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Study on the Effect of Si-Ca-K-Mg Fertilizer Prepared from Molybdenum Tailings on the Promotion of Cherry Radish Production and the Improvement of Acidic Soils

(Kajian Kesan Baja Si-Ca-K-Mg Disediakan daripada Amang Molibdenum terhadap Promosi Pengeluaran Lobak Ceri dan Penambahbaikan Tanah Berasid)

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ABSTRACTS

Acidic soil extensively distributes in southern China, exerting an adverse influence on crop growth. The grade of molybdenum ore resources in China is relatively low, and a considerable amount of tailings are generated during the beneficiation process, which poses a significant threat to the environment. The application effect of converting molybdenum tailings into Si-Ca-K-Mg fertilizer on crops and acidic soils was studied. In this work, we used cherry radish and acidic soil in southern China as experimental materials, a 3-month pot experiment was conducted to study the application effect of Si-Ca-K-Mg fertilizer as a soil amendment on acidic soil and its growth promoting effect on cherry radish. Results indicated that the application of Si-Ca-K-Mg fertilizer significantly enhanced the growth indicators of cherry radish plants, encompassing length, weight, and chlorophyll content. The utilization efficiency of Ca, K, and Mg in the treatment group was significantly higher than the control group. Meanwhile, the application of the fertilizer facilitated the absorption of nitrogen (N) and phosphorus (P). Additionally, Si-Ca-K-Mg fertilizer can effectively improve key indicators in the soil, such as pH value, cation exchange capacity (CEC), available Si, K, Ca, and Mg. The experimental results demonstrated that the conversion of molybdenum tailings into Si-Ca-K-Mg fertilizer was a viable and effective approach.

Keywords: Acid soil; cherry radish growth; Si-Ca-K-Mg fertilizer; soil nutrients

ABSTRAK

Tanah berasid bertebaran secara meluas di selatan China, memberikan pengaruh buruk terhadap pertumbuhan tanaman. Gred sumber bijih molibdenum di China agak rendah dan sejumlah besar amang dijana semasa proses pemanfaatan, yang menimbulkan ancaman besar kepada alam sekitar. Kesan penggunaan untuk menukar amang molibdenum kepada baja Si-Ca-K-Mg pada tanaman dan tanah berasid telah dikaji. Dalam penyelidikan ini, kami menggunakan lobak ceri dan tanah berasid di selatan China sebagai bahan uji kaji, uji kaji pasu selama 3 bulan telah dijalankan untuk mengkaji kesan penggunaan baja Si-Ca-K-Mg sebagai pindaan tanah pada tanah berasid dan kesan menggalakkan pertumbuhannya pada lobak ceri. Keputusan menunjukkan bahawa penggunaan baja Si-Ca-K-Mg dengan ketara meningkatkan penunjuk pertumbuhan tumbuhan lobak ceri, merangkumi panjang, berat dan kandungan klorofil. Kecekapan penggunaan Ca, K dan Mg dalam kumpulan rawatan adalah jauh lebih tinggi daripada kumpulan kawalan. Manakala, penggunaan baja memudahkan penyerapan nitrogen (N) dan fosforus (P). Selain itu, baja Si-Ca-K-Mg secara berkesan boleh meningkatkan penunjuk utama dalam tanah, seperti nilai pH, kapasiti pertukaran kation (CEC), Si tersedia, K, Ca dan Mg. Keputusan uji kaji menunjukkan bahawa penukaran amang molibdenum kepada baja Si-Ca-K-Mg adalah pendekatan yang berdaya maju dan berkesan.

Kata kunci: Baja Si-Ca-K-Mg; nutrien tanah; pertumbuhan lobak ceri; tanah berasid

INTRODUCTION

Soil amendments, also referred to as soil regulators, are capable of effectively enhancing soil properties and augmenting its fertility (Garbowski et al. 2023). Currently, the prevalent types encompass organic amendments (Scott et al. 2020), mineral amendments (Radziemska et al. 2020), microbial amendments (Nuzzo et al. 2020), and chemical amendments (Yoon et al. 2019). Among these, minerals such as wollastonite, phosphate rock powder, and gypsum are capable of increasing the inorganic components in the soil, optimizing the soil structure, thereby enhancing fertility, aeration, and water retention capacity. As a result, they have garnered extensive attention from researchers and have been extensively applied in agricultural production in multiple regions on a large scale. For instance, Tan et al. (2019) prepared Si-Ca-K-Mg fertilizer through the mixed calcination of K-feldspar and phosphogypsum, to enhance the yield and quality of tobacco leaves. Additionally, Zheng et al. (2024) discovered that using natural oyster as soil amendments could significantly increase the biomass of tomato seedlings and concurrently enhance the contents of organic matter, available P, and exchangeable salts in the soil. The research conducted by Panhwar et al. (2016) indicated that the application of basalt not only facilitated the output of rice but also improved the survival rate of plants. Regarding the influence of basalt on crops, Skov et al. (2024) also carried out similar studies. They applied crushed basalt to spring oat cultivation, resulting in an increase in the dry-weight yield of spring oats by 20.5%. Liu et al. (2017) combined the use of humic acid, gypsum, and N-fertilizer, achieving a 10.4% growth in rice grain yield and simultaneously reducing methane emissions by 70%.

According to Chinese standard of T/CI 015-2023 (Technical Guidelines for Soil Formation of Typical Bulk Solid Wastes), if the pH value of the soil is within the range of 4.5 to 5.2, it is defined as mildly acidic soil. There are many factors that contribute to the formation of acidic soil, among which strong rainfall-induced alkaline cation loss (Wang et al. 2021) and improper fertilization patterns (Augustin & Buetow 2024) are the causes of accelerating the soil acidification process. Soil acidification can lead to soil crusting at the surface (Tusar et al. 2023), nutrient deficiency, and a decline in crop yields and productivity (Garbowski et al. 2023). The acidified soil area in southern China is 2.18 million square kilometers, accounting for 22.7% of China's total land area (Zhao et al. 2023), and the solution to this problem is urgently needed. Research findings show that mineral soil amendments have significant effects on improving acidic soil (Abdul Halim et al. 2018) and helping to restore the fertility and vegetative productivity of degraded soil (Albuquerque et al. 2021). Shamshuddin et al. (2011) used ground granite to increase the pH value and Ca, Mg, K, and P concentrations in the soil, and increase the cation exchange capacity, thereby enhancing soil fertility. Ramos et al. (2017) found that vermiculite contains large amounts of key cation elements such as Ca, K, and Mg, and can be used in poor acidic soil to significantly increase soil nutrient content. Researchers have demonstrated that the combination of beetroot residue and gypsum results in an increase in pH, Ca content, and total organic carbon in the soil, while simultaneously reduces the toxicity of Al^{3+} ions in the soil layer up to 0.50 m. The mixture of beetroot residue and gypsum has been found to be an effective method for reducing the toxicity of Al^{3+} ions in the soil layer (Hontoria et al. 2018).

Among numerous mineral soil amendments, the Si-Ca-K-Mg fertilizer fabricated from molybdenum tailings holds substantial significance in the improvement of soil for crop growth. On one hand, the grade of molybdenum ore resources in China is relatively low (Zhang et al. 2020), and a considerable amount of tailings are produced during the beneficiation process (Bai et al. 2019), which profoundly affects the surface layer of the original soil and leads to the contamination of the surrounding soil by toxic substances (Hu et al. 2024a). To control the detrimental impact of molybdenum tailings on the environment, one approach is to convert them from waste to valuable resources by transforming them into mineral soil amendments, and scholars have made corresponding research advancements (Xu, Gao & Meng 2018) in this regard. On the other hand, molybdenum (Mo), as a trace element essential for the human body (Kuang et al. 2024), is reported to be capable of effectively enhancing the yield, quality, and N-fertilizer utilization efficiency of various crops (Banerjee & Nath 2022); nevertheless, the high price of molybdenum (Shao & Zhang 2020) restricts its application in the agricultural domain. In previous research, we innovatively carried out research on the preparation of Si-Ca-K-Mg fertilizer from molybdenum tailings (Li et al. 2024). However, the relevant research reports on the preparation of Si-Ca-K-Mg fertilizer from molybdenum tailings, including our previous research work, focus mainly on the preparation method of fertilizer and its formation process and mechanism, but the beneficial effects of the fertilizer on plants and soil are rarely reported.

Therefore, the objective of this study was to investigate the growth-promoting effect of Si-Ca-K-Mg fertilizer prepared from molybdenum tailings on cherry radish in typical acidic soil in southern China. Furthermore, the improvement effect of physical and chemical properties of the soil in planting process is analyzed in depth. It is expected to provide basic data for the improvement of plant growth quality and acidic soil properties by Si-Ca-K-Mg fertilizer prepared from molybdenum tailings, and provide new insights for the application of tailings resources in agricultural field.

MATERIALS AND METHODS

EXPERIMENTAL MATERIALS

Compositional Analysis of Molybdenum Tailings

In this experiment, the Si-Ca-K-Mg fertilizer was prepared using molybdenum tailings (from Hebei province, China), and the chemical composition analysis (Table 1) shows that it contains 8.461% K_2O and a suitable amount of Si, Ca and Mg. The XRD analysis result (Figure 1(a)) indicates that this tailings mainly comprises minerals such as K-feldspar ($KAlSi_3O_8$), albite ($NaAlSi_3O_8$), dolomite ($CaMg(CO_3)_2$), and quartz (SiO_2). Due to the relatively stable crystal structures of K-feldspar, albite, and quartz (Figure 1(b), 1(c) & 1(d)), their nutrient components are hardly absorbed effectively by plants under weak acid conditions. However, these minerals provide the compositional basis for the preparation of qualified Si-Ca-K-Mg fertilizer. In addition, the contents of heavy metals in the molybdenum tailings are very low, which ensures that the content of harmful elements in prepared fertilizer can meet the specified requirements.

Additives for the Preparation of Fertilizer

Limestone ($CaCO_3$) and anhydrite ($CaSO_4$) were used as the additives, both of these high-purity raw materials were commercially supplied and used without further purification.

Soil for Planting

The experimental site located at Central South University in Changsha, Hunan Province. This area falls under the subtropical monsoon climate, featuring an annual average temperature of 19.6 °C and an annual precipitation of 1674 mm. Meanwhile, the precipitation from April to August accounts for 69.3% of the total annual precipitation (Hu et al. 2024b). The soil employed in the experiment was sourced from Changsha with a pH value of 4.92, which is a typical of acidic soil. The fundamental properties of soil were presented in Table 2.

Vegetable Seeds and Basic Fertilizers

Cherry radish was used to evaluate the performance of Si-Ca-K-Mg fertilizer in this experiment. Urea and ammonium dihydrogen phosphate (DAP) are used as basic fertilizers to ensure the normal plant growth.

PREPARATION AND CHARACTERIZATION OF Si-Ca-K-Mg FERTILIZER FROM MOLYBDENUM TAILINGS

Experimental Conditions and Preparation Process

The preparation of Si-Ca-K-Mg fertilizer was conducted following the experimental conditions outlined by Li et al. (2024). Specifically, the molybdenum tailings, limestone and anhydrite are homogeneously mixed in a mass ratio of 1:0.7:0.2 and calcined at 1200 °C for 120 min. After cooling, the calcined product is ground to obtain the Si-Ca-K-Mg fertilizer in powder form.

Characterization of the Product

The XRD pattern of the prepared Si-Ca-K-Mg fertilizer is shown in Figure 2(a), in which the main minerals are kaliophilite ($KAlSiO_4$), wollastonite ($CaSiO_3$), gehlenite ($Ca_2Al_2SiO_7$), akermanite ($Ca_2MgSi_2O_7$) and arcanite (K_2SO_4), and their crystal structures are shown in Figure 2(b)-2(f). These minerals can be dissolved in weak acids soil, providing nutrients for plants such as K, Mg, Si, and Ca. Table 3 shows the analysis results of the effective element and heavy metal content of the prepared Si-Ca-K-Mg fertilizer, it can be seen that the contents of effective K_2O, Ca, Mg, and Si are 3.58%, 24.72%, 2.59% and 14.71%, respectively, which meet the specified values of the Type I product in the national standard GB/T 36207-2018 (Fertilizer of Calcium Silicon Magnesium Potassium). Meanwhile, the contents of Pb, As, Hg, Cd, and Cr are far below the standard requirements, suggesting that a high quality of Si-Ca-K-Mg fertilizer is prepared from molybdenum tailings.

Experimental Design and Potted Plant Experiment Management

The experiment was conducted from April to July 2024. We categorized the experiment into four groups, encompassing the control group and the treatment groups T1, T2, and T3. The principal distinction among the groups lay in the application dosage of Si-Ca-K-Mg fertilizer. The specific experimental configuration is elaborated in Table 4. The flowerpot has a height of 15 cm, its upper and lower surfaces are rectangular, with dimensions of 50×20 cm and 40×12 cm, respectively. The total volume of each pot is approximately 10,000 cm^3. Each pot is filled to approximately half its capacity with roughly 8 kg of soil. Each group comprises two flower pots, with seven plants cultivated in each pot, resulting in a total of 14 plants per group. Cherry radish seedlings were planted in each pot after 5 days after germination with approximately 5 cm in height, and had the same growth vigor. The fertilizer was mixed thoroughly with the surficial to a depth of 2-3 cm, and water was added until the soil was saturated. In planting period, the weeds were removed manually, and no pesticides were used.

SAMPLE COLLECTION AND ANALYSIS

This study investigates the effects of Si-Ca-K-Mg fertilizer on the growth and development of cherry radish. Data processing and statistical analysis were performed using Microsoft Excel 2019 and SPSS Statistics 27.0. Based on the appearance and growth cycle of the cherry radish plants, the harvest was conducted on the 90th day after planting. The procedure for selecting cherry radishes

TABLE 1. Molybdenum tailings chemical composition (wt.%)

Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Fe_2O_3	PbO	P_2O_5
2.863	6.213	10.697	58.963	8.461	9.942	0.278	4.575	0.005	0.083
SO_3	Cl	MnO	CuO	ZnO	Rb_2O	SrO	Y_2O_3	CeO_2	MoO_3
0.336	0.045	0.181	0.009	0.049	0.006	0.012	0.001	0.091	0.004

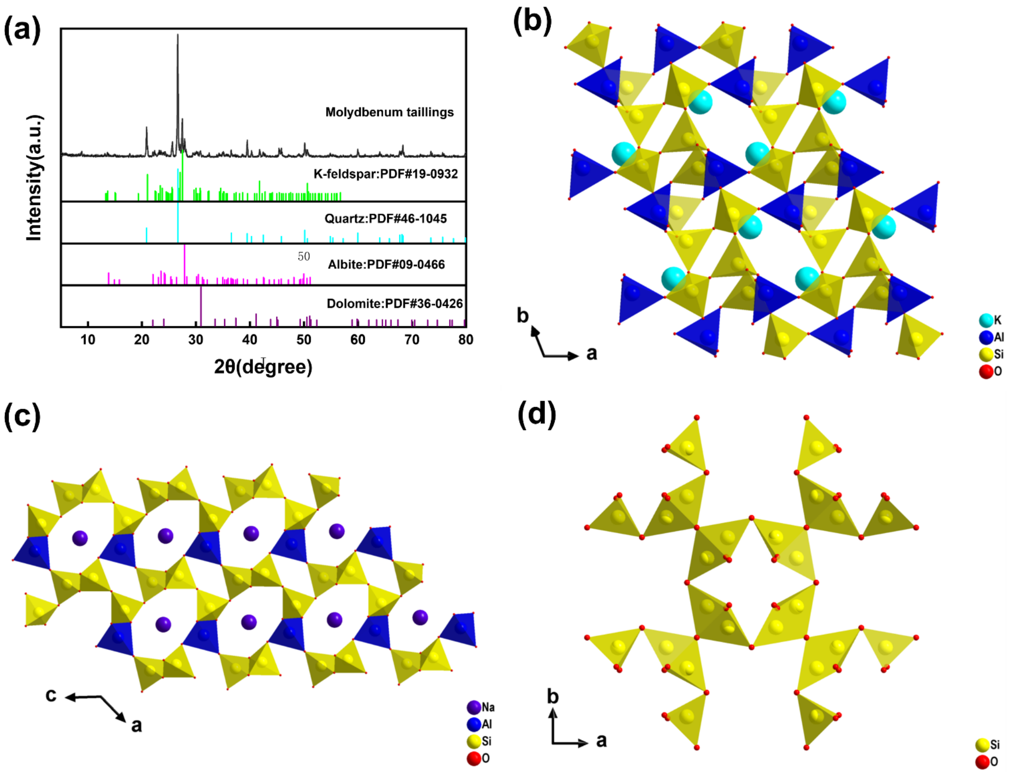

FIGURE 1. XRD pattern of molybdenum tailings (a) and crystal structures of K-feldspar (b), albite (c) and quartz (d)

TABLE 2. Fundamental properties of the test soil

Index	pH	CEC (cmol/kg)	Available Si (g/kg)	Available K (g/kg)
Content	4.92	5.432	0.081	0.133
Index	Available Ca (g/kg)	Available Mg (g/kg)	Organic matter (%)	Water content (%)
Content	7.787	1.63	0.83	28.38

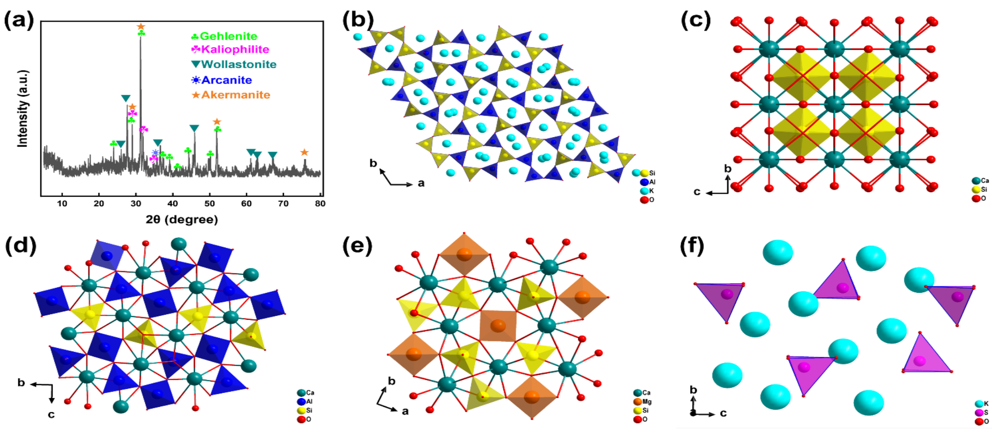

FIGURE 2. XRD pattern of Si-Ca-K-Mg fertilizer (a) and crystal structures of major minerals in the fertilizer (b. Kaliophilite, c. Wollastonite, d. Gehlenite, e. Akermanite, f. Arcanite)

TABLE 3. Indicators of Si-Ca-K-Mg fertilizer

Index	Si-Ca-K-Mg fertilizer prepared from molybdenum tailings	National Standard (GB/T 36207-2018)	
		Type I	Type II
Activated K_2O/wt.%	3.58	3.00	3.00
Activated Ca/wt.%	24.72	20.00	14.00
Activated Mg/wt.%	2.59	2.00	2.00
Activated Si/wt.%	14.71	9.00	6.00
pH	8.77	8.0~11.0	
Pb/ wt. %	0.0047	0.0200	
As/ wt. %	0.0010	0.0050	
Hg/ wt.%	0.00003	0.0005	
Cd/ wt. %	0.0006	0.0010	
Cr/ wt. %	0.0009	0.0500	

TABLE 4. Fertilizer dosage control for planting experiment

Treatment groups	Basic fertilizer dosage (g/plant)		Si-Ca-K-Mg fertilizer dosage (g/plant)
	ADP	Urea	
Control	0.16	0.16	0
T1	0.16	0.16	0.5
T2	0.16	0.16	1.0
T3	0.16	0.16	1.5

was as follows: From each group of plants, excluded the four most vigorous and the four least vigorous individuals. Six plants that exhibited uniform growth were selected to further analysis. Chlorophyll content in fresh leaves was measured using visible spectrophotometry (model BC0990). The concentrations of N, P, K, Mg, and Ca in dried cherry radishes were determined following digestion by the Kjeldahl method for N, the vanadium-molybdate yellow colorimetric method for P, and atomic absorption spectrometry for K, Mg, and Ca, respectively.

To evaluate the efficacy of Si-Ca-K-Mg fertilizer in improving acidic soil, the key soil indicators were analyzed following the harvest of cherry radish. Soil samples were collected from five distinct points at a depth of 0 to 7.5 cm within the flowerpot for property analysis. In total, about 500 g of soil was collected for each group. Before detection, soil was mixed uniformly, dried and ground to powder.

The indicators that needed to be measured for the soil include pH value (referenced to NY/T 1121.2-2006), cation exchange capacity (referenced to HJ 889-2017), available Si (referenced to NYT 1121.15-2006), available K (referenced to NY/T 889-2004), available Ca and Mg (sum of water-soluble and exchangeable Ca and Mg referenced to NY/T 3242-2018 and NY/T 1121.13-2006).

RESULTS AND DISCUSSION

APPLICATION EFFECT OF Si-Ca-K-Mg FERTILIZER ON CHERRY RADISH CULTIVATION

The Impact on the Growth and Development of Cherry Radish

The yield and quality of agricultural products are direct indicators for evaluating fertilizer performance. Commonly used key metrics for evaluating the growth performance of plants treated with fertilizer include plant height, root length, leaf width, fresh weight, dry weight, as well as the content of essential elements and chemical components (Sim et al. 2021). Plant length constitutes one of the significant characteristics for assessing crop growth (Brouwer-Brolsma et al. 2020). As depicted in Figure 3(a), with the escalating application dosage of Si-Ca-K-Mg fertilizer, the cauline leaf length and total length of the cherry radish gradually rose, while the root length exhibited a gradually diminishing trend. Specifically, the T3 treatment group exhibited the greatest plant length, cauline leaf length, and root length, measuring 38.06±2.48 cm per plant, 31.34±3.02 cm per plant, and 6.72±0.91 cm per plant, respectively. Compared to the control group, the plant length and cauline leaf length of the cherry radish in the T3 treatment group were 1.37 times and 1.72 times greater, respectively. Conversely, the root length of the control group was 1.43 times that of the T3 treatment group.

Root diameter and leaf width serve as critical parameters in assessing the growth and development of plants (Bi et al. 2023; Henningsen et al. 2023). The root diameter of the cherry radish was measured as shown in Figure 3(b). As the application rate of Si-Ca-K-Mg fertilizer increased, the root diameter of cherry radish progressively enlarged. In the T3 treatment group, the root diameter reached 2.18±0.15 cm/plant, which was 6.10 times that of the control group. The application of Si-Ca-K-Mg fertilizer has been observed to significantly promote root system development. This may be attributed to role of K in activating the cell membrane proton pump, maintaining cellular turgor pressure, and promoting the division and elongation of root meristem cells, thereby directly influencing root thickening growth (Sustr, Soukup & Tylova 2019). Moreover, an appropriate leaf width can effectively enhance the absorption and transformation of light energy by plants, which holds significant meaning in biology. According to Figure 3(b), the application of Si-Ca-K-Mg fertilizer in all experimental groups (T1, T2, and T3) promoted the growth of the leaf width of cherry radish. Among them, the leaf width of T3 treatment group was the largest, reaching 8.82 ±1.31 cm, which was 1.56 times that of the control group. The application of Si-Ca-K-Mg fertilizer has been observed to promote the widening of leaves. This effect may be attributed to role of Mg in enhancing photosynthetic efficiency, regulating cellular expansion, and facilitating the coordinated absorption of nutrients, all of which indirectly contribute to the development of broader leaf structures (Li et al. 2023, 2020).

According to Table 5, the application dosage of Si-Ca-K-Mg fertilizer had a significant promoting effect on the fresh weight, dry weight, cauline leaf fresh weight, cauline leaf dry weight, root fresh weight, and root dry weight of cherry radish plants. The average fresh weight of the control group plants was 5.4±0.94 g/plant, the dry weight was 0.95 ±0.09 g/plant, the cauline leaf fresh weight was 5.22±0.78 g/plant, the cauline leaf dry weight was 0.92±0.08 g/plant, the root fresh weight was 0.18±0.06 g/plant, and the root dry weight is only 0.03±0.02 g/plant, respectively. Correspondingly, compared with the control group, these indicators of the T3 treatment group exhibited increases of 78.77%, 59.57%, 76.81%, 56.19%, 93.98%, and 88.00%, respectively. These results indicated that the application of Si-Ca-K-Mg fertilizer can significantly enhance the biomass of cherry radish. This may be attributed to K and Mg from Si-Ca-K-Mg fertilizer can enhance the photosynthesis of plants and promote the accumulation of carbohydrates in plant (Raza et al. 2019). Additionally, increasing the contents of K and Mg in the soil can facilitate the absorption of N and P, and other nutrients elements by plants, thereby promoting plants growth (Oldroyd & Leyser 2020; Senbayram et al. 2015; Soumare, Sar & Diédhiou 2023). The data analysis from Tables 6 and 7 show that the contents of N and P elements in the plants exhibited a positive correlation with the weight of cherry radish plants, which was consistent with the results.

The chlorophyll content in the leaves of cherry radish is a significant indicator reflecting the intensity of its photosynthetic activity (Moynier & Fujii 2017), and the dry matter of cherry radish is mainly generated through photosynthesis in the leaves. The chlorophyll a and chlorophyll b contained in the leaves are capable of effectively collect light energy and converting it into chemical energy to form organic substances (Sineshchekov & Belyaeva 2019). The chlorophyll contents of plants in the control, T1, T2, and T3 treatment groups were measured. As shown in Figure 4, the chlorophyll, chlorophyll a, and chlorophyll b contents in the control group were 2.01±0.01 g/kg, 1.47±0.02 g/kg, and 0.54±0.01 g/kg, respectively. After the application of Si-Ca-K-Mg fertilizer, the chlorophyll content had a significantly increase. Particularly, in T3 treatment group, chlorophyll, chlorophyll a, and chlorophyll b contents increased by 29.85%, 20.41%, and 55.56%, respectively. Notably, the content of chlorophyll in the leaves exhibited a positive correlation with the content of Mg. Si-Ca-K-Mg fertilizer can provide abundant availability Mg that is an important component of chlorophyll. It will affect the normal physiological functions of plants when Mg deficiency, and thereby inhibiting the growth of roots and stems, resulting in the chlorosis and necrotic lesions and subsequently reduction of crop yield (Guo et al. 2024; Zhang et al. 2023).

THE EFFECT OF Si-Ca-K-Mg FERTILIZER ON THE NUTRIENT CONTENT, ABSORPTION, AND UTILIZATION EFFICIENCY IN CHERRY RADISH

The major elements essential (Ca, K, Mg, P, and N) play specific functions in maintaining the normal metabolism of plants. Ca is a fundamental component of cell walls, contributing to cell division and signal transduction. Deficiency in Ca causes malformation in new leaves and death of terminal buds (de Bang et al. 2021). K enhances plant resilience against environmental stresses such as drought, pests, and diseases, while also regulating stomatal function. K deficiency leads to leaf margin necrosis and increased susceptibility to lodging (Johnson et al. 2022). Mg, a central element in chlorophyll, activates various enzymes and its deficiency results in interveinal chlorosis in older leaves (Guo et al. 2016). P plays a critical role in root development, flower and fruit maturation, and energy metabolism through adenosine triphosphate production. A deficiency in P results in weakened root systems and smaller fruits (Heydari, Brook & Jones 2019). N is essential for the growth of branches and leaves, as well as for chlorophyll synthesis. When plants lack nitrogen, the leaves exhibit chlorosis and the overall plant growth becomes stunted

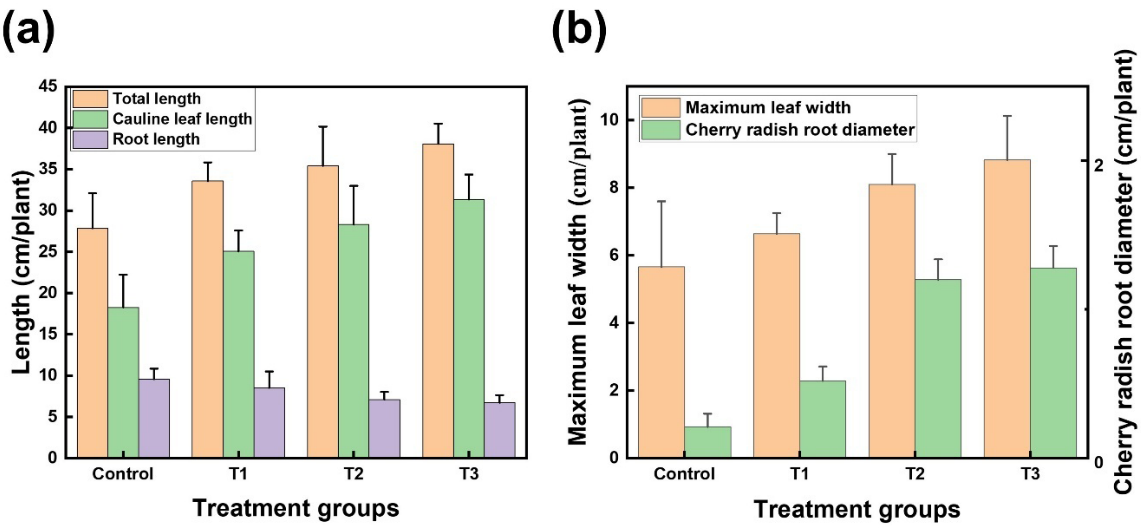

FIGURE 3. Lengths of cherry radish plants (a) and Root diameter of cherry radish plants, maximum leaf width of cherry radish plants (b)

TABLE 5. Average weight of cherry radish in each group (g/plant)

Treatment groups	Control	T1	T2	T3
Total fresh weight	5.40±0.94	10.25±0.82	21.20±0.13	25.44±0.73
Root fresh weight	0.18±0.06	0.59±0.05	2.91±0.06	2.93±0.80
Cauline leaf fresh weight	5.22±0.78	9.66±0.32	18.29±0.54	22.51±0.42
Total dry weight	0.95±0.09	1.13±0.04	2.22±0.08	2.35±0.02
Root dry weigh	0.03±0.02	0.04±0.04	0.23±0.02	0.25±0.06
Cauline leaf dry weight	0.92±0.08	1.09±0.06	1.99±0.11	2.10±0.03

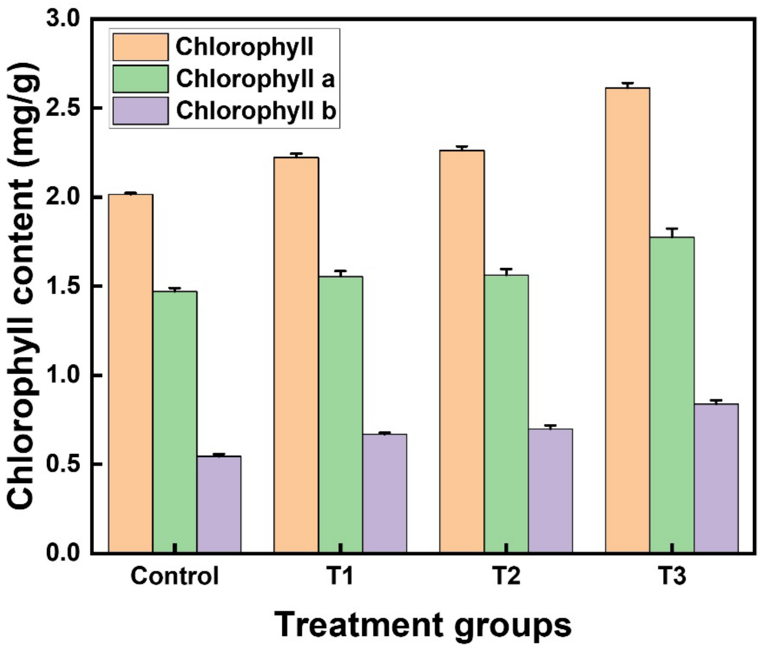

FIGURE 4. Chlorophyll content in cherry radish leaves

(Liu et al. 2022). As can be observed from Table 6, with the increasing dosage of the Si-Ca-K-Mg fertilizer, the contents of Ca, K, Mg, P, and N in the roots and cauline leaves of cherry radish plants generally exhibited an upward trend. The Ca content in the cherry radish plants of the control group was 34.59±1.19 g/kg, which was 1.61 times lower than that of the T3 treatment group. Meanwhile, the Ca content in the leaves was significantly higher than that in the roots. Similarly, the Mg content in the leaves was 98.02% higher than that in the roots. This indicated that the Ca and Mg contents were mainly distributed in the leaves. Ca is primarily responsible for reinforcing the structural integrity of leaves and enhancing stress resistance in both stems and leaves, whereas Mg plays a crucial role in facilitating photosynthesis and energy metabolism. Conversely, the K content in the roots was 34.00% higher than that in the leaves. Moreover, the contents of N and P in the cherry radish plants with treatment of Si-Ca-K-Mg fertilizer were significantly higher than those in the control group, indicating that the application of the Si-Ca-K-Mg fertilizer can facilitate the absorption of N and P by the crops. Cakmak (2010) reported that the addition of K and Mg would enhance the adsorption capacity of N and P by plant.

The absorption amounts of Ca, K, Mg, P, and N were all significantly higher than those of the control group. As presented in Table 7, the Ca, K, Mg, P, and N absorption amounts in the roots of the T3 treatment group were 2.54±0.01 mg/plant, 6.86±0.12 mg/plant, 0.92±0.02 mg/plant, 1.84±0.10 mg/plant, 8.44±0.03 mg/plant, respectively. Among them, the absorption amounts of these elements in the leaves were 37.41 times, 6.67 times, 16.86 times, 10.21 times and 10.54 times those of the root systems, respectively. The application of Si-Ca-Mg-K fertilizer significantly promoted the accumulation of nutrients in leaves.

The utilization efficiency of Ca, K, and Mg elements is defined as the ratio of the difference in absorption between the area where Si-Ca-K-Mg fertilizer is applied and the blank control area to the total amount of fertilizer applied. Studying the utilization efficiency of Ca, K, and Mg elements in plants is conducive to understanding the roles of these nutrients in the process of plant growth and development, as well as how to optimize plant growth conditions and increase yields by regulating their absorption (Sun et al. 2024). As presented in Table 8, with the increasing application rate of Si-Ca-K-Mg fertilizer, the utilization efficiency of Ca, K, and Mg by cherry radish plants initially increased and subsequently decreased. Treatment group T2 exhibited the highest utilization efficiencies for Ca, K, and Mg, reaching 26.58±0.53%, 87.35±4.23%, and 32.91±0.40%, respectively. The reason why treatment group T3 did not exhibit the highest utilization efficiency was that the plant's nutrient absorption capacity was inherently limited, leading to saturation when excessive fertilizer was applied.

THE EFFECT OF APPLYING Si-Ca-K-Mg FERTILIZER ON PLANTING SOIL

Soils with the pH value below 5.5 or above 7.5 are generally unsuitable for plant growth (Khaled & Sayed 2023). The pH value of the soil used in this experiment was 4.92, which was typical of acidic soil. It is difficult for cherry radishes to grow in this soil. As indicated in Figure 5, with the increase in the application amount of Si-Ca-K-Mg fertilizer, the overall soil pH value significantly rose. The pH value in the T3 treatment group was measured

TABLE 6. Nutrient content of dried cherry radish plants (g/kg)

Plant part	Treatment groups	Nutrient element content				
		Ca	K	Mg	P	N
Root	Control	7.19±0.22	24.88±0.50	3.03±0.12	6.21±0.05	24.60±0.16
	T1	9.80±0.95	25.62±0.07	3.24±0.04	6.97±0.10	29.05±0.72
	T2	10.09±0.20	26.53±0.25	3.43±0.02	6.98±0.07	32.31±0.65
	T3	10.33±0.05	27.46±0.89	3.67±0.09	7.35±0.05	33.76±0.12
Cauline leaf	Control	27.4±1.11	16.42±0.07	6.00±0.07	8.48±0.09	25.73±0.58
	T1	32.28±1.69	16.55±0.35	6.33±0.14	8.63±0.09	30.08±0.67
	T2	44.61±0.98	17.96±0.67	6.71±0.07	8.74±0.07	39.71±0.65
	T3	45.22±0.84	21.78±0.84	7.38±0.04	8.94±0.09	42.32±0.40
Cherry radish plant	Control	34.59±1.19	41.30±0.61	9.03±0.14	14.69±0.10	50.33±0.73
	T1	42.08±1.76	42.18±0.10	9.57±0.16	15.60±0.17	59.13±1.10
	T2	54.71±1.13	44.49±0.77	10.13±0.06	15.72±0.12	72.02±1.29
	T3	55.55±0.89	49.24±1.20	11.05±0.12	16.29±0.05	76.08±0.33

TABLE 7. Nutrient absorption of dried cherry radish plants (mg/plant)

Plant part	Treatment groups	Nutrient element absorption content				
		Ca	K	Mg	P	N
Root	Control	0.22±0.01	0.75±0.02	0.09±0.04	0.19±0.01	0.74±0.02
	T1	0.43±0.04	1.13±0.01	0.14±0.02	0.31±0.04	1.29±0.03
	T2	2.34±0.05	6.18±0.03	0.80±0.03	1.62±0.02	7.50±0.15
	T3	2.54±0.01	6.86±0.12	0.92±0.02	1.84±0.10	8.44±0.03
Cauline leaf	Control	25.23±1.02	15.12±0.04	5.53±0.06	7.81±0.09	23.94±0.43
	T1	35.24±1.84	18.07±0.05	6.91±0.16	9.42±0.09	32.84±0.73
	T2	88.79±1.94	35.74±1.34	13.35±0.14	17.40±0.15	79.04±1.29
	T3	95.02±1.77	45.76±1.76	15.51±0.09	18.78±0.18	88.93±0.84
Cherry radish plant	Control	25.44±1.02	15.86±0.05	5.62±0.06	8.00±0.09	24.68±0.43
	T1	35.67±1.83	19.21±0.05	7.05±0.16	9.73±0.10	34.12±0.74
	T2	91.14±1.98	49.92±1.31	14.14±0.13	19.02±0.15	86.64±1.44
	T3	97.56±1.78	52.62±1.84	16.43±0.10	20.62±0.17	97.37±0.82

TABLE 8. The utilization efficiency of K, Ca and Mg element in cherry radish plants (%)

Plant part	Treatment groups	Nutrient element utilization efficiency		
		Ca	K	Mg
Root	T1	0.18±0.03	2.60±0.11	0.41±0.04
	T2	0.86±0.02	18.22±0.14	2.72±0.01
	T3	0.64±0.01	13.67±0.24	2.13±0.07
Cauline leaf	T1	8.10±1.32	19.79±0.42	10.66±1.11
	T2	25.71±0.51	69.13±4.36	30.19±0.47
	T3	18.82±0.72	68.48±3.88	25.69±0.38
Cherry radish plant	T1	8.28±1.30	22.39±0.53	11.07±1.08
	T2	26.58±0.53	87.35±4.23	32.91±0.47
	T3	19.46±0.72	82.15±4.02	27.82±0.40

at 6.91±0.01, representing a 9.86% increase compared to the control group. There are two primary reasons for the increase in soil pH following the application of Si-Ca-K-Mg fertilizer. First, the fertilizer exhibited alkaline properties with a pH value of 8.77, which effectively neutralized acidic soils. Second, during the cultivation period of cherry radishes in Changsha, the city experienced prolonged periods of heavy rainfall, particularly in April and June, with recorded precipitation amounts of 145.5 mm and 393.9 mm, respectively (Weather 2024). Our measurements indicated that the average pH value of the rainwater during this period was 6.02.

Cation exchange capacity (CEC) serves as a critical indicator for assessing retain positively charged ions of the soil, which directly influences its structural stability, nutrient availability, and pH value (Zhang et al. 2021). Under acidic conditions, the elevated concentration of hydrogen ions on the surface of soil colloids leads to partial neutralization of negative charges, thereby reducing the CEC (Barrow & Hartemink 2023). Following the application of Si-Ca-Mg-K fertilizer, the soil pH increases, resulting in an increase in the number of negative charges on the soil colloids' surface, thus enhancing the CEC. In this study, the initial CEC of the soil was rated as extremely deficient according to the T/CI 015-2023 standard. However, the application of Si-Ca-K-Mg fertilizer effectively raised the CEC from 5.432 cmol/kg before the experiment to 9.394±0.081 cmol/kg in T3 treatment group, having a significantly increase (Figure 5). Overall, the application of Si-Ca-K-Mg fertilizer can enhance the pH value and CEC of the acidic soil, thereby providing a favorable soil environment for crop growth.

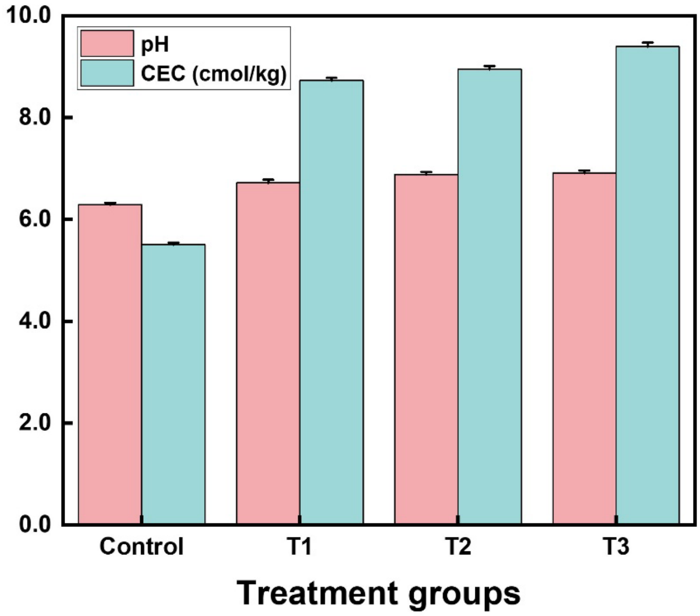

FIGURE 5. Effect of application of Si-Ca-K-Mg fertilizers on pH value and CEC

TABLE 9. Effect of application of Si-Ca-K-Mg fertilizers on available elements in soil (g/kg)

Available elements content	Treatment groups			
	Control	T1	T2	T3
Available Si	0.076±0.003	0.175±0.004	0.292±0.002	0.310±0.012
Available K	0.131±0.002	0.134±0.002	0.138±0.003	0.143±0.003
Available Ca	7.687±0.127	8.197±0.218	8.900±0.046	9.327±0.064
Available Mg	1.569±0.046	2.475±0.071	2.492±0.0913	2.934±0.068

The available Si in the soil plays a crucial role in regulating soil pH and preventing soil acidification and hardening (Barman et al. 2023). As depicted in Table 9, the application of Si-Ca-K-Mg fertilizer can significantly enhance the available Si of the soil. The available Si content increased from 0.081 g/kg before the experiment to 0.310 ± 0.012 g/kg in the T3 treatment group, which was 4.08 times higher than that of the control group. Si-Ca-K-Mg fertilizer could release activated Si to enhance the overall content of available Si in the soil.

As can be observed from Table 9, the application of Si-Ca-K-Mg fertilizer significantly enhanced the content of available K in the soil. The content of available K in the T3 treatment group was the highest, reaching 0.143±0.003 g/kg. A portion of the Si-Ca-K-Mg fertilizer dissolves to form available K, while the remaining fraction converts into citric soluble K that provides sustained nutrient supply to plants over an extended period.

Soil available Ca and Mg play significant roles in soil physicochemical properties as well as plant growth (Bedel et al. 2018; Osemwota, Omuet & Ogboghodo 2007). As shown in Table 9, the contents of available Ca and Mg in T3 treatment group were 9.327±0.064 g/kg and 2.934±0.068 g/kg, representing increases of 21.33% and 87.00% compared to the control group, respectively. The soluble gehlenite and akermanite in the Si-Ca-K-Mg fertilizer provided abundant Ca and Mg elements. Additionally, these mineral components effectively mitigated the loss of available Ca and Mg from the soil during periods of heavy rainfall. Generally speaking, the application of Si-Ca-K-Mg fertilizer enhanced the nutrient components of the cultivated soil for promoting the process of crop growth and development.

CONCLUSIONS

The Si-Ca-K-Mg fertilizer prepared from molybdenum tailings was a mineral-type alkaline fertilizer, rich in essential nutrients such as Si, Ca, K, Mg, Mo, Cu, and Fe for plants. In this paper, compared with the control group, the application of this fertilizer in the treatment groups resulted in significant increases in the fresh weight, chlorophyll content, and other biomass parameters of cherry radish. Specifically, the fresh weight in the T3 treatment group was 4.71 times that of the control group. Additionally, the contents of Ca, Mg, K, P, and N in the cherry radish were also elevated. Furthermore, in terms of soil, we discovered that the Si-Ca-K-Mg fertilizer prepared from molybdenum tailings exhibited a notable improvement effect on acidic soil within the 90-day crop growth cycle. It not only raised the pH value of acidic soil from 4.92 to 6.91±0.01 but also enhanced the cation exchange capacity from 5.432 cmol/kg to 9.394±0.081 cmol/kg. Additionally, it significantly enhanced the levels of available Si, available K, available Ca, and available Mg. Notably, the available Si content in the soil increased from 0.081 g/kg before the experiment to 0.310 ± 0.012 g/kg in the T3 treatment group, which was 4.08 times higher than that of the control group. To sum up, Si-Ca-K-Mg fertilizer is a good compound fertilizer and soil conditioner suitable for acidic soil.

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