Effects of Improved Saline-Alkali Soil with Synergistic Addition of Coal Slime and Silica Calcium Slag on Wheat Growth

Ruixin An, Xinyang Wang, Boda Zhang, and Xiaolin Yan *

The feasibility was explored for synergistic addition of coal slime and silica calcium slag for saline-alkali soil improvement. A pot method was used to evaluate the effects on physicochemical properties of saline-alkali soil and wheat growth. The results demonstrated that the density and bulk density of saline-alkali soil were reduced with the synergistic additions, but the water content and the contents of organic matter, nitrogen, phosphorus, and potassium in the soil were increased. The emergence and growth height of wheat seedlings was found to be effectively improved. In terms of the emergence, no matter what proportion of M-G (coal slime: silica calcium slag ratio) was used, the emergence of wheat was greater than 70% when the addition amount was at 20%. In terms of seedling length, when the aggregate addition reached 35%, the high coal slime content (M-G 3:1) did not play a greater role in fostering the development of wheat. Therefore, with M-G 1:1, 35% addition of the soil can meet the growth needs of wheat in the early stage. In summary, the synergistic addition of coal slime and silica calcium slag has a promising application in the field of saline-alkali soil improvement.

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Keywords: Saline-alkali soil; Coal slime; Silica calcium slag

*Contact information: College of Science, Inner Mongolia Agricultural University, Hohhot Inner Mongolia 010018, China; *Corresponding authors: nmgndyxl@imau.edu.cn*

INTRODUCTION

Soil salinization is the accumulation of soluble salt in the soil surface because of natural environmental causes (*e.g.* mineral weathering, high evaporation in arid regions) or human activities (*e.g.* excessive irrigation with saline water, overuse of chemical fertilizers) (Pereiraa *et al*. 2020). According to the global saline-alkali soil distribution map in 2021, more than 833 million hm^2 of soil in the world was affected by salinization, and these numbers are growing (FAO 2021; Ma and Rao 2023). Soil salinization is a serious threat to food security. To upgrade soil quality from salinization usually requires a combination of physical, chemical, and biological improvements. The physical improvement method mainly adopts engineering measures to adjust the conditions of water, fertilizer, gas, and heat in the soil to achieve soil quality (Zhang 2019; Zhao *et al*. 2022; He *et al*. 2023). The chemical improvement involves adding chemical amendments and organic substances to the soil to encourage the transformation, adsorption, or fixation of salt and alkali components in the soil (Howell *et al*. 2023). The addition of chemical amendments can reduce the functional contents and activities of heavy metals in the soil, inhibit the migration of heavy metals from the soil to the plant system, and facilitate the safe production of plants (Yue 2008). Biological fertilizers can effectively improve the physical and chemical properties of stabilized soil, decrease osmotic resistance, and promote microbial cooperative plant restorations (Jia *et al*. 2024; Li *et al*. 2024; Zhou *et al*. 2024).

Coal slime (CS) is the product of coal that has undergone peatification but no coalification process. It often appears as a by-product in the coal flotation process, which is characterized by high ash content, low calorific value, elevated moisture content, and small particle size (Dong *et al*. 2021; Zhou *et al*. 2023). These properties limit its application in combustion. The storage of CS is generally wasteful of land space and can give rise to dust pollution. A large amount of water is therefore required, and it is difficult to transfer, which limits CS's widespread application. Therefore, it is urgent to seek a new way to utilize CS resources (Wang *et al*. 2022b). At present, CS is employed in a number of ways, such as hybrid combustion (Wang *et al*. 2022a), co-pyrolysis with biomass (Guo *et al*. 2021), preparation of catalytic materials (Li *et al*. 2024), and use in building materials (Shen *et al*. 2022).

In recent years, solid waste from the coal industry has also been extensively used as a soil conditioner. The addition of coal gangue can increase soil organic matter content, improve soil conditions, and promote plant growth (Chu *et al*. 2020). The addition of modified fly ash to sandy soil can enhance the cohesion of soil (Li *et al*. 2022).

Biochar can also be used as a soil conditioner, but the anaerobic fermentation of biochar will produce methane, which may lead to instability in certain conditions. Some researchers have utilized pyrolyzed biochar for soil improvement, which primarily focusing on its ability to influence soil phosphorus content (Dannhauser *et al*. 2024). However, to enhance its effectiveness in soil amendment, pyrolyzed biochar is often combined with nitrogen fertilizer application (Zhang *et al*. 2024). In contrast, the coal slime discussed in this paper originates from the peatification stage during coal formation. Its fermentation process was completed underground in ancient times, resulting in stable properties rich in organic matter, which provide advantages for soil improvement. Therefore, the application of CS in the improvement of saline-alkali soil is expected to improve the fertility and tillage performance of saline-alkali soil and promote the healthy growth of crops.

Silica calcium slag is a solid residue obtained after adding alkaline substances and limestone to fly ash for sintering, wet extraction of alumina, and recovery of alkaline components (Song *et al*. 2013). Silica calcium slag can be utilized to make cement, prepare calcium silicate insulation materials, and capture carbon dioxide to produce silicon fertilizer (Wen 2012; Wang *et al*. 2024). In addition, silica calcium slag is rich in silicon (Si) element, and studies have shown that silicon can improve the resistance of many plants to biological stresses (pests and diseases, *etc*.) and abiotic stresses (drought, heavy metals, *etc*.) (Yang *et al*. 2019a; Yang *et al*. 2019b; Fan *et al*. 2021). Silicon can also improve photosynthetic gas exchange of various plants, increase plant resistance to salt stress, and reduce salt damage to crops (Shu and Liu 2001; Zhang *et al*. 2019; Zhu *et al*. 2019). Consequently, the silica calcium slag provides an opportunity to be applied to the improvement of saline-alkali soil.

Although a few researchers have used coal slime or silica calcium slag to improve soil quality, there is only limited information on the synergic effect of the two on soil improvement. Therefore, this study took the emergence and growth of wheat as an example to study the synergistic effect of coal slime and silica calcium slag on the improvement of saline-alkali soil.

EXPERIMENTAL

Materials

The test sample of saline soil was taken from Toketuo, Hohhot City, Inner Mongolia Autonomous Region, and the coal slime (CS) and silica calcium slag used were obtained from Ordos City, Inner Mongolia Autonomous Region. Before the test, the sample was air-dried and screened at 2.8 mm. The basic physical and chemical properties of saline-alkali soil, coal slime, and silica calcium slag are shown in Table 1.

Table 1. Physical and Chemical Properties of the Tested Sample

Test Sample	pH	Density (g/mL)	Bulk Density (g/mL)	Water Content (%)	Organic Carbon (%)	Available Potassium (mg/kg)	Total Nitrogen (%)	Available Phosphorus (mg/kg)
Saline-alkali soil	8.30	1.43	1.42	0.71	0.87	6	0.0082	11
Coal slime	6.01	0.89	0.73	17.15	51.03	8	0.2627	7
Silica-calcium slag	11.88	0.84	0.81	3.19	3.99	75	0.0704	15

Experimental Design

Potted wheat planting experiment was used to measure the improvement effect of saline-alkali soil. 0.5-gallon pots with a diameter of 12 cm and a height of 13 cm were used in this research. The total amount of coal slime and silica calcium slag was 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40% (mass fraction). At the same time, under the same total addition amount, the ratio of coal slime and silicon calcium slag used were 3:1, 1:1, and 1:3, respectively (all the ratios in the following are coal slime: silicon calcium slag denoted as M-G), and the three different ratios were recorded as M-G 3:1, M-G 1:1, and M-G 1:3, respectively. Three repeated tests were scheduled for each test group.

The treated CS and silica calcium slag were fully mixed with saline-alkali soil. The absolute mass of 800 g of soil sample was put into a flowerpot. About 200 mL water was added to the pot at one time in order to make the soil fully soaked, and the pH was set to 6.5 to 7 with phosphoric acid. Eight wheat seeds were soaked for 24 h and were evenly placed in each pot, and the daily seed emergence and seedling height were recorded. During planting, water was inserted as needed, and the position of the pot was changed every 2 to 3 days to avoid the impact of light.

Test Methods

The following test methods were used respectively: Soil density was determined dry density method (Zhen 2012); Soil moisture content by drying method (Zhen 2012); Soil bulk density by ring knife method (Zhen 2012); Soil water retention using gravimetric method (Zhen 2012); Soil pH by potentiometer method (Zhen 2012); and Soil organic matter content by high temperature burning weight loss method (Qian *et al*. 2011).

Determination of soil phosphorus content was obtained using sodium bicarbonate extraction - molybdenum antimony resistance colorimetric method (Liu *et al*. 2018). Soil nitrogen determination was done by the Kay method for nitrogen determination (Wang *et al*. 2024).

RESULTS AND ANALYSIS

Influence of Amounts of Coal Slime and Silica-Calcium Slag on Physical and Chemical Properties of Saline-Alkali Soil

As illustrated in Figs. 1 to 3, with the increase of the total amount of coal slime and silica calcium slag, soil density and bulk density decreased, and soil water content increased. The soil density and water content increased with the increase of CS proportion under the equal addition amount. The decrease of bulk density can increase soil porosity, which can help air enter the soil and provide sufficient oxygen for the root system. The increase of water content is also beneficial to crop growth. Therefore, the addition of CS and silica calcium slag can improve soil physical properties. As shown in Fig. 4, the pH of the soil decreased with increasing CS and increased with the increase of silica calcium slag.

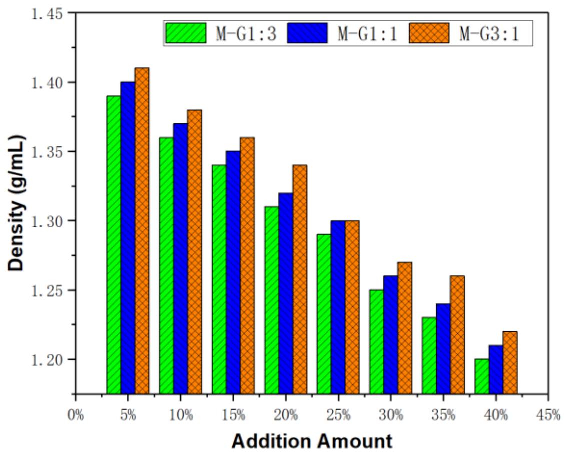

Fig. 1. Effect of different addition amount on the density of saline-alkali soil

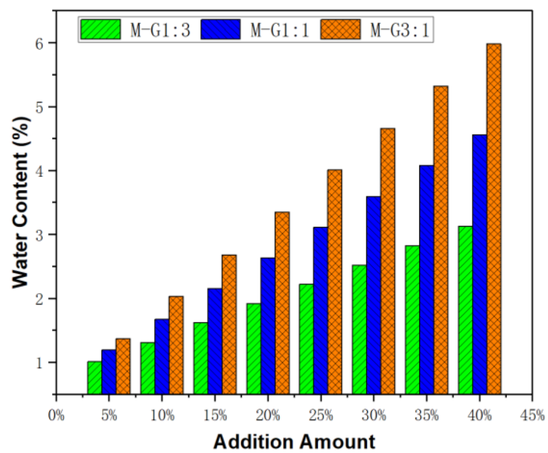

Fig. 2. Effect of different addition amount on the water content of saline-alkali soil

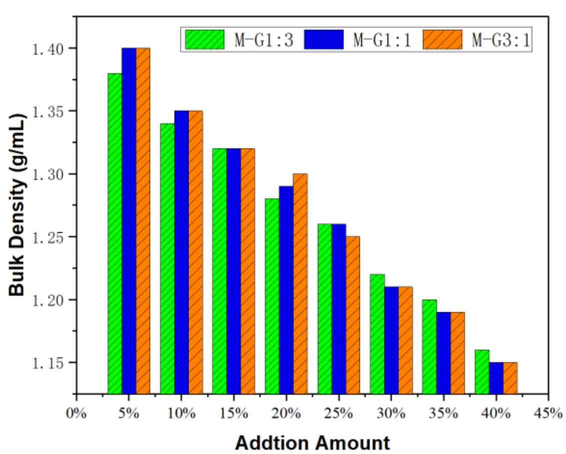

Fig. 3. Effect of different addition amount on the bulk density of saline-alkali soil

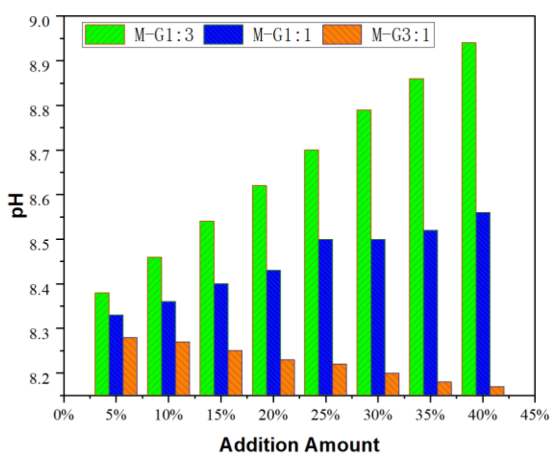

Fig. 4. Effect of different addition amount on pH of saline-alkali soil

As illustrated in Figs. 5 to 8, the contents of organic matter, available potassium, and total nitrogen in the test soil increased with the increase of the total addition of coal slime and silica calcium slag. The content of available phosphorus in soil increased with the addition of silica-calcium slag. Through the comparison of samples with the same amount and different proportions, it was demonstrated that the addition of CS can increase the contents of organic matter and nitrogen in soil samples, and the addition of silica-calcium slag can improve the contents of available potassium and available phosphorus in soil samples. Therefore, the synergistic addition of CS and silica-calcium slag is conducive to the increase of soil nutrient indexes.

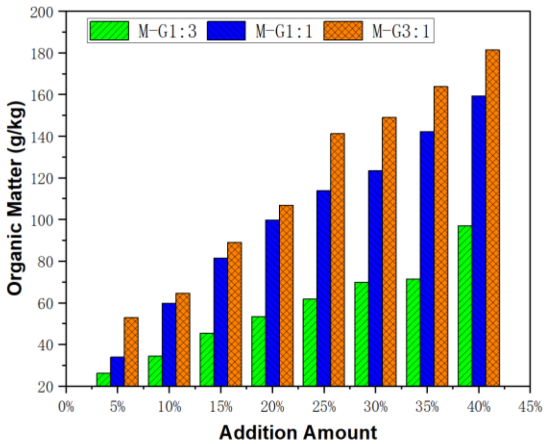

Fig. 5. Effects of different addition amount on organic matter content in saline-alkali soil

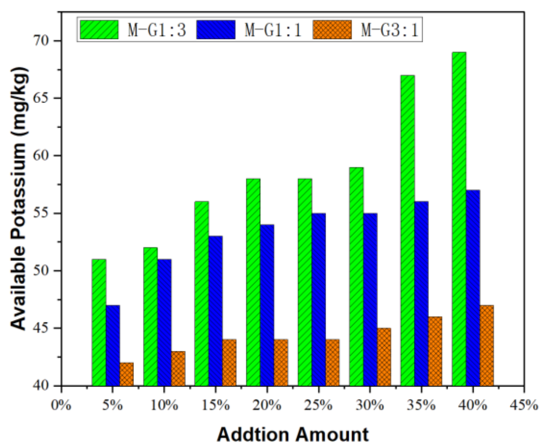

Fig. 6. Effect of different addition amount on available potassium content in saline-alkali soil

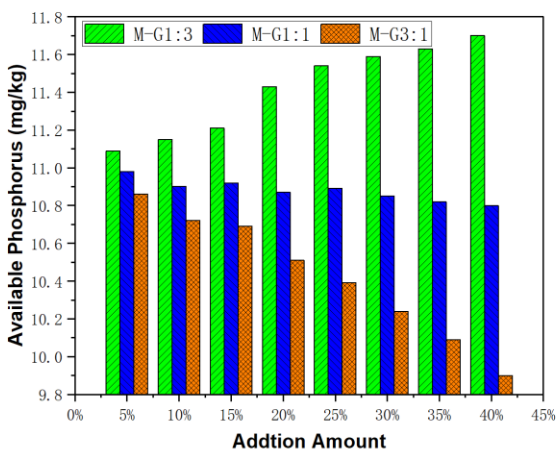

Fig. 7. Effect of different supplemental levels on available phosphorus content in saline-alkali soil

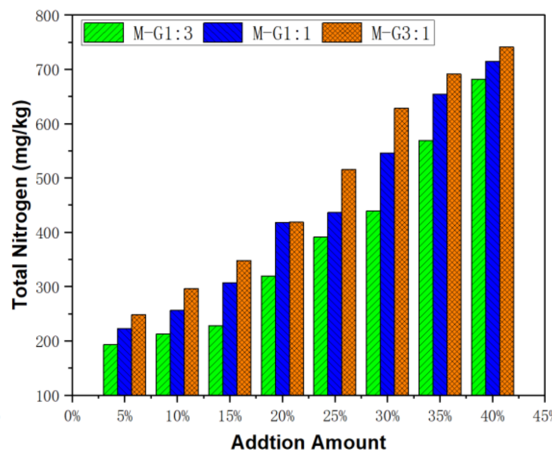

Fig. 8. Effects of different supplemental levels on total nitrogen content in saline-alkali soil

Effects of Different Amounts of Coal Slime and Silica-Calcium Slag on Wheat Growth in Saline-Alkali Soil

Effects of coal slime and silica-calcium slag on wheat emergence

In this experiment, a total of 24 seeds were planted in three pots of pure saline-alkali soil control planting group, of which only one seedling emerged in one pot, with a seedling emergence of about 0. Therefore, no blank control was contained in the subsequent pots. Figure 9 shows the emergence of seedlings from 1 to 20 days when the coal slime: silica-calcium slag ratio was 1:3. The seedling emergence in this study was the average value of each repeat group. In general, with the increase of the aggregate addition amount, the emergence of wheat showed an increasing trend. In the growth stage of 1 to 20 days, the emergence reached its maximum at about 12 days and it did not vary. The seedling emergence of wheat in the soil of 20% added amount showed the same value as that of 40%, which was at 75% level. In addition, the seedling emergence of wheat under 20% added amount was quick, and the seedling emergence reached 75% on the third day of planting and remained unchanged.

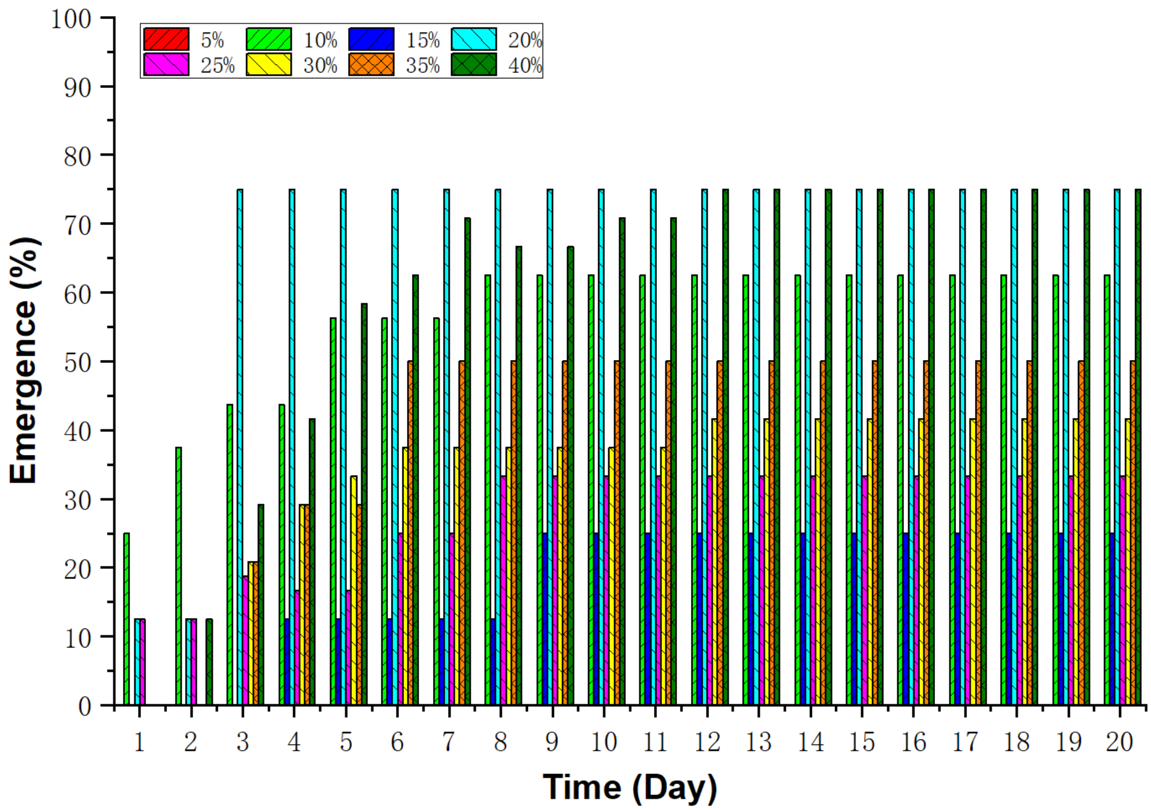

Fig. 9. Emergence of M-G 1:3

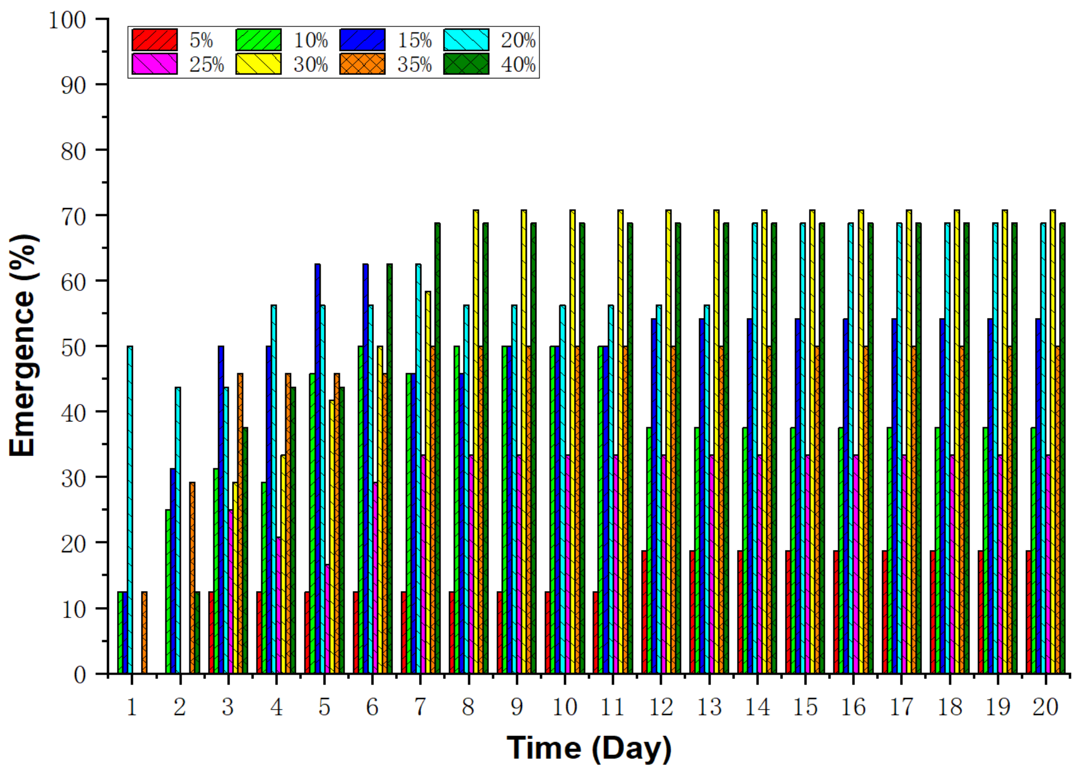

Fig. 10. Emergence of M-G 1:1

Figure 10 shows the emergence of seedling from soil in 1 to 20 days with separate aggregate addition amount when the coal slime: silica-calcium slag is 1:1. In general, soil with high additive content showed high wheat emergence. However, similar to M-G 1:3, the seedling emergence of wheat in the soil with 20% addition was the same as that of 40%, which is at 70%. In addition, the emergence speed is the fastest, the emergence of the first day of planting reached 50%.

Figure 11 shows the emergence from soil in 1 to 20 days with singular aggregate addition amount when the coal slime: silica-calcium slag ratio was 3:1. Overall, for M-G 3:1 added soil, high accumulation did not result in superior wheat emergence. When the aggregate addition amount reached 40%, the emergence decreased. This may be due to the high proportion of coal slime in M-G 3:1, when the total amount of addition is large, the absolute content of coal slime in the soil is high, and the emergence is decreased due to the high density of slime and poor permeability. Similar to the first two ratios, the seedling emergence of wheat in the soil supplemented by 20% was the highest (87.5%). It also showed a faster seedling emergence, and the emergence reached 50% on the second day of planting.

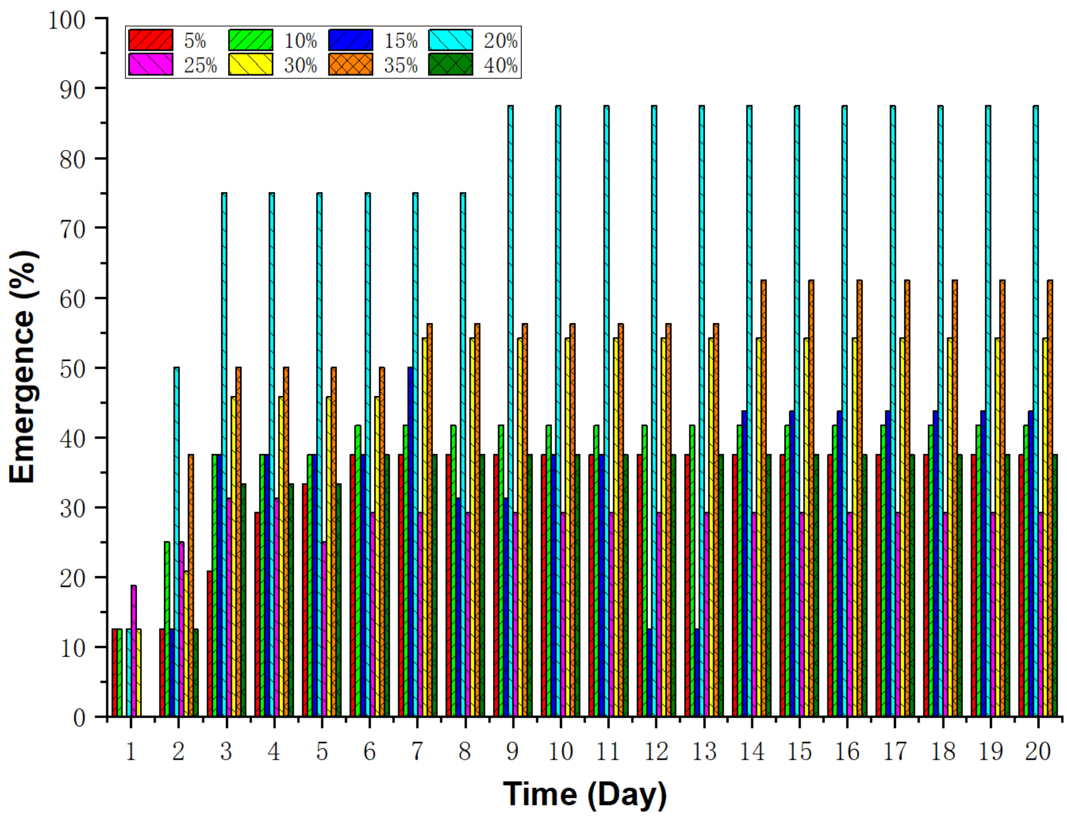

Fig. 11. Emergence of M-G 3:1 proportion

Figure 12 displays the 20-day absolute emergence of all soil proportions. When the addition amount was 20%, no matter what proportion, the emergence of wheat was greater than 70%. The emergence of M-G 1:1 was the most stable with an average of 50%.

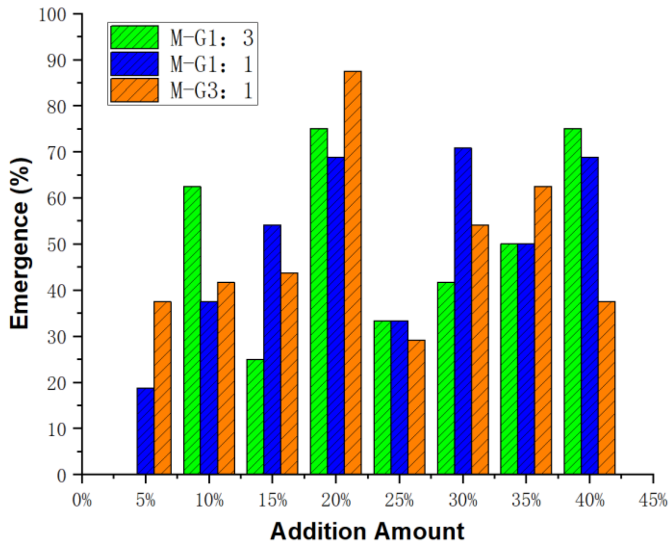

Fig. 12. Emergence on the 20th day

Effects of coal slime and silica-calcium slag proportion on wheat seedling length

Figure 13 shows the maximum seedling length from soil in 1 to 20 days with scarce aggregate addition amount when the coal slime: silica-calcium slag was 1:3. The highest seedling length in this study was the average highest seedling length of each replicate group. In general, when the aggregate supplemental amount was less than 30%, there was little difference in wheat seedling length among all groups, which was no more than 4.0 cm. This may be explained by the low proportion of coal slime in M-G 1:3 soil and the insufficient contents of organic matter and nitrogen in soil, which lead to the unfavorable growth of wheat seeds. When the total proportion was greater than 30%, the wheat seedling length increased with the increase of the added amount.

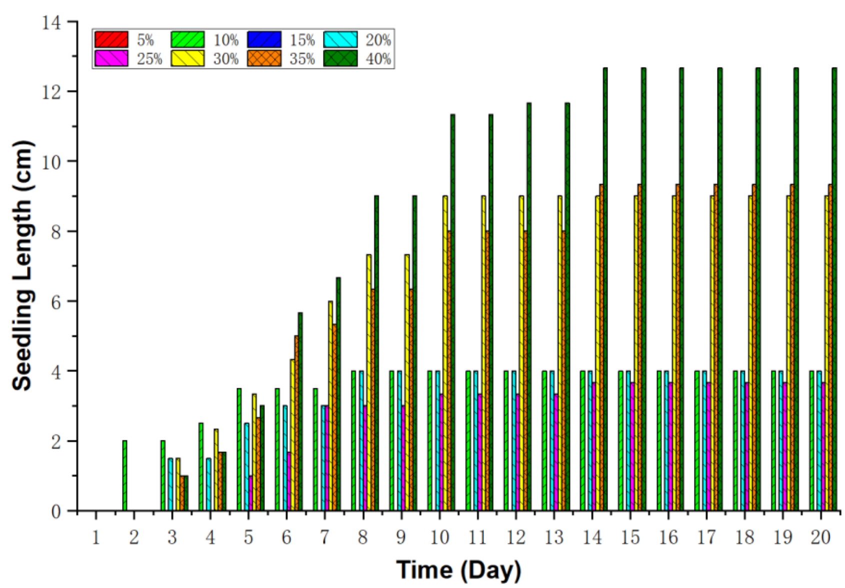

Fig. 13. Maximum seedling length of M-G 1:3 proportion

Figure 14 shows the maximum seedling length from soil in 1 to 20 days with unique aggregate addition amount when the coal slime: silica-calcium slag was at 1:1 proportion. The maximum seedling length of wheat built up over the increase of the total additive amount. When the aggregate addition amount was higher than 35%, the maximum seedling length was basically stable, and all were greater than 12 cm.

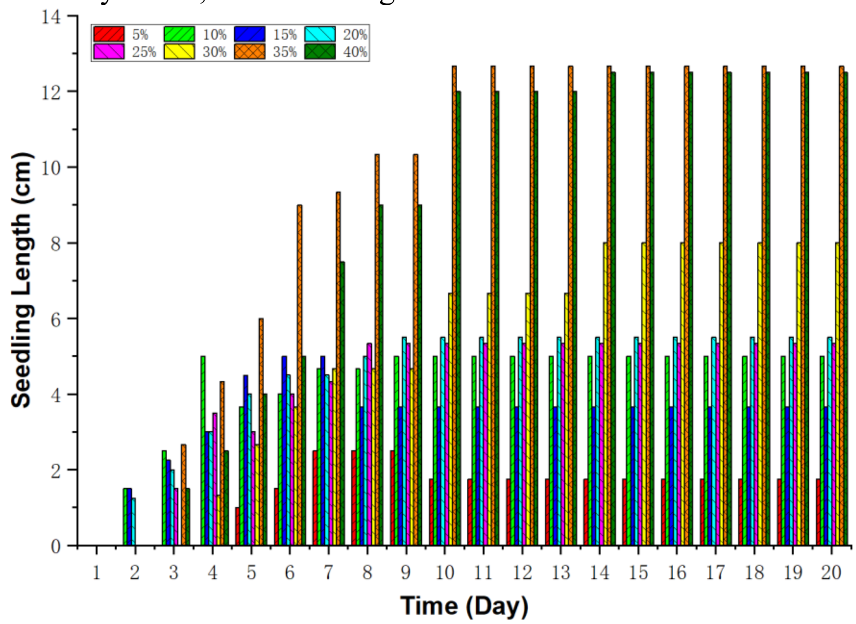

Fig. 14. Maximum seedling length of M-G 1:1 proportion

Figure 15 shows the maximum seedling length from soil in 1 to 20 days with separate aggregate addition amount when the coal slime: silica-calcium slag proportion was 3:1. Similar to M-G 1:1, the wheat seedling length with M-G 3:1 ratio also increased with the increase of the total additive amount. When the aggregate addition amount was greater than 35%, the maximum seedling length was basically stable.

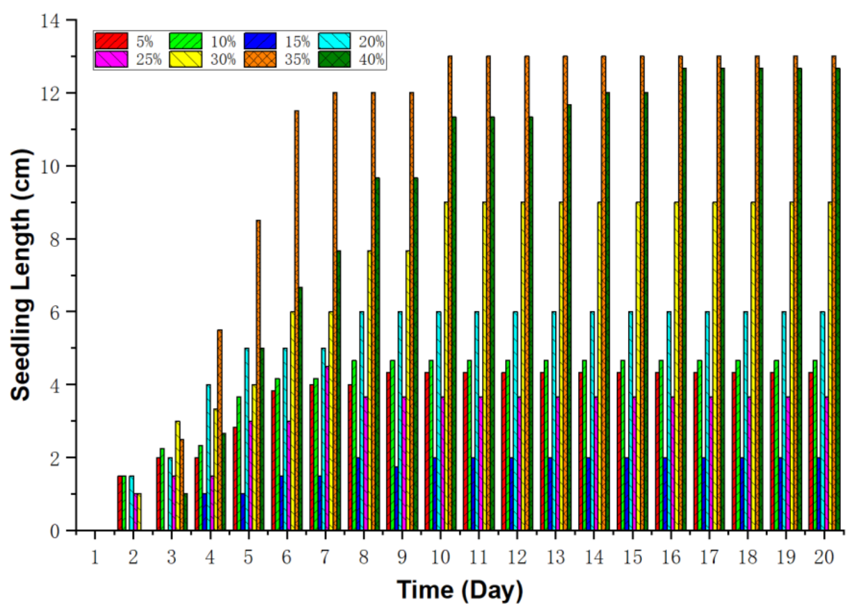

Fig. 15. Maximum seedling length of M-G 3:1 proportion

Figure 16 shows the comparison of the overall seedling length of each proportion at 20 days. The growth of wheat was not good when the aggregate addition amount is less than 30%. The seedling length of each proportion was basically the same when the aggregate addition amount was greater than 35%.

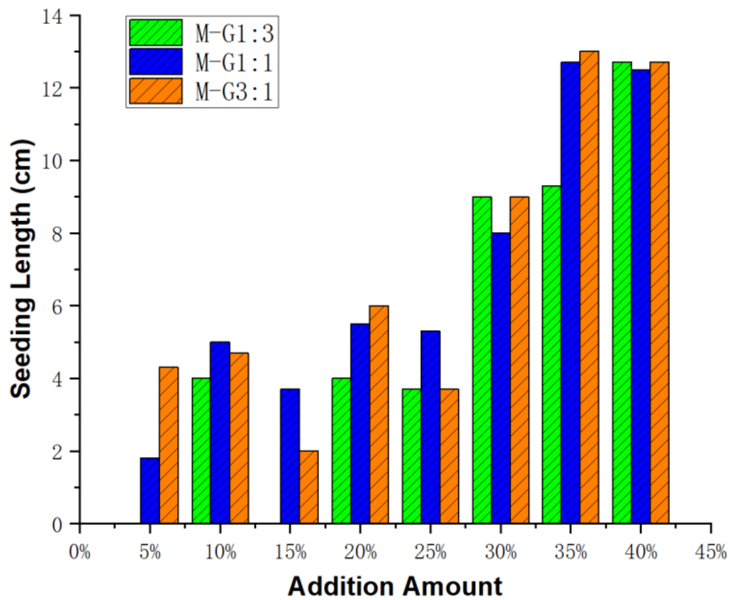

Fig. 16. The seedling length on the 20th day

By comparing the above figures, it is apparent that a lower proportion of coal slime (1:3) was unfavorable to the growth of wheat, but a higher proportion of slime (3:1) did not play a greater role in promoting the development of wheat. So, M-G 1:1 proportion, the absolute addition of 35% of the soil can respond to the growth needs of wheat in the primary stage.

In previous research by the authors, if silica-calcium slag was added alone in saline-alkali soil, since its high pH(11.88) and low organic matter content, wheat could not grow normally in it. In the wheat planting experiment where coal slime was added alone in saline-alkali soil, the wheat could grow normally, but regardless of the addition amount, the emergence of the wheat was all lower than 69%, and as the addition amount of coal slime increased, the emergence of the wheat decreased (the emergence of the 40% addition amount was only 37.5%). This might be due to the smaller particle size and high moisture content of the coal slime, which made the soil air permeability worse. In terms of seedling growth, the addition of coal slime could promote the increase of seedling length, which might be due to its high organic matter content and nitrogen content.

Depending on the overall situation of wheat seedling emergence and seedling length, the synergistic addition of coal slime and silica-calcium slag can change the soil properties of saline-alkali soil which cannot grow wheat and is suitable for wheat growth. In the initial growth stage of wheat, the aggregate addition of 20% M-G 1:1 slime and silica-calcium slag can promote the emergence of wheat. The total addition amount to 35% can respond to the growth demand of wheat seedling in the preliminary stage.

CONCLUSIONS

The synergistic addition of coal slime and silica-calcium slag can improve the physical and chemical properties of saline-alkali soil.

1. With the increase of the total amount of coal slime and silica-calcium slag, the soil density and bulk density decreased, the soil water content increased, and the contents of organic matter, available potassium and nitrogen increased. The content of available phosphorus in soil increased with the addition of silica-calcium slag.
2. Comparing the samples with the same amount and different proportions, it was found that the addition of coal slime can increase the content of organic matter and nitrogen in soil samples, and the addition of silica-calcium slag can increase the content of available potassium and available phosphorus in soil samples. Therefore, the synergistic addition of slime and silica-calcium slag contributes to the increase of soil nutrient index and can create a more favorable soil environment for plant growth.
3. The unimproved saline-alkali soil was not adapted for wheat growth, and the seedling sprouting of wheat was 0. The synergistic addition of coal slime and silica-calcium slag was able to effectively improve the emergence and growth height of wheat plants. The synergistic addition of coal slime and silica-calcium slag was more beneficial for improving saline-alkali soil and the growth of wheat compared to their separate addition.
4. In terms of emergence, when the addition amount was at 20%, the emergence was greater than 70%. Compared with all contents, the emergence of coal slime: silica-calcium slag was 1:1, which was relatively stable, and the average value reached 50%.
5. In terms of seedling length, when the total addition amount was less than 30%, the lower proportion of slime (M-G 1:3) was unfavorable to the growth of wheat. However, when the aggregate addition reached 35%, the high slime ratio (M-G 3:1) did not play a greater role in fostering the development of wheat. So, with M-G 1:1, the addition of 35%, the soil can respond to the growth needs of wheat in the early stage.

In summary, the combined addition of coal slime and silica calcium slag was able to effectively improve the saline-alkali soil environment, and the improved saline-alkali soil is suitable for planting wheat, so it has a promising application in the field of saline-alkali soil improvement.

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