EFFECTS OF SAND COATING TECHNOLOGY ON CARBON POOL AND SOIL ENZYME ACTIVITY IN SALINE SOIL ECOSYSTEM

CAO, T. T.[1,2,3,4*] – ZHANG, H. O.[1,2,3,4] – CHEN, T. Q.[1,2,3,4] – WANG, Y. G.[1,2,3,4] – YANG, C. X.[1,2,3,4] – WANG, J.[1,2,3,4] – SUN, X. B.[1,2,3,4] – HU, Y. T.[1,2,3,4]

[1]*Shaanxi Provincial Land Engineering Construction Group Co., Ltd., Xi'an 710075, China*

[2]*Insititute of Land Engineering and Technology, Shaanxi Provincial Land Engineering Construction Group Co., Ltd., Xi'an 710075, China*

[3]*Key Laboratory of Degraded and Unused Land Consolidation Engineering, the Ministry of Natural Resources of China, Xi'an 710075, China*

[4]*Shaanxi Provincial Land Consolidation Engineering Technology Research Center, Xi'an 710075, China*

[*]*Corresponding author*
e-mail: caotingting@chd.edu.cn

(Received 25th Apr 2023; accepted 21st Jul 2023)

Abstract. In order to study the changes of soil carbon pool and enzyme activities after saline land remediation, carbon, protease, catalase, urease and phosphatase contents in soil samples and plant samples collected from the project area were analysed. After 2 and 4 years of saline-alkali remediation, the total carbon content in 0-20cm soil surface decreased significantly by 24-63%, the organic carbon content in 0-10 cm soil surface decreased significantly by 32-35%, the organic carbon content of 10-60 cm soil increased significantly by 23-42%. The inorganic carbon content of soil profile decreased significantly by 21-72%. In the range of 60~100 cm, it increased significantly by 32~60%. At the early stage of the remediation, the activities of urease and catalase in soil profile decreased gradually with the increase of soil depth. The carbon density of 2 years after remediation is 26 times of that before regulation, and the carbon density of 4 years after remediation is significantly increased by 37.72% compared with that of 2 years after remediation. After the remediation, the project measures accelerated the process of soil cultivation and created a better habitat for the survival of crops in the project area. Under the influence of soil structure and crop root exudates, soil biochemistry has significantly contributed to carbon storage and enzyme activity in the ecosystem.
Keywords: *saline land, land remediation, carbon sequestration, enzyme activity*

Introduction

Land remediation projects are one of the important means of replacing construction land indicators and ensuring food security. According to the current land use situation in China, the most potential land remediation targets are difficult-to-use lands (Zhang et al., 2017). Among them, saline land is one of the important forms. In order to control land salinization, many studies have been carried out in China and abroad (Wang et al., 2021). Saline-alkali land can be improved through various measures such as physical, chemical, biological, and water conservancy engineering. These improvement measures have shown promising results in reducing the risks and hazards associated with saline-alkali land and also in gradually restoring its functions (Lv et al., 2012). There are four methods and technologies for improving and utilizing saline-alkali land both domestically and internationally. Physical improvement technology primarily focuses on regulating the

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

movement of water and salt by improving the physical structure of soil to achieve the goal of soil improvement. Optimizing soil structure can effectively reduce water evaporation and improve soil salt leaching efficiency. Techniques such as land leveling, deep plowing, sun exposure, terrain elevation, and micro-area soil improvement can be employed. Biological improvement measures, such as using salt-tolerant plants, microbial fertilizers, and organic fertilizers, can also be used to improve saline soil. Improving soil structure can be achieved through the life activities of plants and microorganisms. This can increase soil porosity and nutrient content, while also regulating the physical and chemical properties of the soil. Recent studies have demonstrated that planting salt-tolerant plants on saline-alkali land can have multiple benefits. Not only can it effectively suppress soil salinity and improve the quality of saline-alkali soil, but it can also help to maintain soil moisture and improve the ecological environment (Li et al., 2023). Additionally, the use of saline-alkali-tolerant plants can promote agricultural production. The principle behind chemical improvement measures is to utilize chemical amendments and organic matter to transform, absorb or fix the saline-alkali components in the soil, thereby achieving the desired improvement effect (Zhang et al., 2019). Commonly used modifiers include gypsum, phosphogypsum, sodium superphosphate, humic acid, peat, vinegar residue, and so on (Andrade Foronda et al., 2022). Constructing a flood drainage irrigation system that utilizes the water source in the irrigation area can effectively reduce the salinity of the soil and prevent salt return (Yang et al., 2010). This method serves as a water conservancy improvement measure to control saline-alkali land (Wang et al., 2003). Although we have made significant progress in preventing and controlling soil salinization through production practices and scientific research, little attention has been given to the impact of saline-alkali land remediation projects on soil carbon pools and ecosystems (Liu et al., 2023).

The impact of human activities on soil carbon storage is significantly greater than that of natural soil evolution (Wang et al., 2015). Among these activities, changes in land use patterns have a particularly significant impact on global carbon storage, resulting in changes in soil carbon storage (Wu et al., 2015). Land remediation employs engineering techniques to enhance soil structure and quality. This, combined with the cultivation of specific organisms after remediation, alters the inflow and output characteristics of soil carbon pools, and modifies enzyme activity in the soil through biological effects (Lian et al., 2010). These changes indirectly impact soil carbon reserves and the overall ecological environment of the soil (Zhao et al., 2020). Soil enzymes are the products of the activities of plants, animals, and microorganisms in the soil. They are the soil components with extremely small quantities and great effects (Li et al., 2022). Soil enzymes exist in free and adsorbed states, and the vertical and horizontal distributions of soil enzymes have certain regularity (Li et al., 2005). In the vertical direction, the activities of several enzymes weakened with the deepening of the soil layer, and in the horizontal direction, the activities of enzymes in the rhizosphere were greater than those outside the rhizosphere (Cheng et al., 2023). Soil microorganisms are responsible for various biochemical processes in soil, which are carried out through the enzymes they produce. As a result, the activity of soil enzymes is a reliable indicator for assessing the intensity of soil biochemical processes and evaluating soil fertility (Zhao et al., 2012). Some studies have shown that land remediation can directly affect the physical and chemical properties of soil and related ecological processes through engineering means (Bao et al., 2007). Therefore, it will have an impact on soil organic carbon storage, which may be positive or negative. However, the impact of saline-alkali land remediation projects on

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

soil carbon pools and soil ecosystems has not been paid attention to (Li et al., 2019). This study focuses on the soil quality improvement of saline-alkali land and its ecological benefits. The research was conducted on the completed saline-alkali land improvement project area, where indicators such as carbon content in the soil, protease, catalase, urease, and phosphatase were screened. The goal was to analyze the change trend of biological activity and study how to create a soil carbon pool that is conducive to crop growth through land improvement engineering methods. The study aimed to analyze the ecological benefits of the difficult-to-use saline-alkali land after engineering improvement.

Materials and Methods

Experimental field

This study aimed to investigate the changes in soil and vegetation carbon sequestration capacity, soil microstructure, and enzyme activity in saline-alkali land with varying land remediation years. The basic information of the project area is presented in *Figure 1* and *Table 1*. The composition of the saline soil and the applied carbonate-rich sand is presented in *Table 2*.

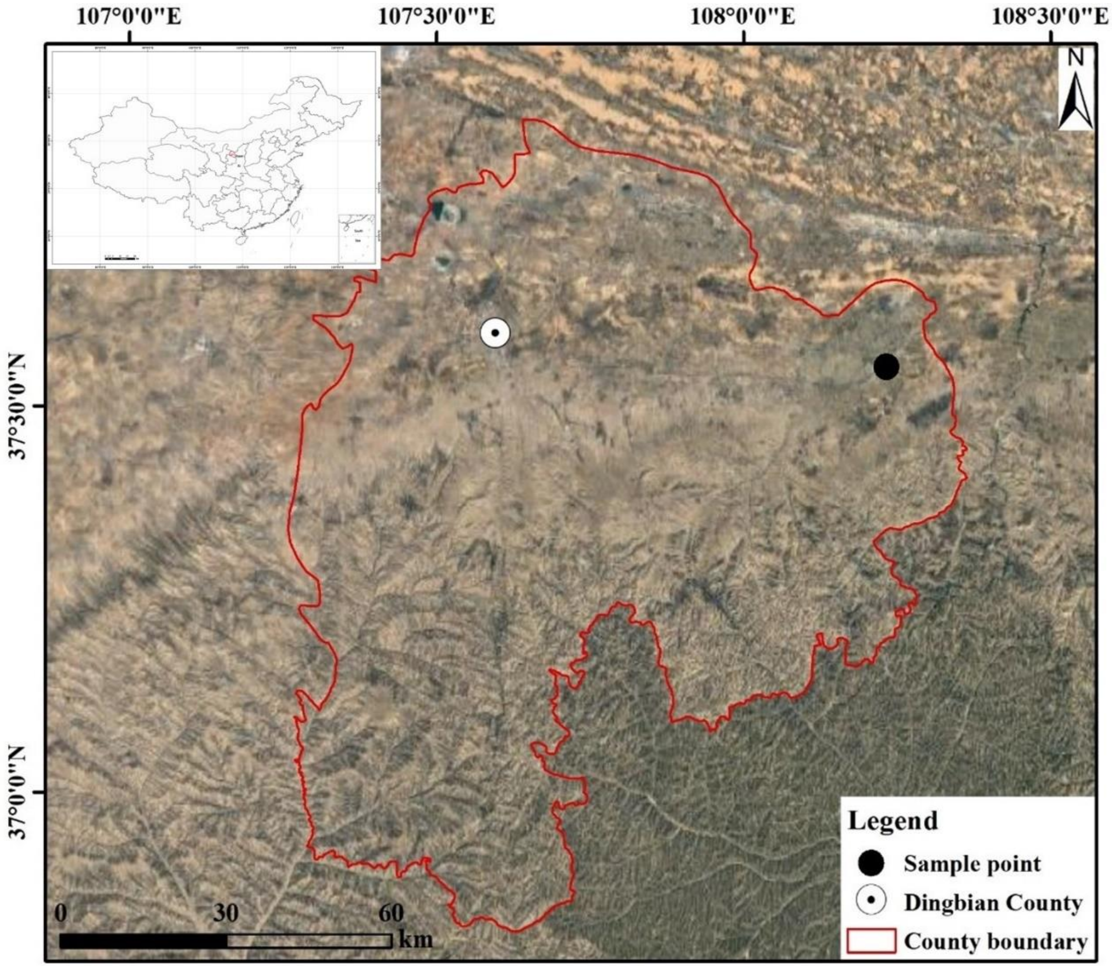

Figure 1. *Map of the study area in Dingbian County, Shaanxi Province, Northwest China*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

Table 1. *Sample plot overview*

Type of remediation	Location of land reclamation project	GPS coordinates	Technical tools	Cultivated crops	Year of cultivation
Saline land remediation	Bai Tu Gangzi Village, Dingbian County, Yulin City	108◦208E,37.583N	Drainage of open ditches to suppress salt, sand on the ground to suppress salt	Millets/corn	2 years
	Wang Tanzi Village, Dingbian County, Yulin	108◦282E,37.637N			4 years

Table 2. *The composition of the saline soil and the applied carbonate-rich sand*

Species	Clay（%）	Silt（%）	Sand（%）	Soil texture
Saline land	13.99	69.37	16.63	Silty loam
carbonate-rich sand	1.49	8.76	89.75	Sandy soil

Experimental design and treatments

The research area is situated in Dingbian County, Yulin City, characterized by low terrain, shallow groundwater, dry climate, high evaporation, serious soil salinization, and compacted soil layer. After sowing, most of the crop seeds cannot germinate or emerge and grow in difficulty. To address ecological issues in the project area, open ditch drainage engineering and ground sand covering measures were implemented. These actions reduced the groundwater level, minimized water evaporation, and altered the soil saturated hydraulic conductivity to create a microenvironment conducive for crop development and growth. The experiment commenced in April 2017, where the original saline-alkali soil surface was layered with 15 cm of sand in the designated experimental area. The area was then cultivated according to the standard process, with three repetitions set up in each experimental area. The plot dimensions were 4 m x 5 m. Improvement measures were implemented prior to the start of the test and will not be adjusted in the subsequent year. The cultivated crops are corn and millets. The corn is planted in the hole and the millets is planted in the ditch.

Sample collection and analysis

In October 2021, the research team initiated soil sampling subsequent to crop harvesting. For this study, three plots that have undergone rehabilitation for 2 and 4 years were selected, with an unremediated area serving as the control. The diagonal 5-point sampling method was used to sample the soil, with samples taken at 10 cm, 10 cm, and 20 cm intervals from top to bottom between 0 and 100 cm. Each layer was sampled separately, with the samples mixed thoroughly before approximately 2 kg of soil samples were reserved according to the principle of quartering. Undisturbed soil samples from 0-10 cm depth were collected and transported in plastic boxes for microstructure analysis. The remaining samples were divided into two parts, sealed, refrigerated, and shipped to the laboratory. One fresh sample was used for soil enzyme analysis while the other was air-dried, ground, sieved, and stored for laboratory testing and analysis. To collect plant samples, we selected 5 plots measuring 1m x 1m each. Whole plants were sampled and analyzed to study the impact of different land consolidation years on soil and vegetation carbon sequestration characteristics.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

Total carbon and organic carbon in the soil were measured using a Multi N/C®3100 total organic carbon analyzer which was produced by Analytica JenaAG in Germany. The undisturbed soil sample was dried and coated with gold before being observed under a scanning electron microscope (SEM) which brand is the American FEI-Q45 for soil micro-morphology analysis. The levels of soil urease were assessed using the indophenol blue colorimetric method. Protease levels were determined using the Gallus River method, while catalase levels were assessed through potassium permanganate titration. Lastly, soil phosphatase levels were determined using the p-nitrophenyl phosphate method. To determine the carbon content of the plant, first rinse the samples with water and air-dry them. Then, place the samples in a constant temperature oven set at 80°C until they reach a constant weight. After weighing the dry weight, grind the plants and mix them evenly. Finally, measure the carbon content using the potassium dichromate oxidation-external heating method (Nurzhan et al., 2022).

The measurement of total soil carbon (TC) involves taking a certain amount of dry soil and directly injecting samples. On the other hand, the measurement of soil organic carbon (TOC) involves taking a certain amount of soil sample, adding excess 0.1mol/L HCI to remove soil inorganic carbon, and then drying the injection. Soil inorganic carbon (TIC) can be calculated by subtracting organic carbon (TOC) from total carbon (TC).

Soil carbon density is a crucial metric used to assess the amount of carbon fixed in soil under varying treatments. It is defined as the absolute storage of soil carbon in a specific depth per unit area. Additionally, soil carbon density can be further categorized into three indicators based on the type of soil carbon: total carbon density, total organic carbon density, and total inorganic carbon density. This paragraph describes the calculation of soil organic carbon density using formula (1) in a specific soil layer.

$$SOC_i = C_\mathrm{i} \times D_\mathrm{i} \times E_\mathrm{i} \times (1 - G_\mathrm{i}) / 10 \qquad \text{(Eq.1)}$$

Formula (2) is used to calculate the soil total organic carbon density (SOC_i, t/hm^2) of a measured soil profile consisting of m soil layers, where m=6.

$$SOC_i = \sum_{1}^{m} C_\mathrm{i} \times D_\mathrm{i} \times E_\mathrm{i} \times (1 - G_\mathrm{i}) / 10 \qquad \text{(Eq.2)}$$

In the formula, *i* is the soil layer code; C_i is soil organic carbon content in layer *i* (g/kg); D_i is the soil bulk density of layer *i* (g/cm^3). E_i is the thickness of soil layer *i* (cm); G_i is the percentage (%) of the volume of pebbles with a diameter > 2 mm in layer *i*.

Data were drawn and analyzed using Origin and the analysis of variance and multiple comparisons were performed using SPSS.

Results

Changes of carbon content in soil profiles under different planting years.

The *Figures 2,3,4* illustrates the change trend of the total soil carbon content, organic carbon content, inorganic carbon content in the soil profile after different cultivation years following the remediation of saline-alkali land. The results indicate that after 2 years of cultivation, the total carbon content of the soil profile decreased significantly by 63% at 0-10 cm and by 47% at 10-20 cm. The study found that the amount of organic carbon in

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

the soil profile decreased by 35% at a depth of 0-10 cm. However, at depths of 10-20 cm, 20-40 cm, and 40-60 cm, there was a significant increase in organic carbon content by 41%, 42%, and 35%, respectively. The amount of inorganic carbon then decreased significantly by 72% and 64% at depths of 0-10 cm and 10-20 cm, respectively. Finally, at depths of 60-80 cm and 80-100 cm, there was a significant increase of 32% and 34%, respectively. After four years of cultivation, the total carbon content of the soil profile decreased significantly by 24% at 0-10 cm, 26% at 10-20 cm, 24% at 60-80 cm, and 35% at 80-100 cm. Similarly, the organic carbon content of the soil profile decreased significantly by 32% at 0-10 cm, but increased significantly by 23%, 30%, and 40% at 10-20 cm, 20-40 cm, and 40-60 cm, respectively. However, at 60-80 cm and 80-100 cm, the organic carbon content decreased significantly by 27% and 21%, respectively. The study found that the amount of inorganic carbon in the soil decreased by 21% and 35% at depths of 0-10 cm and 10-20 cm, respectively. However, it increased significantly by 51% and 60% at depths of 60-80 cm and 80-100 cm, respectively.

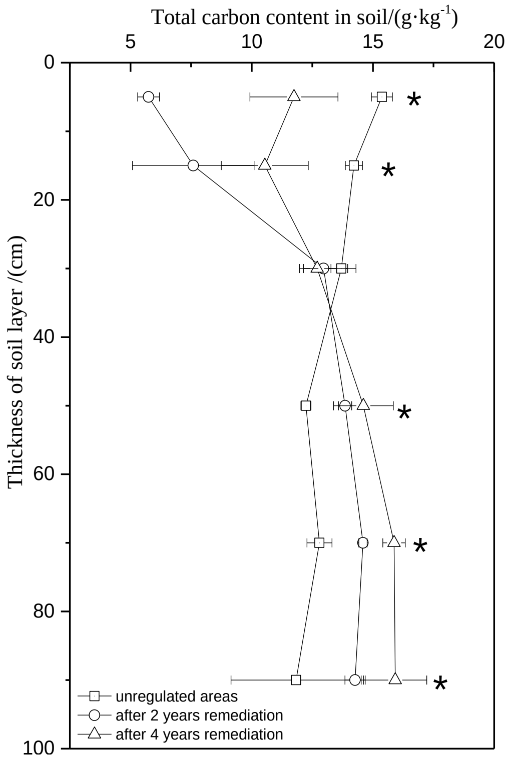

***Figure 2.** Changes in total carbon content of saline soil profiles. Note:Error bars represent Standard Deviation, and asterisks indicate that there are significant differences in carbon content of the same soil layer in different regulation years. The note applies the same as Figure 2-Figure 4.*

The data indicates that the total carbon content in the soil surface at a depth of 0-20 cm decreased significantly after 2 and 4 years of saline-alkali land remediation. Additionally, there was a significant decrease in the organic carbon content in the 0-20 cm layer, while the organic carbon in the 20-100 cm soil layer increased significantly. The phenomenon is caused by the engineering method of sand covering the surface, which contains fine sand rich in carbonates. When rainfall and farming measures are implemented, the carbonates will be leached to deeper layers. The soil profile showed a significant decrease

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

in inorganic carbon content at a depth of 0-20 cm, while an increase was observed at 60-100 cm. This can be attributed to the shallow groundwater table in the saline-alkali land, which caused noticeable leaching of calcium carbonate at deeper levels. After crop cultivation, plant root residues and root exudates gradually accumulate, creating an environment suitable for the reproduction of microbial communities and accelerating the evolution of the soil ecological environment. The inorganic carbon content in the 60-100 cm soil layer significantly increases after cultivation. When the surface layer is covered with sand, the high porosity of the fine sand better fixes CO_2 in the atmosphere and synthesizes carbonate (Zhang et al., 2021). As a result of gravity, the carbonate is leached to the deeper soil layer with the soil moisture, thereby increasing the inorganic carbon content in the deep soil layer (Jia et al., 2006). The shallow groundwater burial mechanism in saline-alkali land leads to the infiltration of inorganic carbon in the form of magnesium carbonate and calcium carbonate into the deeper layers of the soil. This process also introduces calcium, magnesium, and other elements into the salinized soil, which contributes to the inhibition of salt damage (Lian et al., 2010).

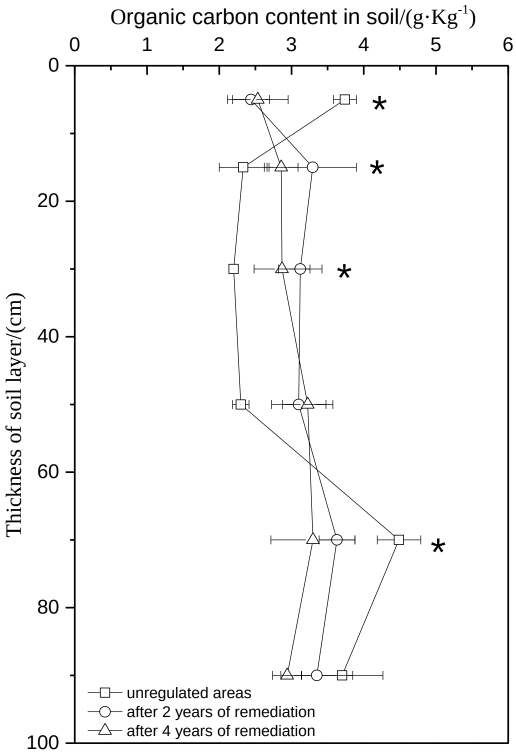

Figure 3. *Changes in organic carbon content of saline soil profiles*

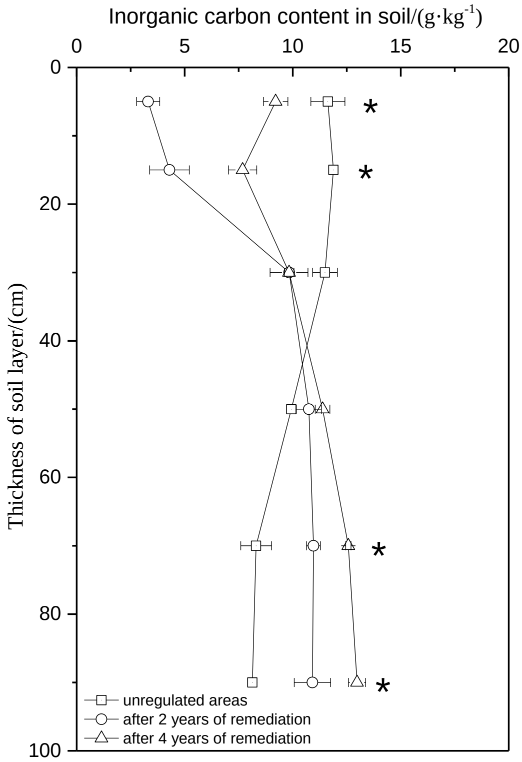

Figure 4. *Changes in inorganic carbon content of saline soil profiles*

Changes of soil profile carbon density under different planting years

Table 3 displays the changes in soil total carbon density, organic carbon density, and inorganic carbon density before and after saline-alkali land remediation at different depths (0-100 cm) and time intervals. The results indicate that after 2 years of remediation, the total carbon density of the soil profile decreased significantly by 61% and 46% at 0-10 cm and 10-20 cm depths, respectively, while it increased significantly by 23% and 27% at 40-60 cm and 80-100 cm depths.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

Table 3. *Difference analysis of carbon density of soil profile in saline-alkali soil under different treatment years*

Carbon density (t/hm²)	**Different test areas**	**Thickness of soil layer**						**Profile carbon reserves**
		0-10 cm	10-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	
Total carbon density (t/hm²)	Untreated area	21.01±0.59a	21.36±0.53a	40.87±0.18a	37.19±0.63b	41.24±0.66c	39.16±0.89b	200.82±2.35b
	2 years after remediation	8.13±0.63c	11.61±0.38c	41.33±0.31a	45.66±0.90a	47.34±0.55b	49.76±1.45a	203.82±1.76b
	after 4 years remediation	18.71±0.29bc	16.26±0.27b	42.25±1.88a	45.66±0.38a	51.03±1.49a	46.38±3.80a	220.29±2.78a
Organic carbon density(t/hm²)	Untreated area	5.11±0.58a	3.50±0.50c	6.57±0.10b	6.99±0.34b	14.47±0.42a	12.25±0.51a	48.89±1.98b
	after 2 years remediation	3.45±0.36c	5.04±0.24a	9.95±0.96a	10.22±1.24a	11.78±0.40b	11.69±0.52a	52.13±2.38a
	after 4 years remediation	4.03±0.67b	4.41±0.36b	9.54±0.28a	10.08±1.09a	10.60±1.87b	8.57±0.58b	47.23±0.98b
Inorganic carbon density(t/hm²)	Untreated area	15.90±0.18a	17.86±0.09a	34.30±1.71a	30.20±0.30b	26.77±0.52c	26.91±0.71b	151.94±0.26b
	2 years after remediation	4.68±0.76b	6.57±0.14c	31.37±1.88a	35.44±1.91a	35.56±1.29b	38.07±2.43a	151.69±3.11b
	4years after remediation	14.67±0.49a	11.85±0.55b	32.71±0.92a	35.58±1.41a	40.43±0.39a	37.82±1.06a	173.05±2.77a

Note: Different lowercase letters indicate significant differences at the $P<0.05$ level between different years of remediation for the same indicator

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

The organic carbon density of the soil profile decreased significantly by 33% at 0-10 cm, and increased significantly by 44%, 52%, and 46% at 10-20 cm, 20-40 cm, and 40-60 cm, respectively. The inorganic carbon density of the soil profile decreased significantly by 71% and 63% at 0-10 cm and 10-20 cm, respectively, and increased significantly by 33% and 41% at 60-80 cm and 80-100 cm. After four years of saline-alkali treatment, the total carbon density of the soil profile decreased by 24% at a depth of 10-20 cm but increased by 23% and 24% at depths of 40-60 cm and 60-80 cm, respectively. Additionally, the organic carbon density of the soil profile decreased significantly by 21% at a depth of 0-10 cm, but increased significantly by 26%, 45%, and 44% at depths of 10-20 cm, 20-40 cm, and 40-60cm, respectively. However, the organic carbon density decreased significantly by 27% and 30% at depths of 60-80 cm and 80-100cm, respectively. The density of soil inorganic carbon decreased by 34% at a depth of 10-20 cm but increased by 51% and 41% at depths of 60-80 cm and 80-100 cm, respectively. The trend of carbon density was found to be consistent with that of carbon content in saline-alkali land that had been treated for 2 to 4 years. As the regulation years and crop planting years increased, the organic carbon in soil profile also increased, particularly in the 20-60 cm range. It has been observed that over time, soil organic carbon gradually moves to deeper layers along with water due to years of soil cultivation. Furthermore, after land consolidation and continued cultivation, the soil matures and the quality of the soil's ecological environment, which is created by the interaction between plant roots and soil, is significantly improved. The impact of remediating saline-alkali land on the soil carbon pool may be diminished initially due to engineering disruptions or minor alterations in the soil carbon pool (Liu et al., 2023). However, after several years of planting, the remediation project area can make a notable contribution to the storage of soil carbon (Lian et al., 2010).

Changes of four enzyme activities in soil profiles under different planting years

Figure 5 illustrates that in untreated areas and after 2 years of treatment, urease activity in the soil decreased initially, followed by an increase, and then a subsequent decrease with increasing soil depth. After 4 years of cultivation, the soil structure tended to be stable, and the urease activity in soil gradually decreased with the increase of soil depth. After 4 years of remediation, the urease activity in each soil layer was significantly higher than that in the unmediated area and the area 2 years after remediation. After 4 years remediation, the urease activity in the soil increased significantly by 48% in the 0-10 cm, 323% in the 10-20 cm, 22% in the 20-40 cm, and 89% in the 40-60 cm compared with the unmediated area. After 2 years remediation, it was 14% lower in 0~10 cm, 35% higher in 10~20 cm, 9% higher in 20~40 cm and 117% higher in 40~60 cm than the unmediated area. The urease in the soil increased from 9 to 323% in the 0-60 cm soil layer.

Figure 6 illustrates the variation of catalase activity in soil with respect to soil depth before and after 2 years of remediation. The activity of catalase first decreased, then increased, and subsequently decreased again. However, after 4 years of remediation, the soil structure became more stable, and the catalase activity gradually decreased with increasing soil depth. In all soil layers, the catalase activity in all soil layers significantly increased after 4 years of treatment compared to the untreated area and the area treated 2 years prior. After a four-year treatment period, the catalase activity in the soil showed a significant increase of 295% at a depth of 0-10 cm, 96% at 10-20 cm, 101% at 20-40 cm, and 252% at 40-60 cm compared to the untreated area. After two years of treatment, the content of catalase in the soil showed a significant increase. Specifically, at 0-10 cm,

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

catalase increased by 110%, while at 10-20 cm it increased by 100%, at 20-40 cm it increased by 73%, and at 40-60 cm it increased by 97%, when compared to the untreated area. Overall, the increase in catalase content across the entire 0-60 cm soil layer ranged from 73% to 295%.

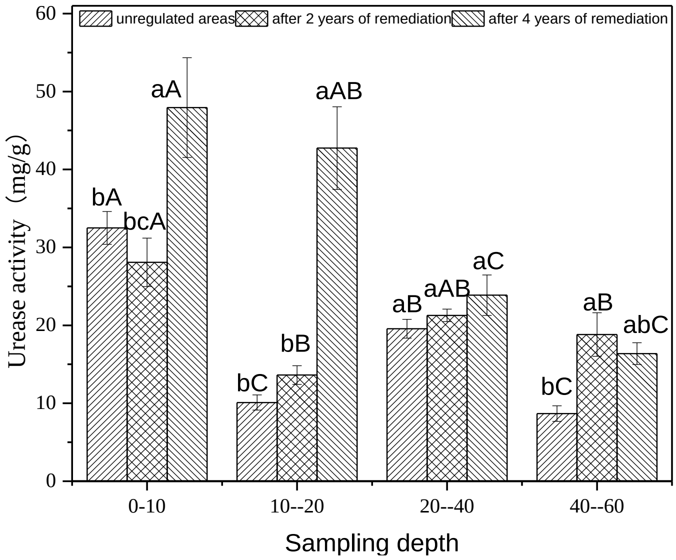

Figure 5. *Urease activity content in soil. Notes: a, b, c indicate the differences between different years in the same soil layer; A, B, C indicate the differences between different soil layers in the same year*

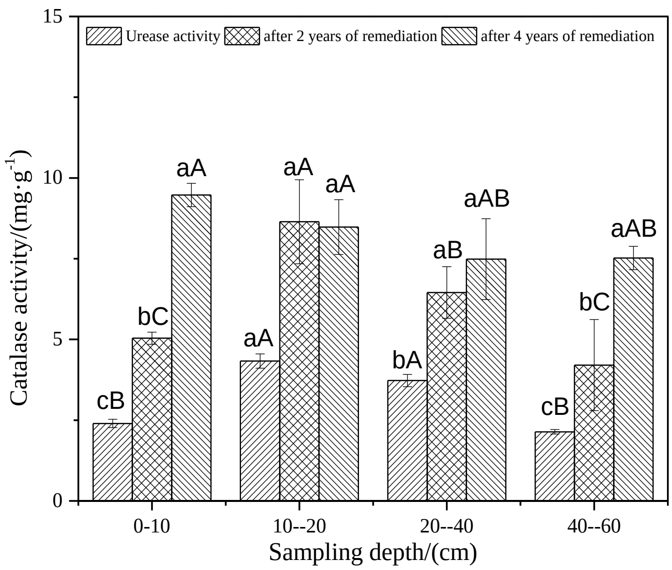

Figure 6. *Catalase activity content in soil. Notes: a, b, c indicate the differences between different years in the same soil layer; A, B, C indicate the differences between different soil layers in the same year*

The results presented in *Figure 7* indicate that protease activity in soil does not show a clear trend with increasing soil depth across different treatment years. However, it is

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

noteworthy that the protease activity in the 0-40 cm soil layer is significantly higher compared to that in the 40-60 cm soil layer. After 4 years of treatment, the soil protease activity was significantly increased by 10% at 0~10 cm, decreased by 18% at 10~20 cm, increased by 51% at 20~40 cm, and decreased by 12% at 40~60 cm. After 2 years of treatment, compared with the untreated area, the soil protease increased by 7% at 0~10 cm, decreased by 38% at 10~20 cm, had no significant change at 20~40 cm, and decreased by 51% at 40~60 cm. In conclusion, although the protease activity in soil decreased after 4 years of treatment compared with that before treatment, the decrease of protease activity in soil after 4 years of treatment had a trend of recovery compared with that after 2 years of treatment. The activity of protease in soil was greatly affected by the practical activities of land consolidation engineering, but it would recover gradually after cultivation and showed a benign development. The increase of protease in 0-60 cm soil layer ranged from 7% to 51%.

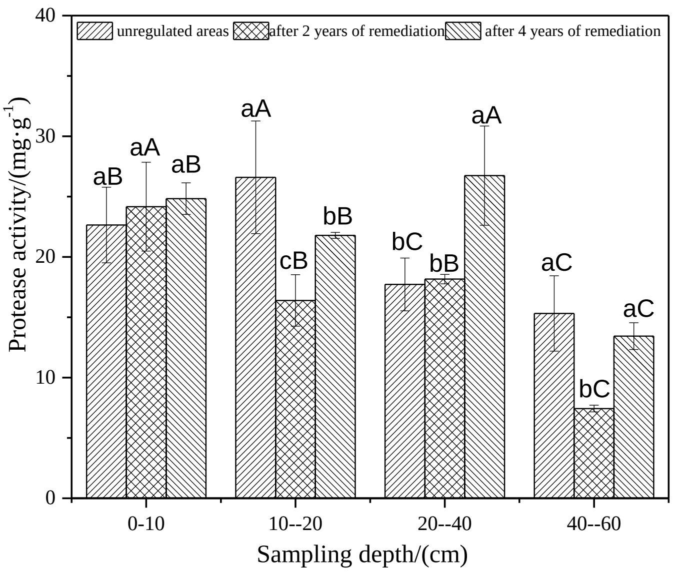

Figure 7. *Protease activity content in soil. Note: a. b. c indicate the differences between different years in the same soil layer; A. B. C indicate the differences between different soil layers in the same year*

The study presented in *Figure 8* indicates that there is no significant correlation between phosphatase activity and soil depth change under different regulation years. However, it was observed that the phosphatase activity in the 0-40 cm soil layer is significantly higher than that in the 40-60 cm soil layer. Phosphatase activity in soil increased significantly by 25% at 0~10 cm, 135% at 10~20 cm, 55% at 20~40 cm and 33% at 40~60 cm after 4 years treatment compared with that in the untreated area. The study found that there was no significant change in soil phosphatase content in the 0-10 cm layer after a two-year treatment period compared to the untreated area. However, there was a significant in-crease of 90% in the 10-20 cm layer, 100% in the 20-40 cm layer, and 13% in the 40-60 cm layer. Overall, the increase in phosphatase content across the entire 0-60 cm soil layer ranged from 13% to 135%.

The study revealed that soil remediation significantly impacted the activities of urease, catalase, protease, and phosphatase in saline-alkali land. Prior to remediation, the land

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

was deemed unusable, but after undergoing remediation, it became productive agricultural land. With the intervention of engineering means, the urease and protease in the soil showed a decline trend at the beginning. However, after the improvement of engineering means, the soil structure and soil quality were improved, and the unused land was transformed into the soil suitable for cultivation. Under the action of soil structure and crop root exudates, the enzyme activity in the soil was significantly increased after a long period of cultivation (Yang et al., 2022). In addition, the enzyme activities in the soil layer of 0~40 cm showed a strong activity, and the activity in the soil layer of 40~60 cm showed a downward trend compared with that in the upper soil. The roots of planted crops were mainly distributed in the range of 0~40 cm, indicating that root exudates and root microenvironment changes were significantly correlated with enzyme activities in soil (Wang et al., 2003). The good soil environment created by saline-alkali land remediation not only is suitable for crop growth, but also speeds up the succession process of soil organic and biological, making the soil environment develop in a benign and sustainable way (Liu et al., 2023).

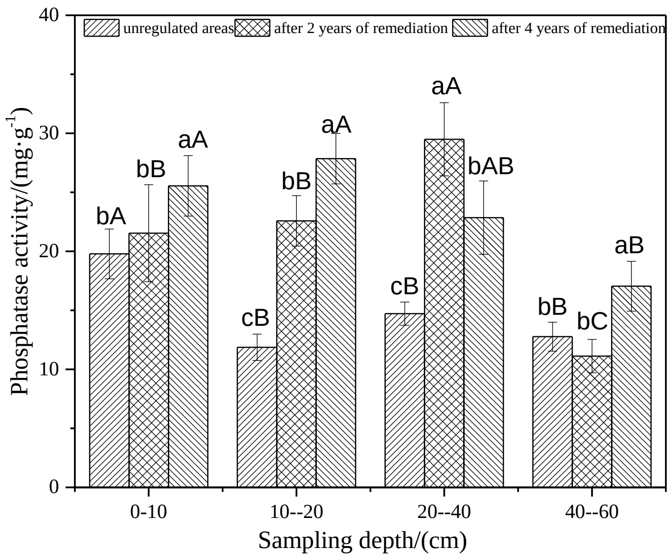

Figure 8. *Phosphatase activities content in soil. Note: a, b, c indicate the differences between different years in the same soil layer; A, B, C indicate the differences between different soil layers in the same year*

Changes of soil profile carbon density under different planting years

Following the remediation of the saline-alkali land, corn was successfully planted. Prior to the remediation, the soil in the project area was characterized by its saline-alkali nature, high groundwater levels, and large amounts of salt. As a result, only sparse salt-tolerant weeds were able to grow in the area.

The analysis of changes in vegetation carbon content and density under different remediation years, as displayed in *Table 4*, indicates that while there was no significant difference in the carbon content of above-ground biological grasses and crops before and after the remediation of saline-alkali land, there was a noticeable difference in vegetation carbon density across different remediation years. The carbon density increased significantly after treatment. In the two years following treatment, it was 26 times higher

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

than before treatment. Furthermore, in the four years after treatment, there was an additional increase of 37.72% compared to the two-year period after treatment. When the change of carbon content was not significant, the change of carbon density in the remediation area increased significantly with the extension of remediation years. Although there was no significant change in the carbon content of grass and crops before and after remediation, the saline-alkali land before remediation resulted in a large area of wasteland, which had low carbon density of soil and low carbon storage of vegetation due to its unutilizability. Following the implementation of remediation, the project measures were successful in accelerating soil cultivation processes, thus creating a more favorable habitat for crop survival. Within a mere 2~4 years after the remediation, there was a significant increase in vegetation carbon density, demonstrating exponential growth when compared to premediation levels. With the increase of the regulation years, the improved saline-alkali land has become a large area of good farmland, which has been realized by large-scale and mechanized planting. Vegetation carbon density increased significantly, which had a significant positive effect on increasing local carbon storage (Wang et al., 2003).

Table 4. *Changes in vegetation carbon content and carbon density under different land reclamation*

Type of remediation carbon	**Carbon content (%)**			**Carbon intensity (t/hm²)**		
Saline land	Unregulated areas	After 2 years remediation	After 4 years remediation	Unregulated areas	After 2 years remediation	After 4 years remediation
	37.22±1.10a	37.99±0.98a	38.14±0.76a	1.52±0.43c	39.57±3.88b	54.49±6.54a

Note: Different lowercase letters indicate significant differences at the $P<0.05$ level between different years of remediation for the same indicator

Changes of soil microstructure under different years of land consolidation

Samples of undisturbed soil in saline-alkali soil of different treatment years were collected and observed by scanning electron microscope. The measurement results are shown in *Figure 9*. With the improvement of saline-alkali soil by sand coating technology, although the composition and character of bone particles did not change, there were obvious differences in their distribution. The application of sand coating technology results in improved dispersion of sand on the soil surface of saline-alkali soil with strong original bonding force and less apparent soil bonding structure (Wang et al., 2021). This process also causes varying degrees of cracking on the surface of the soil with strong original bonding property. After four years of planting, there were notable differences in the soil microjunction structure compared to before remediation due to the increase in planting years. After planting crops, the soil structure becomes more complex due to the extension, interpenetration, and entanglement of the crop roots (Lin et al., 2012). This results in a more concave-convex and accumulative surface structure of the soil particles, as well as improved aggregate structure and soil granulation effect (Yin et al., 2012). The degree of fragmentation is increased, leading to an increase in porosity (Gu et al., 2013). The implementation of sand cover improvement technology has a notable positive impact on the microstructure of saline-alkali soil.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

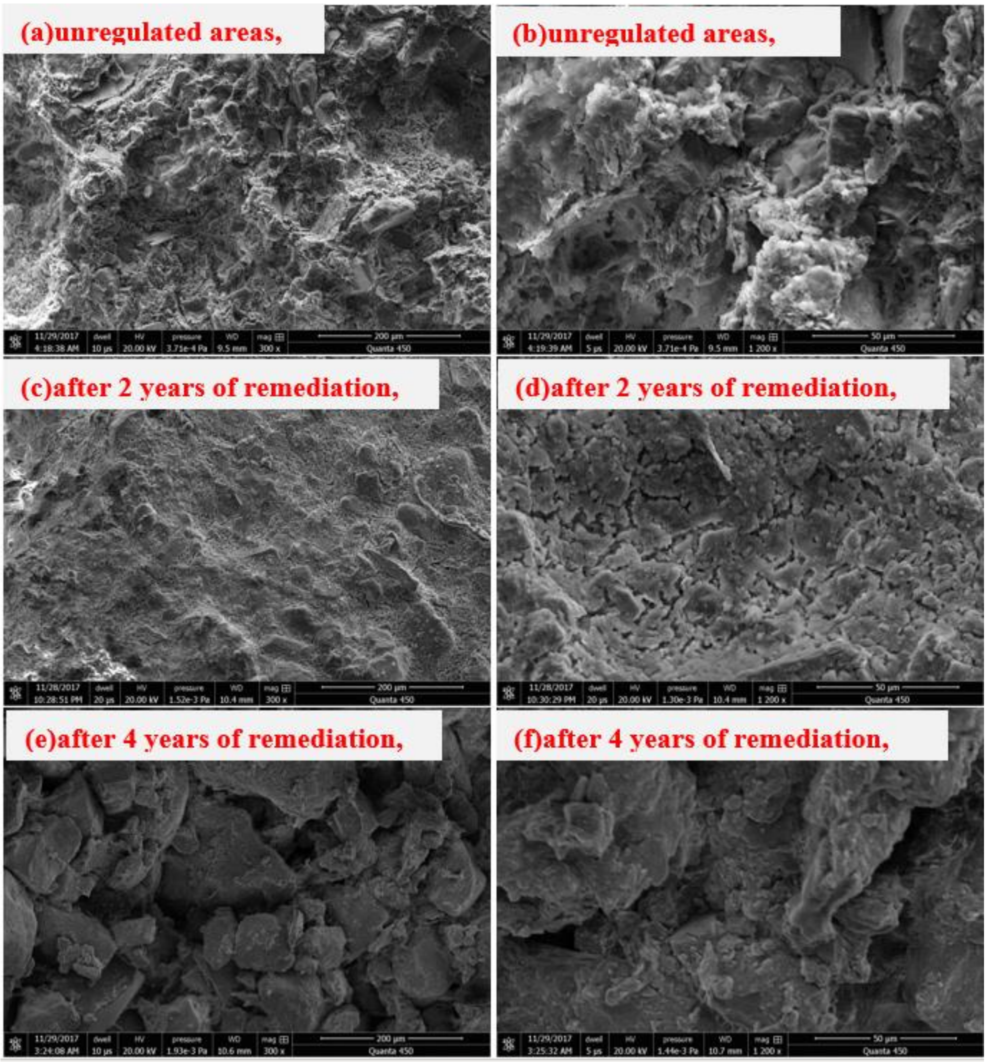

Figure 9. *SEM images of soil under different treatment years. (a-b) are 300 and 1200x magnification images of soil samples in untreated plots, (c-d) are 300 and 1200x magnification images after 2 years of treatment, (e-f) are 300 and 1200x magnification images after 2 years of treatment*

Conclusions

After 2 and 4 years of treatment, there was a significant decrease in total carbon content of the 0-20 cm soil by 24-63%, as well as a significant decrease in organic carbon content of the 0-10 cm soil by 32-35%. However, there was a significant increase in organic carbon content of the 10-60 cm soil by 23-42%. The content of inorganic carbon in soil profile decreased by 21-72% at 0~20 cm and increased by 32-60% at 60~100 cm. After planting and cultivation, the soil accumulates root exudates and plant root residues, which increases the soil's organic carbon density. Additionally, the surface fine sand fixes atmospheric CO_2 and synthesizes carbonate. Due to the improvement of saline-alkali soil by sand coating technology, the surface compaction of saline soil is improved, and the capillary pores of soil are increased. With the help of rainfall and gravity, the soil water causes carbonate leaching, resulting in decalcification of the surface soil and infiltration into the deep layer. This process significantly increases the inorganic carbon content and

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

reserves. The remediation of saline-alkali land may initially cause a decrease or no significant change in the soil carbon pool due to engineering disturbance. However, after several years of planting, the remediation project area can make a significant contribution to the soil carbon pool.

Improving saline-alkali land has a significant impact on the activity of four enzymes in the soil. Initially, the content of urease and protease in the soil tend to decrease. Through engineering techniques, the soil structure and quality of the saline-alkali soil were improved, allowing for previously unused land to become suitable for cultivation. Over time, the enzyme activity in the soil was significantly increased due to the effects of the improved soil structure and crop root exudates.

The carbon content of vegetation grasses and crops did not show a significant difference before and after treatment. However, there was a significant difference in the carbon density of vegetation based on the different soil remediation years. The carbon density increased significantly after treatment, with a 26 times increase in the first two years and a further 37.72% increase in the following four years. Prior to remediation, the saline-alkali land was rendered unusable, resulting in a large area of barren land with low soil carbon density and limited vegetation carbon storage. Following the implementation of engineering measures, the soil cultivation process was expedited, creating a more hospitable environment for crops in the project area. Within 2-4 years of regulation, the vegetation carbon density significantly multiplied, resulting in a substantial increase from pre-regulation levels.

After planting crops, the soil bonding structure becomes more complex due to the extension, interpenetration, and entanglement of crop roots. This results in a more concave-convex and accumulative surface structure of soil particles, an improved aggregate structure of soil, and an obvious soil granulation effect. The degree of fragmentation is increased, and the porosity is also increased. As the remediation years progressed, there was a notable increase in soil biochemical activity, leading to a significant contribution to the storage of soil carbon pool and enzyme activity. This is likely due to the combined impact of crop planting and engineering measures.

Acknowledgements. The authors express their gratitude to Shaanxi Province land engineering construction group internal project (DJNY-YB-2023-27); Shaanxi Province Key R&D Program (2023-ZDLSF-28) (2023-ZDLNY-48); The Natural Science Basic Research Program of Shaanxi (2022NY-082).

REFERENCES

[1] Andrade Foronda, D., Colinet, G. (2022): Combined Application of Organic Amendments and Gypsum to Reclaim Saline-Alkali Soil. – Agriculture 12(7): 1049.

[2] Bao, C. H., Xu, L. S., Wu, Y. J., Zhang, S. W. (2007): The Landscape Change of Salt and Alkaline Land in Semi-Arid District before and after Flooding: A Case Study in Zhenlai County. – Resources Science 29(4): 92-96.

[3] Cheng, Y. L., Xie, X. W., Wang, X. Q., Zhu, L., Qiu, Q. S., Xu, X. (2023): Effects of the Salt-Tolerant Gramineous Forage Echinochloa frumentacea on Biological Improvement and Crop Productivity in Saline-Alkali Land on the Hetao Ningxia Plain in China. – Sustainability15(6): 5319.

[4] Gu, L. J., Ren, R. Z., Cao, J. S., Sun, J. (2013): Saline alkali land classification using MODIS data in Western Jilin Province, China. – Satellite Data Compression, Communications, and Processing 8871: 62-71.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

[5] Jia, X. Y., Wu, H. Y., Li, X., Fu, B. Z. (2006): Study on floristics component of saline-alkali land in hetao irrigation region. – Journal of Inner Mongolia Agicultural University Natural Science Edition 27: 78-82.
[6] Li, X. Y., Zhang, S. W. (2005): Tempo-Spatial Dynamics and Driving Factors of Saline-Alkali Land in Daan City of Jilin Province. – Resources science 27: 92-97.
[7] Li, L., Bai, X. G., Jiang, Z. D. (2019): The generic technology identification of saline-alkali land management and improvement based on social network analysis. – Cluster Computing 22: 13167-13176.
[8] Li, Y. F., Li, G. H. (2022): Mechanisms of straw biochar's improvement of phosphorus bioavailability in soda saline-alkali soil. – Environmental Science and Pollution Research 29(32): 47867-47872.
[9] Li, C. Y., Wang, Z. C., Xu, Y. T., Sun, J. F., Ruan, X. Y., Mao, X. W., Hu, X. Y., Liu, P. (2023): Analysis of the Effect of Modified Biochar on Saline-Alkali Soil Remediation and Crop Growth. – Sustainability 15(6): 5593.
[10] Lian, Y., Wang, J., Tu, G., Ren, H. L., Shen, B. Z., Zhi, K. G., Li, S. F., Gao, Z. T. (2010): Quantitative Assessment of Impacts of Regional Climate and Human Activities on Saline-alkali Land Changes: A Case Study of Qian'an County, Jilin Province. – Chinese Geographical Science 20(1): 91-97.
[11] Lin, S. J., Zhang, Z. H., Zhang, D. W., Fu, S. C., Yang, Y. C., Xie, P., Zhao, S. S., Liu, J. B., Zhang, X. H., Tian, F. C. (2012): Research Progress on the Trees Species Choice in Saline-alkali Land and Drought Resistant Forestation Technology. – Chinese Agricultural Science Bulletin 28: 1-5.
[12] Liu, Z., Li, J., Zhang, Y. T., Gong, H. R., Hou, R. X., Sun, Z. G., Ouyang, Z. (2023): Soil Microbes from Saline-Alkali Farmland Can Form Carbonate Precipitates. – Agronomy 13(2): 372.
[13] Lv, X., Xu, H., Li, L., Zhao, Y. T. (2012): Agricultural Sustainable Utilization and Evaluation of Saline-alkali Land. – Soils 44: 203-207.
[14] Nurzhan, A., Tian, H., Nuralykyzy, B., He, W. (2022): Soil Enzyme Activities and Enzyme Activity Indices in Long-Term Arsenic-Contaminated Soils. – Eurasian Soil Science 55(10): 1425-1435.
[15] Wang, Z. C., Sun, C. Z., Li, X. J., Shao, X. W. (2003): Integrated technique model of rice production on saline-alkali land. – System Sciences and Comprehensive Studies in Agriculture 19: 56-59.
[16] Wang, Z. C., Sun, C. Z., Li, X. J., Shao, X. W. (2003): Evaluation and analysis of the supply and demand of agricultural water resource in Sanjing Plain based on AHP method. – System Sciences and Comprehensive Studies in Agriculture 19: 56-59.
[17] Wang, Y. H., Jiang, F. C., Si, Q. Z., Han, Y. J., Li, S. J. (2015): Key Techniques of Afforestation in Saline-alkali Soil in Yellow River Delta. – Bulletin of Soil and Water Conservation 35(3): 203-206.
[18] Wang, W. N., Ge, J. Z., Yang, H. C., Yin, F. T., Huang, T. L., Kuai, J., Wang, J., Wang, B., Zhou, G. S., Fu, T. D. (2021): Adaptation of feed crops to saline-alkali soil stress and effect of improving saline-alkali soil. – Acta Agronomica Sinica 48: 1451-1462.
[19] Wang, X. Q., Zhang, F. J., Zhang, B., Xu, X. (2021): Halophyte Planting Improves Saline-Alkali Soil and Brings Changes in Physical and Chemical Properties and Soil Microbial Communities. – Polish Journal of Environmental Studies 30: 4767.
[20] Wu, S., Jiang, Q. G. (2015): Inversion classifications of saline-alkali lands based on the hyperspectral data from the environmental mitigation Satellite. – Advances in Computer Science Research, Proceedings of the 4th International Conference on Information Technology and Management Innovation, pp. 1195-1202.
[21] Yang, J. C., Zhang, S. W., Li, Y., Bu, K., Zhang, Y. B., Chang, L. P., Zhang, Y. Z. (2010): Dynamics of Saline-alkali Land and Its Ecological Regionalization in Western Songnen Plain, China. – Chinese Geographical Science 20: 159-166.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701

[22] Yang, S. A., Hao, X. H., Xu, Y. M., Yang, J. J., Su, D. R. (2022): Meta-Analysis of the Effect of Saline-Alkali Land Improvement and Utilization on Soil Organic Carbon. – Life 12(11): 1870.
[23] Yin, X. L., Ding, G. D., Gao, Y. Y. (2012): Response characteristic of soil moisture and salt to salt isolated layer in seashore saline soil. – Applied Mechanics and Materials 195: 1222-1226.
[24] Zhang, L., Zhang, J. Y., Gao, L. H., Lv, L. F., Liang, Y. S., Zhao, Y. (2017): A review of land reclamation technologies of saline-alkali soil in China. – Land Reclamation in Ecological Fragile Areas, pp. 543-545.
[25] Zhang, Z., Gao, M. X., Zhu, C. D. (2019): Dynamic Monitoring System of Water and Salt of Saline-alkali Land Based on WebGIS. – Soils 51: 413-417.
[26] Zhang, B. Q., Wang, N. (2021): Study on the Harm of Saline Alkali Land and Its Improvement Technology in China. – IOP Conference Series: Earth and Environmental Science 692(4): 042053.
[27] Zhao, L. P., Feng, J., Wang, Y., Wang, H. B., Geng, Y. H., Wang, S. H., Li, C. L. (2012): Theoretical and Technological Problems in the Development of Planting Paddy in Saline-alkali Land of Songnen Plain. – Journal of Jilin Agricultural University 34(3): 237-241.
[28] Zhao, W., Zhou, Q., Tian, Z. Z., Cui, Y. T., Liang, Y., Wang, H. Y. (2020): Apply biochar to ameliorate soda saline-alkali land, improve soil function and increase corn nutrient availability in the Songnen Plain. – Science of The Total Environment 722: 137428.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2105_46854701