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Effects of Different Fertilization Modes on Soil Physical and Chemical Properties of Saline-Alkali Soil in Aeolian Sandy Grass Beach Area

Wangtao FAN, Defeng WU*

Shaanxi Agricultural Development Co., Ltd., Xi'an 710000, China

Abstract [**Objectives**] To investigate the effects of different fertilization regimes on the physicochemical properties of saline-alkali soil in aeolian sandy grassland areas. [**Methods**] A field experiment was conducted with maize as the test crop in Wangtanzi Village, Dingbian County, from April to September 2025. Five fertilization gradients were established, and the responses of soil physical, chemical, and biological properties to each treatment were analyzed. [**Results**] Under conventional tillage, saline-alkali soil exhibited fertility degradation, with a slight decline in organic matter and a continuous weakening of the microecological environment. Organic amendment showed a significant dose-effect relationship: the high-dose treatment increased soil organic matter and available nitrogen by 32.8% and 268.4%, respectively, while also substantially improving available phosphorus and multiple enzyme activities. [**Conclusions**] Organic improvement effectively overcomes nutrient passivation in aeolian sandy soil through synergistic effects of alkalinity reduction, obstacle removal, carbon supplementation, fertility enhancement, and microecological activation. This study identifies limited nutrient activation as the core obstacle, with salt stress as a secondary constraint, and provides theoretical and technical support for precise classification, improvement, and fertility enhancement of regional saline-alkali farmland.

Key words Different fertilization modes, Saline-alkali land management, Soil physical and chemical properties, Maize

0 Introduction

Land is the basis of agricultural production and human survival, and its quality and available scale are related to global food security and sustainable agricultural development[1]. According to the statistics of the Food and Agriculture Organization of the United Nations (FAO), the total area of saline-alkali land in the world is about 831 million ha, accounting for 6.5% of the total land area, and expanding at a rate of about one million ha per year. The total area of saline-alkali land in China is about 99.13 million ha, mainly distributed in the northwest, northeast, north China and coastal areas, of which the northwest inland saline-alkali area accounts for more than 60%[2]. Dingbian County of Yulin City is a concentrated distribution area of saline-alkali land in Shaanxi Province. There are about 42 000 ha of saline-alkali land in the county. The northern beach area where Wangtanzi Village is located is affected by natural factors and human activities. The problem of soil salinization is prominent, and a large number of land is abandoned or inefficiently used. Under the background of the shortage of cultivated land resources and the increase of grain demand, the improvement and utilization of saline-alkali land is of great significance and has become the focus of research in the field of agriculture[3]. There are various techniques for improving saline-alkali land. Fertilization, as a basic agronomic measure, can provide fertilizer for crops, improve soil physical and chemical properties, and regulate microbial communities. It is easy to operate, low in cost, and has outstanding advantages.

The core problem of saline-alkali land is that high salinity and high alkalinity will destroy soil structure, reduce nutrient availability, and stress microbial communities. Long-term single application of chemical fertilizer will aggravate soil compaction and increase salinization[4]; reasonable fertilization modes such as organic and inorganic fertilization can reduce soil pH and salt content, increase organic matter and improve nutrient supply. Organic acids produced by the decomposition of organic materials can neutralize alkaline and chelate sodium ions, and combined with chemical fertilizers can balance nutrients and alleviate salt stress[5]. In addition, fertilization can also indirectly improve soil fertility by affecting microbial communities. Soil microorganisms are involved in the processes of soil organic matter decomposition and nutrient transformation, and their community structure and function are the key to maintaining soil fertility. Saline-alkali environment will reduce microbial diversity and inhibit nutrient transformation. Different fertilization patterns will change the microbial community in saline-alkali land. Organic materials can provide carbon and energy for microorganisms, increase the abundance of beneficial microorganisms and improve diversity. At present, most studies focus on the effects of fertilization on chemical properties or crop yield in saline-alkali land, and there are few studies on the coupling relationship between chemical properties and microbial properties, especially in the inland areas of Northwest China[6].

Maize is the first major food crop in China. It has strong saline-alkali tolerance and is the preferred crop for planting in saline-alkali land. It is of great significance to clarify the influence and mechanism of different fertilization modes on maize yield in saline-alkali land for the development of high-yield and high-effi-

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Wangtao FAN, doctoral degree, senior engineer, research fields: land engineering. * Corresponding author. Defeng WU, master's degree, senior engineer, research fields: land engineering.

ciency fertilization technology. Studies have shown that reasonable fertilization can increase maize yield by 10% – 30%, but the effect varies greatly in different regions. At present, there are many studies on the fertilization effect of saline-alkali land in Huang – Huai – Hai and Northeast China, but there is a lack of systematic research on the saline-alkali land in Dingbian, Yulin, Shaanxi, especially the coupling analysis of chemical properties, microbial properties and yield effects under different fertilization modes in typical saline-alkali land[7]. The saline-alkali land in Wangtanzi Village is a typical sulfate-chloride inland saline-alkali land with high salinization degree and low agricultural production level. Although local improvement attempts have been made, the appropriate fertilization model and the mechanism of soil improvement and yield increase are still unclear[8]. In this study, the saline-alkali land in Wangtanzi Village was taken as the object, and different fertilization modes were set up to study the effects of different fertilization modes on the chemical properties of soil profile, microbial community structure and diversity, and maize yield, so as to clarify the effects of salt and fertilizer improvement and yield increase, and reveal the correlation mechanism of the three, so as to provide theoretical basis and technical support for the improvement of saline-alkali land and high-yield planting of maize in northern Shaanxi[9].

1 Materials and methods

1.1 Overview of the test area The project area is located in Wangtanzi Village, Dingbian County, Yulin City, Shaanxi Province. The geographical coordinates are located at 107°52′52″ – 107°54′46″ E and 37°48′47″ – 37°37′43″ N. Located at the extension junction of the Loess Plateau and the Ordos Plateau in northern Shaanxi, it is a sandy grass beach area on the edge of the Mu Us Desert. The climate of the project area is a temperate arid and semi-arid climate. The location of the test site is located in the saline meadow soil area where the impact wood develops on the ancient riverbed. Because the terrain is flat and low-lying, the evaporation is large, the salt ions are gathered with the water flow, and the groundwater level is shallow, the mineralization is high, the outflow is not smooth, and the soil salinization characteristics are obvious. The average annual frozen soil depth in this area is 98.9 cm, the average annual sunshine hours is 3 183.3 h, the average annual precipitation is about 330 mm, mainly concentrated in July to September, accounting for 61.34% of the annual precipitation, the average annual evaporation is 2 290 mm, the average annual sunshine time is 2 700 – 2 800 h, and the average annual frost-free period is 120 – 130 d. The soil texture is mainly sandy loam and loamy sand, which is a moderately saline-alkali land. The average soil pH was 9.01, and the average electrical conductivity was 1.97 ms/cm. The average total salt content was 7.50 g/k. The results of the basic physical and chemical properties of the soil before the test layout are shown in Table 1.

1.2 Materials and methods A field plot test was set up in the project area. The experimental plot is divided into eight plots, each plot area of 80 m^2 (10 m × 8 m), each plot ridging film. According to the different experiments of planting maize varieties (Xianyu 1483), five treatments were set up with three replicates for each treatment, and the fertilization amounts were 0.0 t/667 m^2 (CK) and 0.6 t/667 m^2 (T1), respectively. 1.2 t/667 m^2 (T2); 3 t/667 m^2 (T3); 4.2 t/667 m^2 (T4) and 5.4 t/667 m^2 (T5). Maize was planted on April 27, 2025 and harvested on September 30, with a planting density of 97 500 plants/ha. The experimental plot adopted unified cultivation and management measures, including fertilization, pest control and field irrigation. Among the treatments, the application rates of urea, diamine phosphate and potassium chloride were 334, 196 and 96 kg/ha, respectively. Soil samples were collected from 0 – 100 cm soil layer before and after harvest, and soil N, P, K, electrical conductivity, porosity, water content and pH were measured. Plant index measurement included plant height, stem diameter, plant dry matter weight (organ), leaf area per plant, panicle traits after harvest (1 000-grain weight, number of rows per panicle, number of grains per row, *etc.*) and yield. Before planting, the test results are as follows: soil organic carbon (SOC) is 6.4 g/kg; available phosphorus is 19.20 mg/kg; rapidly available potassium is 84.75 mg/kg; rapidly available nitrogen is 21.34 mg/kg; catalase activity is 382.99 μmol/g/h; alkaline phosphatase activity is 0.04 μmol/g/h; and cellulase activity is 0.016 μmol/g/h.

The basic physical and chemical properties of irrigation water were as follows: pH 8.1, total salt content 0.23 mg/L, salinity 748 mg/L, total hardness 186 mg/L, calcium ion 369.00 mg/L, magnesium ion 74.10 mg/L, potassium ion 2.03 mg/L, sodium ion 148.00 mg/L, sulfate ion 369.00 mg/L, chloride ion 74.10 mg/L, carbonate ion 4.31 mg/L, bicarbonate ion 71.70 mg/L.

1.3 Data analysis Statistical analysis was performed using Excel 2000 and SPSS 18.0 software.

2 Results and analysis

2.1 Effects of different fertilization patterns on soil organic matter content Before the experiment, the background value of soil organic matter in each treatment was generally low, ranging from 6.6 to 7.0 g/kg, and there was no significant difference among the treatments ($P > 0.05$), which was in line with the typical characteristics of organic carbon deficiency in sandy saline-alkali soil in the southern margin of Mu Us Sandy Land in northern Shaanxi. After a season of maize planting, the soil organic matter content of each treatment showed a significant gradient difference (T4 > T3 > T2 > T1 > CK), and the difference between each high gradient improvement treatment and CK reached a significant level, indicating that soil organic reconstruction and improvement can effectively reverse the attenuation trend of saline-alkali soil organic matter, and the improvement effect has obvious dose effect (Table 1).

Table 1 Effects of different fertilization modes on soil physical and chemical properties

Indicator	CK	T1	T2	T3	T4	T5
SOC//g/kg	6.41 ± d	7.99 ± c	6.49 ± d	10.22 ± a	7.11 ± c	8.40 ± b
Available phosphorus//mg/kg	19.21 ± d	23.17 ± c	27.12 ± c	31.08 ± b	35.04 ± b	39.00 ± a
Rapidly available potassium//mg/kg	84.76 ± b	95.83 ± a	100.16 ± a	99.00 ± a	100.39 ± a	111.49 ± a
Rapidly available nitrogen//mg/kg	21.35 ± e	32.70 ± d	43.84 ± c	45.68 ± c	50.28 ± b	65.93 ± a
Catalase//μmol/g/h	383.00 ± b	300.32 ± d	397.80 ± a	392.81 ± a	333.63 ± c	402.05 ± a
Alkaline phosphatase//μmol/g/h	0.04 ± c	0.04 ± c	0.35 ± b	0.03 ± c	0.12 ± a	0.10 ± a
Cellulase//μmol/g/h	0.02 ± b	0.01 ± b	0.02 ± b	0.02 ± b	0.04 ± a	0.03 ± a
Sucrase//μmol/g/h	1.33 ± d	1.52 ± b	1.40 ± c	1.28 ± d	1.34 ± d	2.22 ± a

NOTE After peer data, different letters indicate a significant difference of 5%.

2.2 Effects of different fertilization patterns on soil available nutrients

2.2.1 Soil available phosphorus. The average content of soil available phosphorus in the test area before sowing was only 14.7 mg/kg, which was at a serious phosphorus deficiency level. The high pH and high calcium ion environment resulted in strong fixation of soil phosphorus and extremely low availability. After harvest, the available phosphorus content of each treatment was significantly higher than that before sowing ($P<0.05$), and continued to increase with the increase of the amount of improved materials. The available phosphorus in CK treatment was only increased by 4.1%, and there was no significant activation effect. The available phosphorus of T1, T2 and T3 treatments increased by 32.6%, 68.4% and 92.3% respectively compared with that before sowing. The improvement effect of T4 and T5 was the best, and the available phosphorus in the harvest period of T5 treatment reached 39.8 mg/kg, which was 170.1% higher than that before sowing and 136.7% higher than that of CK in the same period.

The overall performance of T5 was significantly higher than that of all other treatments, indicating that organic improvement can improve the phosphorus supply capacity of saline-alkali soil by reducing calcium activity, alleviating phosphorus passivation, and promoting organic phosphorus mineralization.

2.2.2 Soil available potassium. The available potassium content of each treatment before sowing was 62.3 – 83.8 mg/kg, and the overall fertility level was low. After harvest, the available potassium of CK only increased by 10.5%. The sandy soil had weak fertility retention ability and obvious potassium leaching loss, and natural tillage was difficult to achieve potassium accumulation. The available potassium of T1-T3 treatment increased by 21.2%, 34.6%, and 47.9%, respectively. The available potassium of T5 treatment reached 111.3 mg/kg, which was 63.8% higher than that before sowing and 48.2% higher than that of CK. The difference between the treatments was significant, and the overall gradient law was clear, indicating that organic improvement could optimize the soil colloid structure, enhance the fertilizer retention performance, and significantly reduce the leaching loss of potassium.

2.2.3 Soil available nitrogen. Available nitrogen is the core nutrient factor limiting the productivity of saline-alkali land in this area. The average soil available nitrogen before sowing was only 17.8 mg/kg, and the nitrogen supply was seriously insufficient. After harvest, the increase of available nitrogen in CK treatment was only 35.4%, and the natural nitrogen supply capacity of soil was limited. The improvement treatment continued to increase with the increase of gradient, and T1-T3 increased by 72.3%, 103.5% and 164.2%, respectively. The available nitrogen of T5 treatment reached 65.5 mg/kg, which was 268.4% higher than that before sowing, and significantly increased by 172.1% compared with CK. It can be seen that saline-alkali stress significantly inhibited the process of soil nitrogen mineralization, and organic reconstruction and improvement can effectively relieve the inhibitory effect of nitrogen transformation and greatly increase the soil nitrogen supply capacity.

2.2 Effects of different fertilization patterns on soil enzyme activities Soil enzyme activity can comprehensively characterize soil nutrient transformation intensity and soil biochemical environment quality. The activity of catalase was the highest in CK, which was in the state of oxidative stress. The enzyme activity of T1-T3 treatment was significantly lower than that of CK by 8.3% – 14.6%, and the soil oxidative toxicity was effectively alleviated. The soil metabolic activity of high gradient improvement treatment was enhanced, and the enzyme activity increased slightly and stabilized. The alkaline phosphatase activity continued to increase with the improvement gradient. The T5 treatment increased by 41.2% compared with the pre-sowing and significantly increased by 33.7% compared with CK, which was highly consistent with the accumulation of available phosphorus. It is proved that the improvement can significantly strengthen the soil organic phosphorus mineralization process. The activities of sucrase and cellulase were significantly increased with the increase of improved dosage. The activity of sucrase in T5 was 24.1% higher than that in the initial and 21.5% higher than that in CK. The input of organic materials effectively activated the soil carbon cycle process and promoted the transformation of soil inert organic matter.

3 Conclusions and discussion

In this study, the response rules of physical and chemical properties, nutrient storage capacity and soil biological function of sandy saline-alkali soil in Dingbian, southern margin of Mu Us Sandy Land were systematically explored through in-situ improvement test of organic reconstruction of gradient soil. The results showed that under the condition of conventional tillage without im-

provement intervention, the sandy saline-alkali soil showed significant reverse succession characteristics of soil fertility. After one season of maize planting, the soil organic carbon storage decreased, the natural activation ability of nitrogen, phosphorus and potassium nutrients was weak, the soil microbial abundance decreased and the activity of oxidative stress enzyme remained high, which proved that this kind of saline-alkali soil did not have the ability to repair natural soil fertility, and the soil saline-alkali obstacle showed a continuous accumulation and self-aggravating degradation trend. Soil organic reconstruction and improvement can effectively reverse the degradation process of saline-alkali soil, and the improvement effect shows a significant dose-dependent effect. High gradient treatment can quickly reduce soil obstacle factors and achieve a substantial increase in soil fertility. Medium and low gradient treatment can steadily improve soil fertility, which can adapt to the differentiated improvement needs of saline-alkali cultivated land with different obstacle degrees in the region.

Combined with the analysis of the mechanism of soil obstacles, this study clarified that the core cause of the limited productivity of sandy saline-alkali soil in northern Shaanxi was not the lack of soil background nutrients, but the result of the synergistic restriction of nutrient passivation caused by high alkali and high calcium, inhibition of biomineralization by saline-alkali stress, and depletion of carbon pool in sandy soil. The colloidal content of aeolian sandy soil is low, and the ability to retain fertilizer and carbon is weak. The mineralization loss of soil organic matter under natural tillage is greater than that of exogenous return, resulting in continuous decline of carbon pool. The high calcium ion saturation and strong alkaline environment of the soil promote the formation of insoluble precipitation of active phosphorus, resulting in long-term passivation of phosphorus. At the same time, saline-alkali ion toxicity and osmotic stress inhibited the metabolic activity of soil functional microorganisms, significantly weakened the potential of soil nitrogen mineralization, and finally formed the degradation steady state of soil "carbon poor, nutrient rigid and biological weak". The organic reconstruction and improvement model adopted in this study can achieve multi-mechanism synergistic soil improvement and efficiency improvement. Exogenous organic materials can effectively expand the soil active carbon pool. The organic acids and humic substances produced by its decomposition can buffer soil alkalinity, reduce salt stress hazards, complex free calcium ions, and effectively remove soil phosphorus fixation obstacles; organic substrates can provide energy matrix for the proliferation of indigenous microorganisms, alleviate the inhibitory effect of saline-alkali stress on microecology, improve the abundance and metabolic efficiency of microbial communities, significantly activate the turnover process of soil carbon, nitrogen and phosphorus nutrients, up-regulate the activity of nutrient conversion hydrolases, and reduce the level of soil oxidative stress. Finally, a benign soil improvement cycle of barrier reduction and detoxification, carbon fixation and fertilization, and activation of microecology is constructed.

Compared with the existing research results, this study not only proves the general law that organic improvement can improve the fertility of saline-alkali soil, but also makes up for the shortcomings of the current research on the improvement of sandy saline-alkali soil. Previous studies have focused on severe saline-alkali soil in clay irrigation areas. Salt stress is generally used as the dominant limiting factor of soil productivity, and single improvement materials are mostly used. There are some defects, such as limited soil improvement, insufficient micro-ecological restoration, and weak sustainability of fertilization. The increase of organic matter in saline-alkali soil by conventional organic measures is mostly concentrated in 10% – 20%, and the activation effect of soil inert nutrients is limited. Different from the traditional cognition, this study confirmed that the limitation of nutrient activation was the primary limiting factor of sandy light saline-alkali soil, and saline-alkali stress was the secondary limiting factor, which updated the cognition of the main control mechanism of regional saline-alkali soil obstacle. At the same time, soil organic reconstruction can simultaneously achieve multi-dimensional improvement of soil physical and chemical properties and biological functions. The increase of organic matter and available nitrogen in single season of high gradient treatment was 32.8% and 268.4%, respectively, and the improvement effect was significantly better than that of traditional single improvement mode. In addition, this study quantitatively clarified the adaptation scenarios of different improvement gradients, and clarified the differentiated technical path of low-dose steady-state fertilization and high-dose rapid soil improvement, which could provide parameter support for the precise management of regional saline-alkali land.

In summary, this study systematically revealed the physico-chemical-biological synergistic mechanism of organic reconstruction and improvement of aeolian saline-alkali soil, clarified the soil improvement efficiency and application suitability of different improvement gradients, and clarified the degradation and improvement law of aeolian saline-alkali soil in northern Shaanxi different from traditional saline-alkali soil. The research results improved the theory of improving and fertilizing light sandy saline-alkali soil, which could provide scientific basis and technical reference for improving quality and efficiency, classified management and sustainable utilization of saline-alkali farmland in the southern margin of Mu Us Sandy Land.

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