several enzyme activities reached the maximum value in M20 treatment group, which were higher than that of M0 treatment group by 16.04% ($P < 0.05$), 28.22% ($P < 0.05$), 25.52% ($P < 0.05$), and 20.15% ($P < 0.05$), respectively. The urease activity was conspicuously increased with water-soluble fertilizer in M20 treatment group by 2.64% ($P < 0.05$). Soil polyphenol oxidase activity increased gradually with the increase of modifier dosage, and appeared the highest value in the M40 treatment group, which was 41.39% ($P < 0.05$) higher than that of the M0 treatment group. However, there was no significant difference between that of the M50 treatment group and the M40 treatment group.

Correlation analysis

The single matrix correlation analysis of soil indicators was shown in Figure 7a. All indicators reached a highly significant positive correlation at the 0.001 level except for soil pH value. The soil pH value reached a highly significant negative correlation with concentration of calcium ion, magnesium ion, organic matter, available potassium, available phosphorus and nitrate nitrogen at the 0.001 level, and reached a highly distinctive negative correlation with concentration of alkalinity, water-soluble salt and ammonium nitrogen at the 0.001 level, and reached pronounced negative correlation with concentration of soil effective nitrogen the 0.05 level.

The correlations between alfalfa growth and soil enzyme activities were shown in Figure 7b. It can be seen the alfalfa growth was positively correlated with alkaline phosphatase activity of both batches of alfalfa and catalase activity of the first batch of alfalfa. The correlation with sucrase and urease activities was low, especially in the second batch experiment. The alfalfa growth was negatively correlated with polyphenol oxidase activity. The correlation of *L. chinensis* growth and soil enzyme activities was similar to that of alfalfa (Figure 7c).

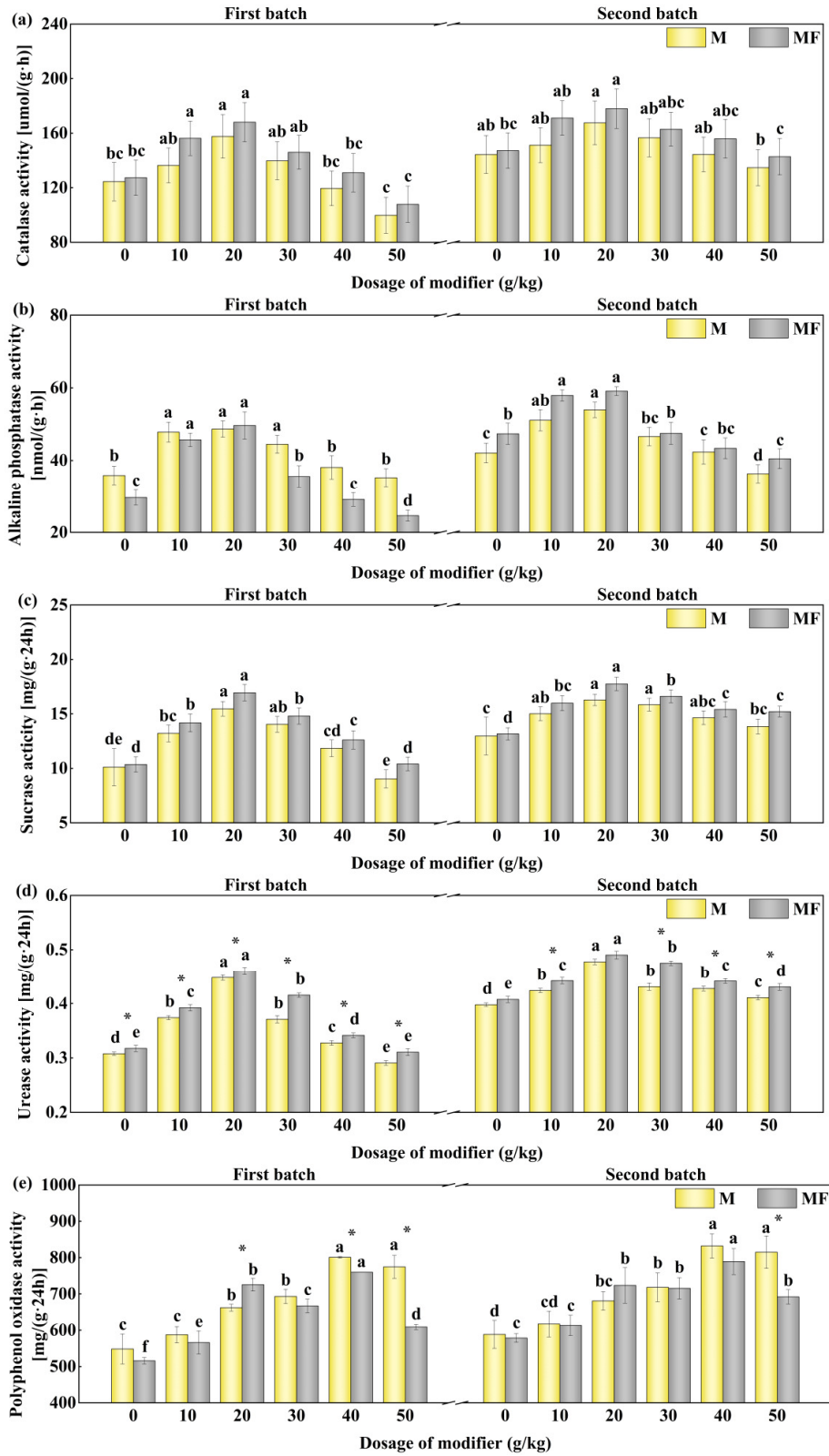


Figure 6. Effect of modifiers and water-soluble fertilizers on soil enzyme activity of planting *L. chinensis* in saline soil

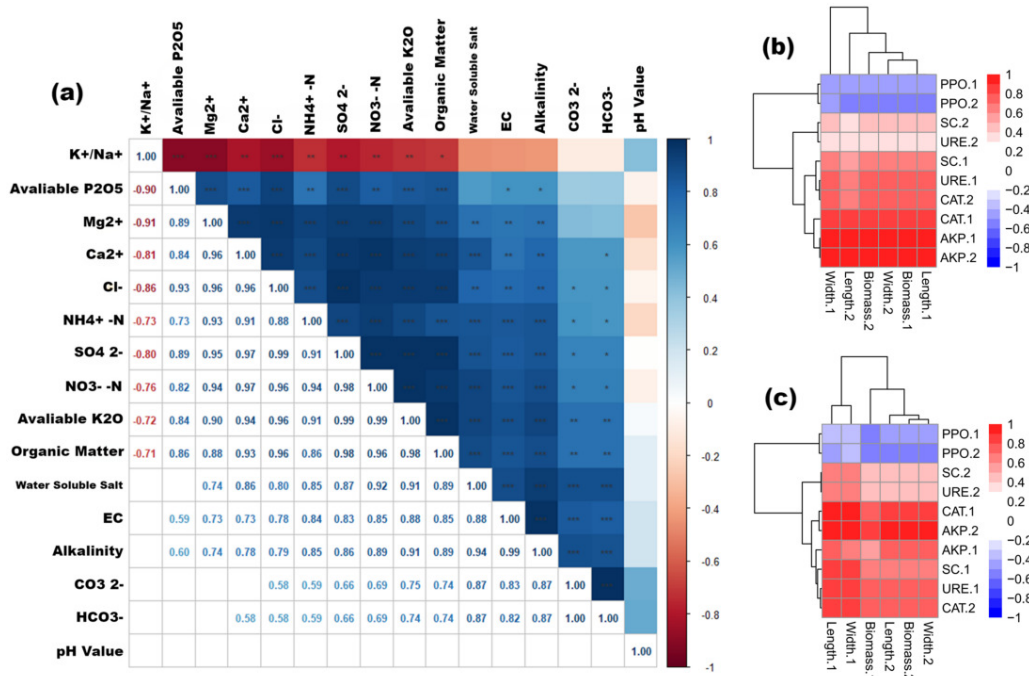


Figure 7. Correlation analysis

Results of two factor analysis variance

The impact of modifiers and water-soluble fertilizers on the enzyme activity of saline soil and forages were analysed by two-way ANOVA (Tables 3-5). The results of two-way ANOVA appeared that indicators of alkaline soil appeared noteworthy effect with modifier on the growth of two kinds of forage and soil enzyme activity. In addition to alkalinity, available potassium, electrical conductivity and water-soluble anions, water-soluble fertilizer displayed a significant effect ($P < 0.05$) on all chemical indicators of saline soil. At the same time, the growth indicators of the first crop of forage grasses ($P < 0.05$) were significantly affected, and these were hardly appeared on the leaf length and width of the second batch of alfalfa and on the biomass and leaf width of the *L. chinensis*. Moreover, except for polyphenoloxidase of second batch soil, water-soluble fertilizer presented marked effects on the growth and enzymatic activity of the two kinds of forages. In terms of chemical indexes of saline soil, the interaction between modifier and water-soluble fertilizer exhibited prominent effect on soil calcium ions, magnesium ions, Na^+/K^+ , pH value, organic matter, available potassium and other indexes. In addition, the interaction between the modifier and water-soluble fertilizer had significant effects on the biomass and leaf width of the first batch of alfalfa and the leaf length of the first batch of *L. chinensis*. And they also had certain effects on the activities of other enzymes, except for peroxidase. The interaction also happened on the biomass and leaf width of the first alfalfa crop and leaf length of the first *L. chinensis*.

From the F test, the F value of each index after the application of modifier was generally larger than that of water-soluble fertilizer, indicating that the modifier played an important role. The F-value of the growth index of the first batch of forage after applied modifier was greater than that of the second batch of forage. The reason of above phenomenon might be that after planting first batch of forage, the modifier was partially absorbed by the forage, and thus the effect of the modifier on the forage was reduced. The F values of various enzyme activities of the soil after the application of modifiers were generally greater than that of the water-soluble fertilizer, indicating that the modifiers display a leading role on soil enzyme activities.

Table 3. Two-factor analysis on the effect of modifiers and water-soluble fertilizers on saline soils

Parameter		Water-soluble fertilizer	Ca ²⁺	Mg ²⁺	Na ⁺ /K ⁺	CO ₃ ²⁻	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻
Modifier	F	190.268	251.659	608.754	300.004	39.156	47.57	211.739	756.601
	P	0.000	0.000	0.000	0.000	0.000	0	0	0
Water-soluble fertilizer	F	33.935	54.462	169.458	5.610	0.991	2.226	3.268	2.029
	P	0.000	0.000	0.000	0.026	0.172	0.149	0.083	0.167
Modifier × Water-soluble fertilizer	F	0.593	3.825	8.460	6.077	0.179	0.214	1.039	0.344
	P	0.706	0.011	0.000	0.001	0.861	0.953	0.417	0.881
		Alkalinity	Organic matter	Available P ₂ O ₅	Available K ₂ O	NH ₄ ⁺ -N	NO ₃ ⁻ -N	pH	EC
Modifier	F	255.175	1118.403	42.081	4823.380	49.688	453.085	333.052	170.239
	P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0
Water-soluble fertilizer	F	0.187	69.683	11.538	1.688	26.247	40.222	53.204	0.551
	P	0.669	0.000	0.002	0.206	0.000	0.000	0.000	0.465
Modifier × Water-soluble fertilizer	F	0.330	15.088	0.672	3.785	1.075	0.084	5.553	0.142
	P	0.890	0.000	0.649	0.011	0.399	0.994	0.002	0.981

Table 4. Two-factor analysis on the effect of modifiers and water-soluble fertilizers on forage growth

Alfalfa		First batch			Second batch		
		Biomass	Leaf length	Leaf width	Biomass	Leaf length	Leaf width
Modifier	F	848.03	189.643	301.137	28.406	1.733	10.093
	P	0.000	0.000	0.000	0.000	0.165	0.000
Water-soluble fertilizer	F	184.439	14.533	53.651	7.192	0.547	1.628
	P	0.000	0.001	0.000	0.013	0.467	0.214
Modifier × Water-soluble fertilizer	F	11.656	0.721	8.626	0.490	0.107	0.173
	P	0.000	0.614	0.000	0.780	0.990	0.970
<i>Leymus chinensis</i>		First batch			Second batch		
		Biomass	Leaf length	Leaf width	Biomass	Leaf length	Leaf width
Modifier	F	423.475	419.322	61.142	53.305	13.546	13.025
	P	0.000	0.000	0.000	0.000	0.000	0.000
Water-soluble fertilizer	F	583.145	28.607	42.481	0.000	7.145	0.367
	P	0.000	0.001	0.000	1.000	0.013	0.551
Modifier × Water-soluble fertilizer	F	4.325	2.094	2.096	0.000	0.569	0.356
	P	0.006	0.101	0.101	1.000	0.723	0.847

Table 5. Two-factor analysis on the effect of modifiers and water-soluble fertilizers on soil enzyme activity

Alfalfa (First batch)		ALP	CAT	SC	URE	PPO
Modifier	F	77.964	10.557	552.323	22.257	28.672
	P	0	0	0	0	0
Water-soluble fertilizer	F	9.579	3.871	120.57	2.144	3.362
	P	0.005	0.061	0	0.156	0.079
Modifier × Water-soluble fertilizer	F	0.242	0.091	13.009	0.208	2.117
	P	0.94	0.993	0	0.956	0.098
Alfalfa (Second batch)		ALP	CAT	SC	URE	PPO

Modifier	F	53.706	3.995	39.069	123.137	28.351
	P	0.000	0.009	0.000	0.000	0.000
Water-soluble fertilizer	F	9.579	3.994	24.460	56.986	3.362
	P	0.005	0.057	0.000	0.000	0.000
Modifier × Water-soluble fertilizer	F	0.242	0.093	2.639	5.515	2.117
	P	0.940	0.992	0.049	0.002	0.098
<i>Leymus chinensis</i> (First batch)		ALP	CAT	SC	URE	PPO
Modifier	F	57.63	13.739	49.182	751.369	104.834
	P	0	0	0	0	0
Water-soluble fertilizer	F	49.446	4.715	10.22	131.269	27.087
	P	0	0.04	0.004	0	0
Modifier × Water-soluble fertilizer	F	4.707	0.275	0.395	8.897	17.573
	P	0.004	0.922	0.847	0	0
<i>Leymus chinensis</i> (Second batch)		ALP	CAT	SC	URE	PPO
Modifier	F	43.018	4.847	18.953	176.161	37.269
	P	0.000	0.003	0.000	0.000	0.000
Water-soluble fertilizer	F	20.078	4.697	12.836	131.269	4.195
	P	0.000	0.040	0.002	0.000	0.052
Modifier × Water-soluble fertilizer	F	1.312	0.274	0.541	8.897	4.052
	P	0.292	0.923	0.743	0.000	0.008

Discussion

Effects of modifiers and water-soluble fertilizers on saline soil

Salinization of land can result in soil nutrient deficiency, seriously restricting plant growth (Zhao *et al.*, 2020). This study revealed that the application of modifiers and water-soluble fertilizers effectively reduced soil pH value and alkalinity, improved soil nutrients, and enhanced saline soil. However, excessive application of modifiers caused a dramatic promotion in soil alkalinity and concentration of water-soluble salt showing negative impact on saline soils and resulting in resource wastage. Conversely, insufficient application of modifiers failed to achieve the optimum amount required. Hence, the experiment chose the modifier at a range of 10 g/kg - 50 g/kg (Gong *et al.*, 2021). When the amount of modifier exceeds 20 g/kg, comprehensive indicators revealed a significant enhancement in concentration of soil water-soluble salt and alkalinity. Therefore, it demonstrated that the amount of modifier should not exceed 20 g/kg. Comparatively, applied 10 g/kg of modifier did not present significantly impact on soil alkalinity. However, employing 20 g/kg of modifier resulted in elevated content of water-soluble salt, decreased Na⁺/K⁺ ratio, and a notable improvement in nutrient levels. The increase nutrient content showed that the optimal amount of soil modifier was 10-20 g/kg. When the dosage of modifier exceeds 40 g/kg, the soil became saturated with larger particles that were challenge for absorption and utilization. The excessive dosage not only adversely affected saline soil but also resulted in the wastage of resources. Additionally, salts were carried by water. When an excess amount of modifier was used, the salts presented in the modifier would enter the soil along with the water. This portion of the modifier did not contribute to soil improvement. Therefore, excessive used of the modifier could significantly raise content of water-soluble salt of soil, negatively impacting its quality.

The pH value is one of the factors that affect soil fertility. Lowering the pH value can minimize damage to crops in saline-alkaline soils. Applying modifiers in saline-alkaline soils can effectively neutralize the alkalinity of the soil due to the acidity of the modification itself. Simultaneously, the application of biochar in the soil resulted in the release of Ca^{2+} , K^+ , and Mg^{2+} ions, displacing the Na^+ , H^+ , and Al^{3+} ions, and they were adsorbed by the soil colloid. This displacement led to the release of acid-generating ions into the soil solution, ultimately declined the pH value of soil. Moreover, in cases of excessive soil alkalinity, humic acid could release H^+ ions reacting with OH^- ions to form H_2O , thus reducing concentration of alkalinity of soil (Zhang *et al.*, 2020). The fungal chaff could similarly reduce pH value of soil. The water-soluble fertilizer distinctly decreased the pH value of the saline soil attributing to its composition, including diluting the acidic mixed solution and inorganic salt.

Alkalinity and water-soluble salt content are important indicators of successful improvement in saline-alkaline soils. Some studies found (Shi *et al.*, 2018) that the cation exchange of the soil was increased after the application of biochar, and led to a decrease in alkalinity. Excessive application of modifiers could lead to the accumulation of unabsorbed and untransformed exchangeable Na^+ in the soil, significantly rising soil alkalinity. Adding modifiers in the soil improved content of water-soluble salt. However, dosage of up to 20 g/kg displayed minimal impact on the content of water-soluble salt, exceeding 20 g/kg result in a substantial increase. Increasing content of water-soluble salt was detrimental to the improvement of saline-alkaline soil. Soil humus contained calcium and magnesium ions (Michalska *et al.*, 2023), which can be extracted into humic acid and applied to the soil to increase the content of calcium and magnesium ions in the soil. Since water-soluble fertilizer contained a certain amount of Ca^{2+} and Mg^{2+} , leading to an increase content of soil water-soluble salt.

Numerous studies found that maintaining a low Na^+/K^+ ratio was the main salt tolerance strategy for plants. In our experiments, adding 10 g/kg of modifier decreased the Na^+/K^+ ratio, while applying 20 g/kg modifier further increased the Na^+/K^+ ratio. Adding the amount of modifier did not appear effect of the Na^+/K^+ ratio, indicating that the optimal amount of modifier should not exceed 20 g/kg (Li *et al.*, 2021). Water-soluble anions presented in the soil typically exerted a detrimental impact. Elevated levels of Cl^- could readily impede the growth of susceptible forage, resulting in leaf discoloration and wilting. SO_4^{2-} could hinder the uptake of essential nutrients like calcium and magnesium. The combination of CO_3^{2-} and HCO_3^- with Na^+ in the soil elevated the content of sodium and exacerbates soil salinization.

The productivity of grasslands in saline-alkaline soils is significantly limited by nutritional deficiencies. Adding nutrients is an effective means of supplementing growth-limiting factors for grassland plants, thereby enhancing productivity (Cao *et al.*, 2023). Augmenting soil organic matter not only enhances soil fertility but also improves soil structure and augments the abundance of soil macroaggregates (Soares *et al.*, 2022). During plant growth, soil effective nitrogen is of paramount importance. Phosphorus plays a critical role in influencing crop yield and quality, while potassium represents a significant component necessary for optimal plant growth. Enhancing soil nutrient levels is pivotal to ameliorate the condition of saline soil. The application of modifiers exhibited the potential to augment the concentrations of key soil nutrients. The notable finding is that there was a significant increase in the effective potassium content in our experiments. The increasing of alkaline nitrogen content of the soil demonstrated insignificant change beyond a dosage of 30 g/kg of modifiers, while the available phosphorus content did not exhibit notable increments when the dosage of modifiers surpassed 20 g/kg. These observations highlight the diminishing returned of excessive using of modifiers in the reclamation of saline-alkaline soils. The materials utilized in the modifier were discovered to possess a substantial quantity of organic matter, which primarily accounted for the observed increase in soil organic matter content following its application. Biochar, renowned for its superior capabilities as a soil modifier, demonstrates the potential to enhance soil organic matter content (Ren *et al.*, 2021). Biochar possesses a specific quantity of phosphorus, and its integration into the soil can augment the levels of effective phosphorus in the soil (Wang *et al.*, 2023). Moreover, incorporating biochar into infertile soils can enhance soil nutrient levels, including nitrogen and potassium, while establishing a micro-saline or non-saline environment within

the inter-root layer of crops. Additionally, the application of biochar can mitigate the rate of nitrogen mineralization and denitrification in the soil, resulting in reduced inorganic nitrogen loss (Li *et al.*, 2016). Simultaneously, biochar exhibited remarkable adsorptive properties to bolster holding water capacity of soil and fortify nitrogen fixation (Zheng *et al.*, 2013), which is one of the reasons why soil ammonium nitrogen and nitrate nitrogen contents were improved by the application of modifiers in this experiment.

Effects of modifiers and water-soluble fertilizers on alfalfa

Assessing soil enzyme activities, serves as a mean to evaluate the effective enhancement of the soil environment under saline stress conditions. Specifically, soil peroxidase is an important redox enzyme, primarily responsible for decomposing hydrogen peroxide in the soil, thereby mitigating its harmful effects on plant roots caused by excessive accumulation (Zhang *et al.*, 2023). Soil phosphatase played a very vital role in the effectiveness of soil phosphorus and was an indicator for evaluating the direction and intensity of soil phosphorus biotransformation. Alkaline phosphatase was a type of phosphatase that solubilizes soil phosphorus compounds (Behera *et al.*, 2017) and hydrolyzed organic phosphates to inorganic phosphates, increasing the availability of soil phosphorus. In terrestrial ecosystems, alkaline phosphatase was mainly produced by microorganisms (Spohn *et al.*, 2013). Soil sucrase, also referred to as soil sucrose converting enzyme, functions as an acidic converting enzyme, exhibiting maximal activity in an acidic environment. It was a commonly assessed parameter in soil analysis. Sucrase was actively involved in the soil carbon cycle, and heightened enzymatic activity contributes to an augmented pool of soil organic carbon. Notably, it facilitated the hydrolysis of sucrose into glucose and fructose, promoting the content of soluble nutrients in the soil (Yang *et al.*, 2022). Soil urease was a kind of hydrolytic enzyme that decomposes nitrogenous organic matter, commonly found in fungi, and was a direct source of plant nitrogen nutrition, which can convert organic nitrogen in the soil into crop-available nitrogen, promote the hydrolysis of the carbon-hydrogen bond in the molecules of urea and organic matter, and provide the necessary nitrogen source for the growth of plants (Dawar *et al.*, 2021). Polyphenol oxidase was pivotal in the process of soil organic matter formation, as it facilitates the conversion of aromatic compounds within soil organic components. Moreover, it promoted the condensation of nitrogen-containing proteins, aliphatic compounds, and other substances. As a result, it significantly contributed to increasing soil organic matter content and enhancing soil fertility (Wang *et al.*, 2017). In this experiment, the activities of various enzymes showed at first increasing and then decreasing trend with the addition of modifiers, which appeared that modifiers could improve soil enzyme activities, but the dosage should not be too much. Biochar is rich in nutrients, which can enhance soil fertility (He *et al.*, 2021), thereby promoting the growth of soil microorganisms and increasing enzyme activity. The rich crude protein, crude fat and other components in the fungal bran provide rich nutrition for the growth and reproduction of soil microorganisms, and the metabolites of microorganisms also enhanced the soil enzyme activity.

The field micro-area test revealed that the application of modifier effectively enhanced the growth of alfalfa. Excessive modifier had detrimental effects on alfalfa growth and resulted in resource wastage. Notably, the optimal application rate of 20 g/kg demonstrates the most favorable comprehensive growth indexes for alfalfa. More than 30 g/kg of the modifier, a black layer was formed on the water surface upon water addition. Subsequently, black material adhered to the soil surface, causing soil to harden. Consequently, it became challenging for seedlings to emerge from the soil or even prevents their emergence. Additionally, the growth rate of emerging seedlings became distinctly slow. The primary solid components of the modifier included biochar, fungal chaff, humic acid, and fine sand. Notably, biochar, fine sand, and other materials exhibited no floating behavior when added to water. In contrast, the yellow fungal chaff serves as an initial indication to attribute the black material floating on the water surface to humic acid. Humic acid undergone neutralization when in contact with alkali, resulting in the formation of water-soluble humates. Biochar can effectively improve the physical and chemical properties of soil, promote crop growth, and then increase forage yield (Wu *et al.*, 2021), which is one of the reasons why the forage growth indexes were enhanced after the application of

modifiers in experiment. Fungus husk with loose texture applied into the soil could retain the water and nutrients in the soil, and provide more excellent conditions for the growth of forage (Thomson *et al.*, 2022; Jara-Samaniego *et al.*, 2017). The more impact of modifiers on the initial batch of alfalfa attributed to the higher nutrient absorption by the first crop resulting in a reduction of nutrient content when subsequently planting the second batch of alfalfa. When the dosage of modifier exceeded 20 g/kg, the growth index of the subsequent of alfalfa did not exhibit a considerable decline due to the prior alfalfa absorption of excess nutrients, leading to a more favorable soil environment for the subsequent alfalfa growth. Conducted cultivation experiments revealed that the application of water-soluble fertilizers can effectively supplement Ca^{2+} and Mg^{2+} in the soil, suggesting that foliar spray of such fertilizers pronouncedly enhanced the growth index of alfalfa.

Effects of modifiers and water-soluble fertilizers on L. chinensis

Fescue had strong tolerance to saline soil and was suitable for planting in the Songnen Plain (Hongna *et al.*, 2021; Xia *et al.*, 2023). In this experiment, it was observed that as the dosage of modifier increased, the soil enzyme activity in *L. chinensis* exhibited a similar pattern to that of alfalfa. Specifically, there was an initial increase followed by a subsequent decrease. The application of modifier significantly influenced the soil catalase activity in *L. chinensis*, whereas no significant effect was presented in alfalfa. Moreover, the soil enzyme activity in *L. chinensis* was slightly higher compared to that of alfalfa. The disparity might be attributed to the more developed root growth in *L. chinensis*, which facilitated the secretion of organic acids and other substances by the root system to improve the soil environment and promote the activity of soil microorganisms.

The experiment determined that in a comparable saline environment, *L. chinensis* exhibited higher biomass and longer leaf length compared to alfalfa. However, unlike alfalfa, *L. chinensis* seedlings did not possess the trait of rapid ground coverage, which hindered their ability to reduce the evaporation of soil moisture. Therefore, the primary advantage of planting *L. chinensis* in saline soil relied on its faster growth rate and higher yield potential. The leaf length of the second batch of *L. chinensis* generally exceeded that of the first batch. However, the biomass of *L. chinensis* did not appear the same increase.

Conclusions

With increasing modifier, pH value of soil was decreased in soil, whereas alkalinity initially was first decreased and then increased. The content of water-soluble salt gradually increased. Furthermore, concentration of Ca^{2+} , Mg^{2+} , and soil nutrient content exhibited gradual increases, while the Na^+/K^+ ratio progressively decreased. The optimal dosage of the modifier was 20 g/kg. Some indicators showed an interaction between the application of the modifier and water-soluble fertilizer, indicating their combined effectiveness.

The application of modifier and water-soluble fertilizer can enhance soil enzyme activity. However, excessive amounts can lead to a decline in enzyme activity. Alkaline phosphatase activity reached maximum value at a dosage of 10 g/kg of modifier, while sucrase and urease activity peak at a dosage of 20 g/kg. However, polyphenol oxidase activity reached the maximum value when the dosage is 40 g/kg, but further increased in dosage did not present a significant rise in enzyme activity. The catalase activity of the soil did not appear improvement with modifier of alfalfa. However, that of in *L. chinensis* displayed a prominent increasing.

The growth indices of alfalfa and *L. chinensis* expounded trend of first increasing and then decreasing as the modifier dosage increased, peaking at 20 g/kg. Both the modifier and water-soluble fertilizer promoted root growth in these two types of forage. Furthermore, the combined use of the modifier and water-soluble fertilizer proved more effective in remedying saline-alkaline soil and enhancing forage yield.

Authors' Contributions

SCZ and BY: Data curation; SCZ and JWX: Formal analysis; DPW: Funding acquisition; SCZ: Investigation; YHL and DPW: Methodology; SCZ and DPW: Project administration; WW and DPW: Resources; DPW and JMY: Software; DPW and JMY: Supervision; DPW and JMY: Validation; BY and DPW: Visualization; JWX and JMY: Writing - original draft; BY and DPW: Writing - review and editing. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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