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Effect of Lithium Slag Application on Saline–Alkali Soil Amelioration and Vegetable Growth

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Abstract: Increased attention has been attracted to saline–alkali soil amelioration due to the growing serious salinization of soils in the world. Lithium slag (LS) is an acid by-product of lithium production with potential properties to ameliorate alkalinity in saline–alkali soils. In this study, LS was reused as a saline–alkali soil amendment and potted plant experiments in a greenhouse were performed to evaluate the effect of LS application on the soil amelioration and the growth of vegetables (roquette and radish) in the saline–alkali soil during the 5-week growth period. LS was added at the amount of 0.5%, 1.0%, 2.0%, 5.0%, 8.0% and 10.0% (w/w) levels. Results showed that saline–alkali soil pH dropped obviously with the increase in LS application. Accordingly, the germination, survival and growth of roquette and radish were significantly improved by LS addition, especially at the optimum amount of 0.5% and 1.0% (w/w) in the saline–alkali soil. In contrast to the untreated saline–alkali soil, LS addition at 0.5% and 1.0% (w/w) levels increased the roquette's height by 49.7% and 36.1% and increased the radish's height by 54.6% and 53.7%, respectively. However, the soil electrical conductivity (EC) and soluble salt content increased with the addition of LS, and the salt stress induced by excessive LS (over 5.0% level) could inhibit the growth of plants. This study proposes a new way for the effective application of LS in the amelioration of saline–alkali soil in order to realize environment and resource sustainability.

Keywords: lithium slag; sustainable application; saline–alkali soil; soil amelioration; vegetable growth

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1. Introduction

Soil salinization resulting in land degradation has become a worldwide problem that limits the development of the agricultural industry and the sustainability of the ecological environment [1–4]. Saline–alkali soils usually contain alkaline salts, such as $NaHCO_3$ and Na_2CO_3, and their soil pH is above 8.5 [5]. According to the statistics data, many once-productive soils have become salt-affected wastelands, the problems of which occur within the boundaries of over 100 countries including China, Australia, India, Egypt, Iraq, Mexico, Pakistan, Syria, Turkey and the United States, etc. [6,7]. FAO has estimated the area of saline–alkali lands worldwide as 397 million ha [8]. In China, there is a large area of saline–alkali soil in coastland (>2 million ha), where seawater invasion and human activities lead to serious land deterioration [9,10]. In Australia, many areas have a higher soil pH above 8.5, particularly in the state of South Australia where there are about 30% of the saline–alkali soils affected by sodium salts and 67% of the agricultural area potentially threatened by "irrigation-induced salinization" [11]. As a significant stock land resource for crop growth, saline–alkali soils play a vital role in catering for the rising demands in agricultural production and environmental sustainability in the context of the global food crisis [12–14]. Therefore, saline–alkali soil amelioration is crucial; accordingly, increased concern has been raised to the sustainable improvement of saline–alkali soils.

As part of efforts toward remediation and amelioration of saline–alkali soils, some common chemicals, such as gypsum, calcium chloride, coal ash, biochar, polymer and organic/inorganic acids, have been applied to large areas as effective soil conditioners [15–22]. These results showed that the chemical amelioration technology can increase the soil porosity and permeability to some extent and reduce the soil pH and Na^+ toxicity [13,18]. For example, sulfuric and gypsum-related agents showed a positive impact on the rapid fall of soil pH and EC and prevented soil compaction [23,24]. Through these effects, soil physicochemical properties were improved, which were good for plant growth. However, the effects of these chemicals on plant productivity are not uniform and many chemical amendments have potential pollution risks to the soil [25].

Lithium slag (LS) is an acid solid by-product of the sulfuric acid method for preparing lithium carbonate products from petalites, spodumene or lepidolite ore through roasting, leaching, washing and filtering processing [26–28]. Along with the fast development of the lithium-based battery industry, LS quantity generation has increased sharply, which has also led to serious environmental problems [29]. Generally, every ton of lithium carbonate produced may be accompanied with about 8 to 10 tons of lithium slag [30,31]. According to statistics from Geoscience Australia, the annual amount of LS discharged from Australia was more than 300,000 tons [32]. In China, over 800,000 tons of LS are yielded annually [33]. However, LS reuse is still relatively low, with a minor share of LS applied as an admixture in cement, concrete, geopolymer and ceramic production, the remainder still being disposed of by landfill or open-air storage, presumably causing the shortage of landfills and serious environmental pollution problems [34–38]. Therefore, the efficient utilization of LS has become a hot issue that must be solved in the production of lithium carbonate, and it is also an effective approach to realize environment and resource sustainability.

Since the LS, composed of alumina, silica, calcium oxide and sulfate, is normally acidic, it is useful for regulating the alkalinity of soils. Therefore, the feasibility of ameliorating saline–alkali soil with LS was studied by a vegetable pot experiment in this study. We presented, first, the effects of LS application on pH, EC and soluble salt of the saline–alkali soil. Second, we reported the effect of LS application on the germination and survival of roquette and radish during a 5-week growth period. Finally, LS-induced changes in soil chemical properties and vegetable growth (plant height, number of leaves and biomass) were determined in the laboratory, which may offer reliable direction for the reasonable utilization of LS in the field of saline–alkali soil amelioration.

2. Materials and Methods

2.1. Materials

LS used in this experiment was the tail residue left after lithium extraction from spodumene by sulfuric acid extraction. It was obtained from Tianqi Lithium Co., Ltd., in Western Australia. The slag sample was sieved gently through a 0.074 mm mesh. It was then dried in the air-drying oven overnight. All the moisture content in the LS was assumed to be removed during that drying process.

The non-saline loam control sample was obtained from the vegetable garden in Ballarat, Australia, which was marked as the clean control check (denoted as CK0). The saline–alkali soil (denoted as CK1) was prepared by artificially mixing sodium carbonate solution with the unfertilized soil CK0. The amount of sodium carbonate added was 4.24 g per kilogram of soil. The homogeneous mixed soil was loaded in plastic bags without drains for one month in a greenhouse and its moisture content was kept at 70% of the field capacity so as to reach ion balance. After one month of aging, it was sieved gently through a 2 mm mesh after air-drying, and the soil properties are listed in Table 1.

Two types of vegetable seeds (roquette and radish seeds) were purchased from Bunnings Warehouse in Melbourne, Australia. Roquette, also known as arugula or rocket, is a green-leafed brassicaceous vegetable. Radish is a root vegetable that belongs to the Brassicaceae family too. They have mild or moderate sensitivity to salt and are often chosen to study the salt stress mechanisms in highly saline environments [39–43]. Here they were selected due to their certain saline–alkali tolerance and relatively short harvest period (about 4–6 weeks).

Table 1. Physicochemical properties of the tested soil.

Soil Samples	pH	EC (mS/cm)	Organic Matter (g/kg)	TSS (g/kg)	TN (g/kg)	TP (g/kg)	TK (g/kg)	AN (mg/kg)	AP (mg/kg)	AK (mg/kg)
CK0	6.8	0.19	15.14	3.32	1.03	0.45	12.76	60.2	15.8	88.7
CK1	9.9	0.38	15.06	6.22	1.01	0.41	12.73	60.2	15.7	88.3

2.2. Experimental Design

Potted plant experiments in a greenhouse were performed to assess the effects of LS addition on saline–alkali soil quality and the growth of roquette and radish. The greenhouse condition was day/night temperature 25 °C/23 °C, 14 h light/10 h dark and 40–70% humidity. A certain amount of LS was added into the tested saline–alkali soil (CK1) and mixed evenly. Then, 1 kg of soil was placed in a plastic flowerpot (12 cm in diameter and 10 cm in height). Before adding soil, the holes at the pot bottom were loaded with a layer of pebbles and coarse sand to ensure good drainage. Eight treatments with three replications were established: (1) CK0, the vegetable garden soil with no LS; (2) CK1, the saline–alkali soil with no LS; (3) LS0.5, CK1 with 0.5% (w/w) of LS; (4) LS1.0, CK1 with 1.0% (w/w) of LS; (5) LS2.0, CK1 with 2.0% (w/w) of LS; (6) LS5.0, CK1 with 5.0% (w/w) of LS; (7) LS8.0, CK1 with 8.0% (w/w) of LS; (8) LS10.0, CK1 with 10.0% (w/w) of LS. So as to better understand the growth of vegetables in saline–alkali soil, no additional fertilizer was added in this experiment.

Fourteen healthy roquette or radish seeds were sowed evenly in every pot for each treatment. The relative moisture of each pot of soil was kept at about 70% of the soil field capacity by daily watering. During the period of growth, the germination, survival rate, plant height and the number of leaves were determined every week. After growth for 5 weeks, shoots were harvested to measure the biomass. Furthermore, the rhizosphere soils were sampled by excavating the surface 0–5 cm soil around the roots in each pot at harvest period to determine the pH, EC and total soluble salts.

2.3. Analyses

The crystalline phases of LS were determined by a powder X-ray diffractometer (D4 Endeavor with CuKα radiation, Brucker, Mannheim, Germany). The chemical constitution of LS was confirmed by an X-ray fluorescence spectrometer (ADVANT XP, Thermos Electron Corporation, Reinach, Switzerland). The surface area (S_{BET}) of LS was determined via N_2 adsorption/desorption isotherms with an Automatic Surface Area and Porosimetry Apparatus (ASAP 2020, Micromeritics, Norcross, GA, USA) and calculated using the BET equation ($p/p_0 < 0.3$). The pH and EC were measured using a pH meter (PH-02, Paola, China) and an electrical conductivity meter (CT-3030, Kedida, Shenzhen, China) in a solid–water (1:5, w/v) suspension after 3 min of shaking, respectively [44]. Total soluble salt (TSS) was abstracted with deionized water (solid–water, 1:5, w/v) and determined with the method of dregs-drying math method, which was as follows: Firstly, 20 ml of soil leaching solution was taken into a porcelain evaporating dish and evaporated in a water bath (if there was any yellow-brown substance present, H_2O_2 was added to oxidize organic matter); secondly, it was dried in a 105–110 °C oven and then weighed to obtain the dried residue mass [44–46]. Exchangeable Na^+ and Ca^{2+} were detected by inductively coupled plasma optical emission spectroscopy (ICP-OES; Varian 720ES, Agilent, Santa Clara, CA, USA) after CH_3COONH_4 extraction [17]. Organic matter and total nitrogen (TN) were measured by elemental analyzer (FlashSmart, Thermo Scientific, Monza, Italy). Total phosphorus (TP) and total potassium (TK) were determined by molybdenum blue spectrophotometry (U-3900, Hitachi, Tokyo, Japan) and ICP-OES following mixed-acid digestion ($HClO_4$-H_2SO_4), respectively. Alkali-hydrolyzed nitrogen (AN) was estimated by alkaline hydrolysis diffusion method; available phosphorous (AP) was detected by molybdenum blue spectrophotometry following $NaHCO_3$ extraction and available potassium (AK) was tested by NH_4Ac extraction plus ICP-OES [20,44,47,48].

The height of individual roquette and radish plants above the soil were measured by a ruler. The fresh and dry weight of shoots were measured per pot after 5 weeks of growing, where dry weight referred to the constant weight after drying at 70 °C in a drying oven.

Experimental data were shown as mean ± standard deviation (SD) of three individuals ($n = 3$) and analyzed by one-way ANOVA using SPSS software (version 18.0, IBM SPSS, Armonk, NY, USA). Statistical difference was assumed at $p < 0.05$.

3. Results and Discussion

3.1. Characteristics of Lithium Slag

XRD patterns of LS are exhibited in Figure 1. The main crystal phase of LS was dilithium sulphate, quartz and aluminosilicate; a wide diffuse diffraction peak appears at 15~30°, indicating the presence of shapeless glass in the slag.

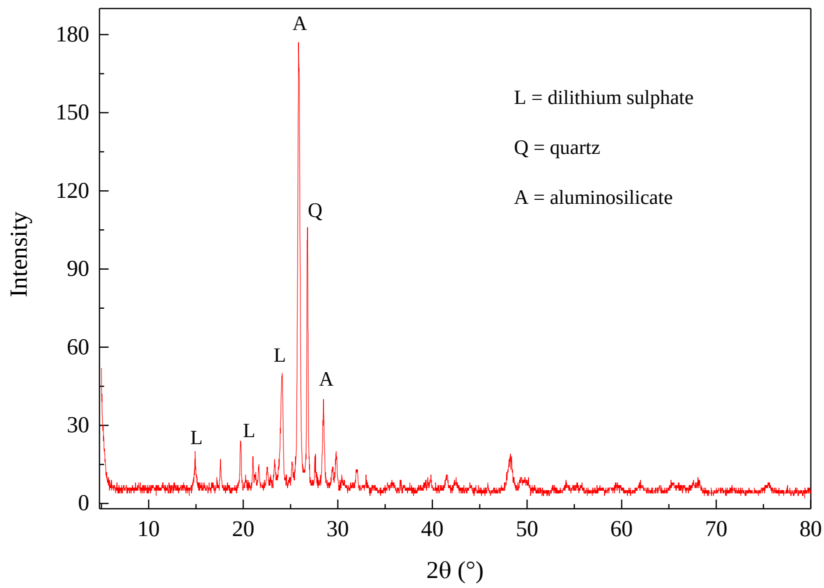

Figure 1. XRD patterns of LS used in the experiments.

The main chemical constitution of LS was determined by XRF as shown in Table 2. The slag was mainly composed of silica, alumina, sulfur oxide and calcium oxide, which was relatively similar to clay minerals, making it suitable as a soil amendment to improve soil performance. Through the analysis of LS composition, a highly chemically selective ion exchange was found between Li^+ in spodumene ($LiAlSi_2O_6$) and H^+ in H_2SO_4 solution [49], which could be explained by the following reaction equation:

$$2LiAl(SiO_3)_2\ (s) + H_2SO_4\ (L) \rightarrow 2HAl(SiO_3)_2\ (s) + Li_2SO_4\ (s) \quad (1)$$

Table 2. Main chemical constitution of LS.

Chemical Composition (%, wt)	SiO_2	SO_3	Al_2O_3	CaO	Fe_2O_3	Na_2O
	39.32	34.96	18.85	3.50	0.86	0.41

Therefore, the sulfur oxides in LS existed in the form of sulfate [50,51]. Meanwhile, the ion exchange theory could also be applied on the lithium slag, where hydrogen ions and mineral cations could dissociate easily along the Li-O covalent bonds [49]. Thus, the slag was acidic (pH = 3.9) and rich in soluble salt (EC = 9.89 mS/cm and total soluble salt = 45.95 g/kg) as shown in Table 3, which would be positive to neutralize the saline–alkali soil. In addition, LS had a large specific surface area (S_{BET} = 3.50 m^2/g), which gave it good adsorption capacity for both water and ions which are beneficial for the amelioration of soil.

Table 3. Main properties of LS.

pH	EC (mS/cm)	Exchangeable Na^+ (g/kg)	Exchangeable Ca^{2+} (g/kg)	TSS (g/kg)	S_{BET} (m^2/g)
3.90	9.89	2.147	14.93	45.95	3.50

3.2. Lithium Slag Affects the Salinization Status of Saline–Alkali Soil

3.2.1. Lithium Slag Reduces pH of Saline–Alkali Soil

The pH value is a critical index reflecting the acid-base status of soil, directly affecting the effectiveness of soil nutrients. If soil pH is too low or too high, it would be adverse for plant roots to absorb nutrients [52]. As shown in Figure 2, pH was remarkably lower with the addition of LS than that of CK1 at the pre-sowing and harvest period both for the roquette and radish cultivation, respectively. This was because of the acidity of the LS (pH 3.9), which was beneficial to the neutralization of saline–alkali soil. As seen from Equation (1), there were acid functional groups left in LS. The free active hydrogen ions in the crystal structure of LS released could be the main reason for the pH decrease in saline–alkali soil, which was achieved through the acid-base neutralization between hydrogen ions and carbonate or bicarbonate ions to generate CO_2 and water [53,54]. In addition, SO_3 in LS generally existed in the form of $CaSO_4 \cdot 2H_2O$, with a high porosity, and Ca^{2+} cations reacted with free $NaHCO_3$ or Na_2CO_3 in the saline–alkali soil, generating insoluble $CaCO_3$ or $Ca(HCO_3)_2$, which in turn lowered the soil pH [55].

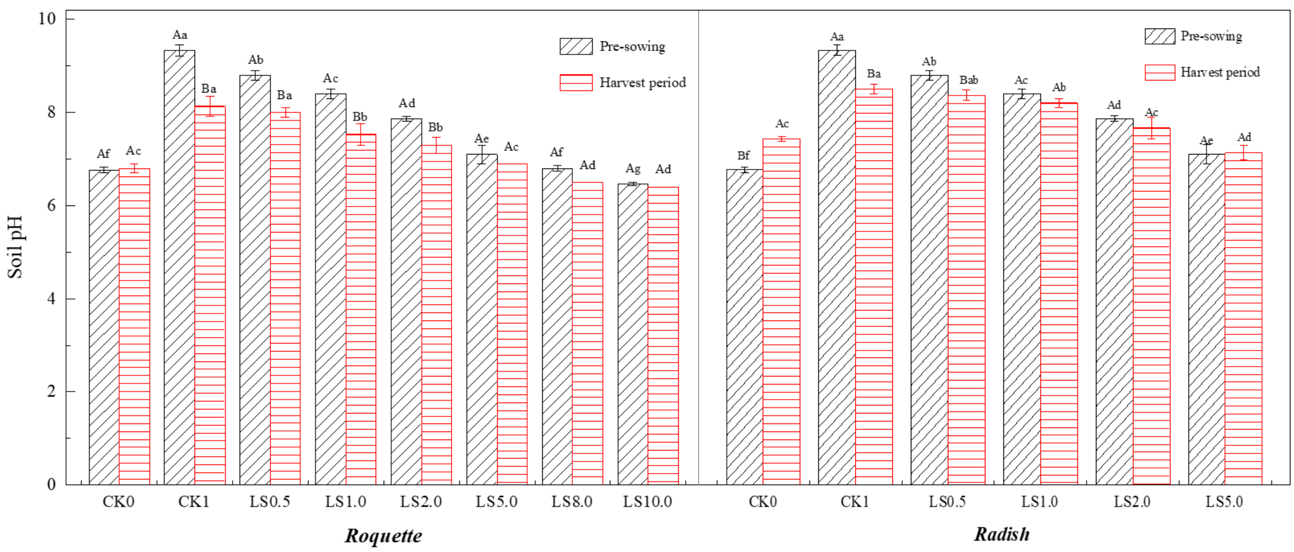

Figure 2. Soil pH under different LS amount treatments at the pre-sowing and harvest period. The upper cases show the variances between the pre-sowing and harvest period at same LS amount ($p < 0.05$). The lower cases indicate the variances between different LS amount treatments ($p < 0.05$).

With the growth of vegetables, the pH of the saline–alkali soil dropped. For roquette cultivation, the pH of CK1, LS0.5, LS1.0 and LS2.0 at the harvest period was obviously lower than those in the pre-sowing stage ($p < 0.05$). For radish cultivation, only the pH of CK1 and LS0.5 at the harvest stage was markedly higher than that in the pre-sowing stage ($p < 0.05$). Meanwhile, at harvest time, the pH of radish planting soils was observably higher than those of roquette planting soils ($p < 0.05$), which may be related to the different ability of vegetables to absorb salt [5,19].

3.2.2. Lithium Slag Increases Salinity of Saline–Alkali Soil

EC and total soluble salt content are two important indicators of soil salinity [12]. Excessive soil salinity can hinder the normal growth of plants, leading to water transport difficulties, physiological drought, abnormal metabolism and leaf green protein formation [55]. As shown in Figure 3, soil EC with the LS addition was observably higher than that of CK1 in both roquette and radish cultivation treatments ($p < 0.05$), which was related to the rich sulfate content in LS. Furthermore, EC of each treatment at the harvest time was obviously lower than those in the pre-sowing period because the roquette and radish consumed some salt in the soil when they grew. Meanwhile the roquette adsorbed more salts than radish during their growth, which coincided with the change in pH.

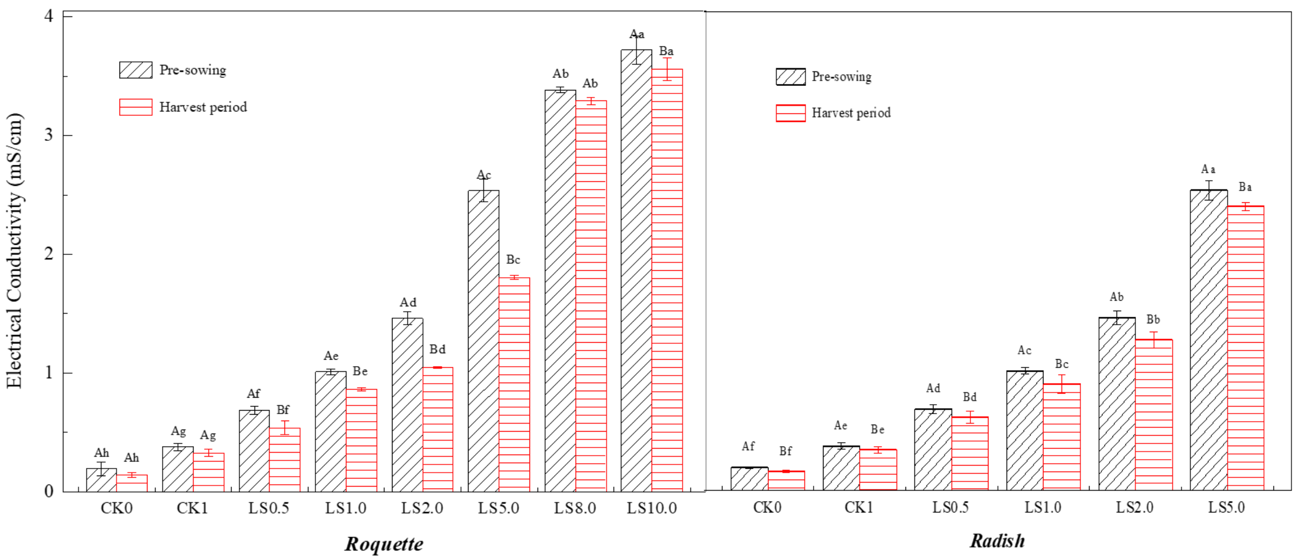

Figure 3. Soil EC under different LS amount treatments at the pre-sowing and harvest period. The upper cases show the variances between the pre-sowing and harvest period at same LS amount ($p < 0.05$). The lower cases indicate the variances between different LS amount treatments ($p < 0.05$).

As seen in Figure 4, the content of total soluble salt had a similar changing trend as the soil EC. As the amount of LS increased, EC and total soluble salt contents were raised significantly, especially when the LS addition exceeded 5%. When the LS addition was 5%, the total soluble salt content in soil was 1.74-fold that of CK1 before seeding. This was because LS released a large amount of sulfate ions while neutralizing the alkalinity of the saline–alkali soil.

3.3. Lithium Slag Promotes Vegetable Growth in Saline–Alkali Soil

Roquette and radish are both cruciferous vegetables, currently popular as salad vegetables, widely grown in different climatic conditions and barren lands around the world [39,56]. Since the application of LS can modify the physicochemical properties of the saline–alkali soil, it would also have a certain impact on the growth of roquette and radish.

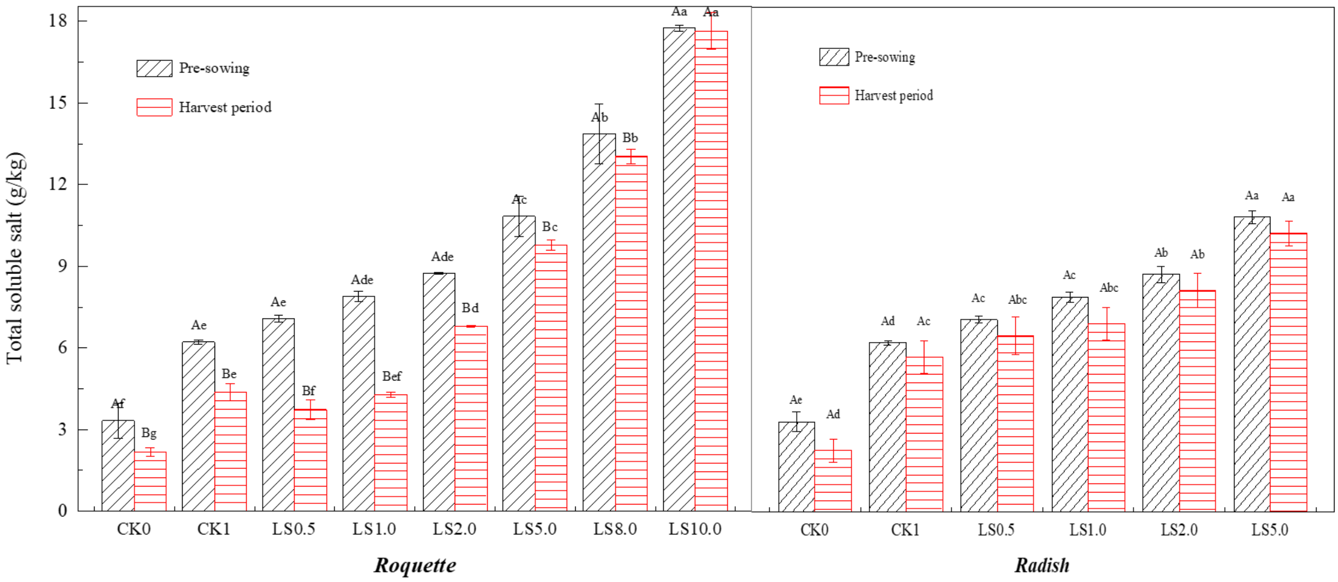

Figure 4. Total soluble salt in soil under different LS amount treatments at the pre-sowing and harvest period. The upper cases show the variances between pre-sowing and harvest period at same LS amount ($p < 0.05$). The lower cases indicate the variances between different LS amount treatments ($p < 0.05$).

3.3.1. Germination of Roquette and Radish Affected by Lithium Slag

Seed germination is one of the most important phases during the crop growth cycle, directly affecting the crop density and yield, but it is vulnerable to drought and salt stress [57]. The germination of roquette and radish seeds were significantly affected by LS. Roquette and radish seeds germinated the earliest in the CK0 treatment, but the last in the CK1 treatment (Table 4), which indicated that the seeds germinated more slowly under salt stress, which was the same as the findings of Fallahi et al. [58]. Moreover, the germination rate in each LS treatment was dramatically higher than that of CK1 except for the LS8.0 treatment, which proved that the application of LS is effective in promoting seed germination. For example, the germination rates of roquette and radish in LS0.5 and LS0.8 treatments were both above 90%, which was not significantly different from CK0 treatment. However, the germination rates of roquette in LS5.0 and LS8.0 treatment were notably lower than that in CK0 treatment. There was the lowest germination rate in LS8.0 treatment and no germination in LS10.0 treatment for the roquette cultivation, so there was no LS8.0 and LS10.0 treatment for the radish cultivation because more salt content was not conducive to germination due to salt stress [59]. Furthermore, the germination rate of radish in other LS treatments was relatively high, but there was no evident difference.

Table 4. Germination of roquette and radish under different LS amount treatments.

Cultivar	Treatment	Seeding Date	Germination Date	Germination Rate (%)	pH	EC (mS/cm)
Roquette	CK0	7th Feb	9th Feb	100 [a]	6.8	0.19
	CK1	7th Feb	14th Feb	42.9 ± 10.9 [c]	9.9	0.38
	LS0.5	7th Feb	10th Feb	93.3 ± 6.7 [a]	8.8	0.69
	LS1.0	7th Feb	10th Feb	90.5 ± 8.3 [a]	8.4	1.01
	LS2.0	7th Feb	11th Feb	90.5 ± 4.1 [a]	7.8	1.46
	LS5.0	7th Feb	12th Feb	78.4 ± 8.9 [b]	7.1	2.54
	LS8.0	7th Feb	12th Feb	9.5 ± 4.9 [d]	6.5	3.38
	LS10.0	7th Feb	–	–	6.4	3.72

Table 4. *Cont.*

Cultivar	Treatment	Seeding Date	Germination Date	Germination Rate (%)	pH	EC (mS/cm)
Radish	CK0	17th Feb	20th Feb	93.3 ± 5.8 [a]	6.8	0.19
	CK1	17th Feb	23rd Feb	53.33 ± 1.27 [b]	9.8	0.38
	LS0.5	17th Feb	21st Feb	93.33 ± 5.77 [a]	8.8	0.69
	LS1.0	17th Feb	21st Feb	91.23 ± 8.79 [a]	8.4	1.01
	LS2.0	17th Feb	22nd Feb	86.67 ± 5.77 [a]	7.8	1.46
	LS5.0	17th Feb	22nd Feb	83.33 ± 10.82 [a]	7.1	2.54

– means no germination in the treatment. The lower cases indicate the variances between different LS amount treatments ($p < 0.05$).

The addition of LS changed the pH and EC of saline–alkali soil, thereby altering the soil–salt composition. The sensitivity of crops to salinity depends upon their species and growth stages. It was reported that roquette seeds germinated well between pH 5 and 8 (>83%), but notably reduced at pH > 8 and pH < 5 [56]. Correlation analysis in Table 5 revealed that the effect of soil pH on roquette and radish germination was not significant, but EC and total soluble salt have significant impacts on the germination of roquette seeds. In most cases, seed germination showed a downward trend with increasing salinity levels. Our results were consistent with the findings of Fallahi et al. (2015) who have stated roquette germination was not apparently influenced by salinity at the concentration of NaCl less than 100 mM and then dropped dramatically along with NaCl concentration up to 200 mM [58]. However, the germination rate of radish seeds was not significantly affected by soil EC and soluble salt in this study due to its relatively higher tolerance to salt stress than roquette. Radish resists salt stress in a variety of ways, such as osmoregulation, hormone regulation, ion homeostasis regulation, reactive oxygen clearance and signal transduction [40,60]. In addition, salt stress could possibly weaken the activity of phosphorolytic enzymes which resulted in a decrease in seed germination [61].

Table 5. Correlation coefficient between the vegetable growth index and the soil physicochemical properties affected by LS addition.

Growth Index \ Soil Properties	Roquette			Radish		
	pH	EC (mS/cm)	TSS (g/kg)	pH	EC (mS/cm)	TSS (g/kg)
Germination (%)	0.372	−0.773 *	−0.817 *	−0.559	0.139	-0.005
Survival (%)	0.478	−0.911 **	−0.870 **	−0.120	−0.731	−0.788
Plant height (cm)	0.373	−0.899 **	−0.881 **	−0.176	−0.653	−0.732
Leaf numbers	0.551	−0.928 **	−0.877 **	0.150	−0.879 *	−0.884 *
Fresh weight (g/plant)	0.152	−0.813 *	−0.837 **	−0.129	−0.655	−0.712
Dry weight (g/plant)	0.167	−0.825 *	−0.844 **	−0.200	−0.516	−0.572

* means significant differences ($p < 0.05$), ** means highly significantly differences ($p < 0.01$).

3.3.2. Survival Rate of Roquette and Radish Affected by Lithium Slag

Figure 5 shows the growth of roquette and radish seeding after 1 week and 5 weeks. Roquette and radish grew best in the CK0 soil. LS application at 0.5% and 1.0% levels markedly encouraged the plant growth of roquette and radish relative to the CK1 soil. The shoot growth in the treatment of LS0.5 and LS1.0 was better than those in the treatment of LS2.0 and LS5.0.

However, some roquette and radish plants began to die during their growing period because of root dehydration. It was shown that there was no roquette survival in LS5.0 and LS8.0 treatment after 3 weeks' growth due to the osmotic stress of their roots, indicating that more LS is bad for plant growth (Figure 6). Osmotic stress was detrimental to the growth of crop seedlings as it impeded the absorption of water and nutrients due to reduced water potential or inhibited cell elongation [58]. However, stress tolerance of the two studied vegetables was significantly different. It seemed that roquette was more sensitive to saline–alkali soil than radish, which was inconsistent with the viewpoint of Bakhshandeh et al. [56]. Compared with CK1, a high survival rate in LS0.5 treatment was obtained. At harvest time, the survival rates of roquette and radish in LS0.5 treatment were 80% and 75.2%, which were 1.27 and 2.16 times that in CK1 treatment, respectively. This suggested that a small amount of LS could be used to improve saline–alkali soil but more LS would inhibit plant growth.

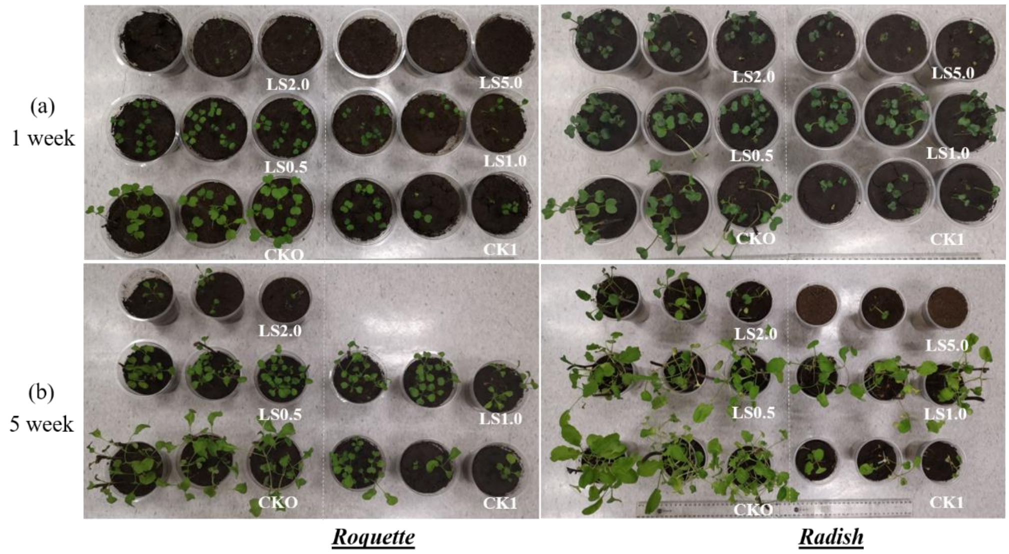

Figure 5. Total growth performance of roquette and radish under different LS amount treatments after seeding for 1 week (**a**) and 5 weeks (**b**).

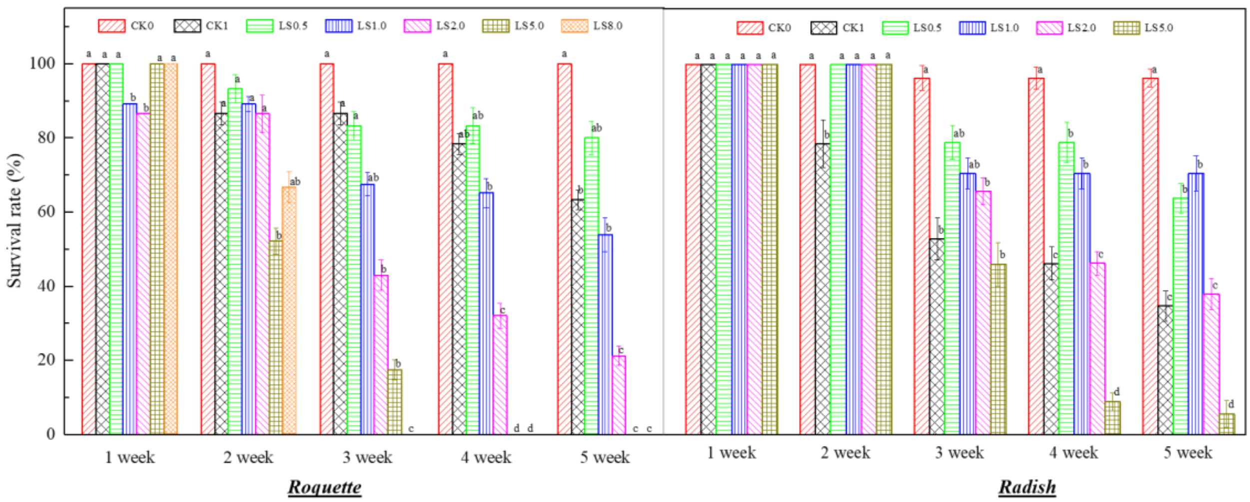

Figure 6. Survival rate of roquette and radish under different LS treatments during the growing period (the lower cases indicate the variances between different LS amount treatments ($p < 0.05$)).

3.3.3. Plant Height and Leaf Number of Roquette and Radish Affected by Lithium Slag

Plant height and leaf number are important indicators of good vegetable growth, directly affecting the quality and yield of vegetables. The application of different amounts of LS had a remarkable effect on roquette and radish growth in potted saline–alkali soil during the 5 weeks' cultivation (Figure 7). The height of roquette and radish was the highest in CK0 during the plant growing period. Particularly, the LS application at the 0.5% and 1.0% levels boosted the shoot height noticeably relative to the CK1 soil. At the harvest stage (after 5 weeks of growing), increases in roquette's height of 49.7% and 36.1% were observed in LS0.5 and LS1.0 treatment, respectively, and increases of 54.6% and 53.7% were observed in radish's height. No significant variance was found in the plant height between roquette and radish when the addition of LS was 0.5% and 1.0%. However, the shoot height in LS2.0 treatment was remarkably shorter than that in the treatments of LS0.5 and LS1.0, which was similar to the height in the CK1 soil. When the addition of LS increased to 5% or more, the height was significantly lower than that in CK1 treatment, and the roquette would all die after 4 weeks' growth. In addition, the radish's height was obviously higher than roquette's, which was in accordance with the significance results of correlation analysis (Table 5). The radish's height and number of leaves were not significantly related to soil EC and total soluble salt because radish was not sensitive to salt stress and could withstand salinity up to 12.7 dS/m [42].

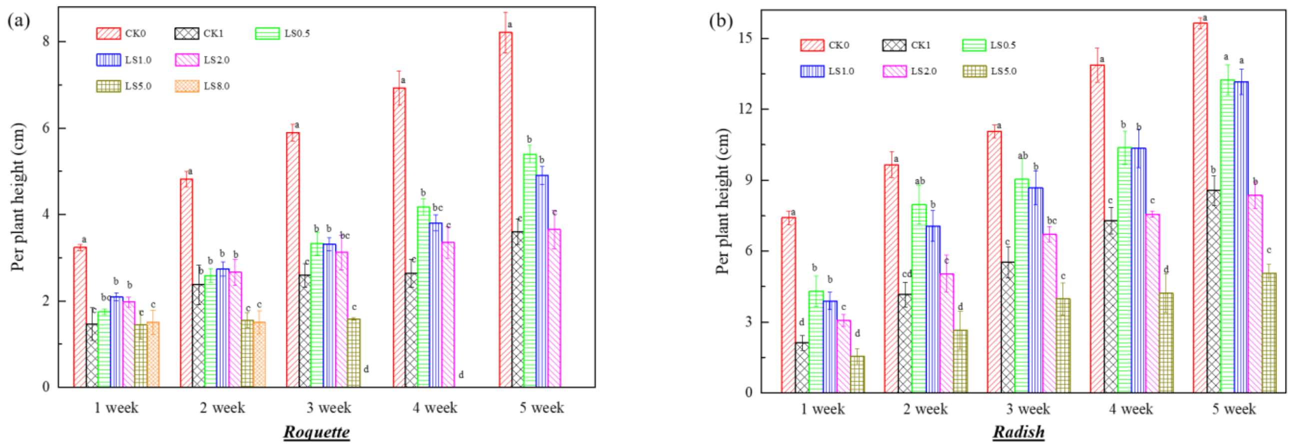

Figure 7. Survival rate of roquette (**a**) and radish (**b**) under different LS amount treatments during the growing period. The lower cases indicate the variances between different LS amount treatments each week ($p < 0.05$).

As shown in Figure 8, less addition of LS was obviously beneficial to the leaf number in the treatment of LS0.5 and LS1.0 at the initial stage of growth. In the harvest time, no significant difference appeared in the number of leaves between the treatment of less than 2.0% of LS addition and the treatment of CK0 and CK1. When the addition of LS increased to 5%, the number of leaves decreased clearly. There was no roquette survival at the 5% of LS application after 4 weeks' cultivation, and the number of radish leaves was 1.35 and 0.83 less than that in CK0 and CK1 treatment. Correlative analysis showed that soil EC and soluble salt significantly influenced the growth and leaf numbers of roquette ($p < 0.01$) and radish ($p < 0.05$).

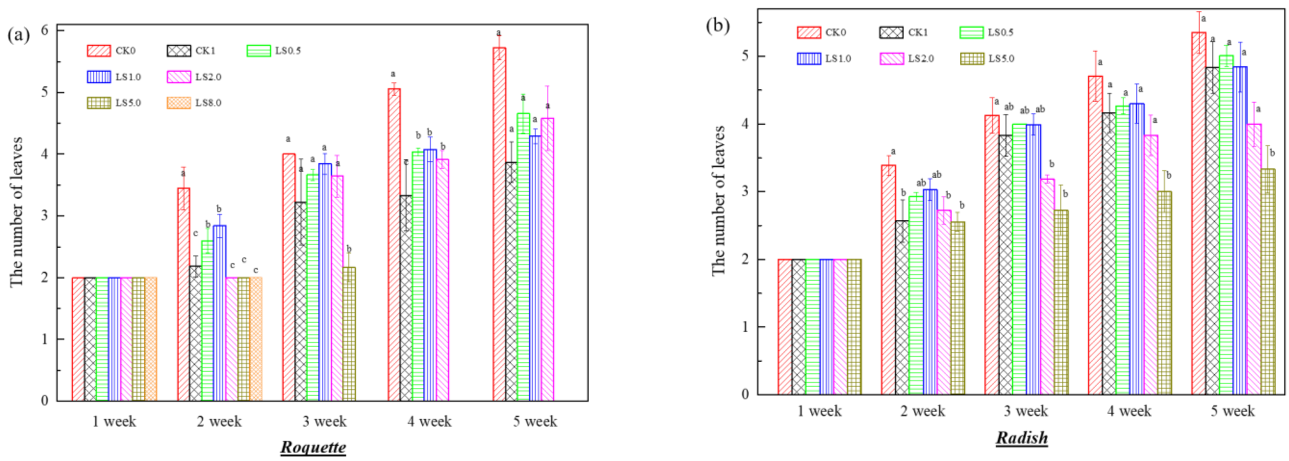

Figure 8. The number of roquette (**a**) and radish (**b**) leaves under different LS amount treatments during the growing period. The lower cases indicate the variances between different LS amount treatments each week ($p < 0.05$).

3.3.4. Biomass of Roquette and Radish Affected by Lithium Slag

Biomass is a direct reflection of the effectiveness of saline–alkali land improvement. After 5 weeks' growing, we harvested the roquette and radish and measured the fresh and dry weight of them. Without extra fertilizer, the biomass of roquette and radish was relatively low in all the treatments (Table 6). For the roquette cultivation, there was no obvious biomass variance between LS treatments and CK1, which may be because roquette prefers nitrogen and organic fertilizers to sulfates [62]. Fortunately, the biomass of radish in LS0.5 and LS1.0 treatments was nearly twice that in CK1 treatment, indicating that a small amount of LS promoted radish growth in saline–alkali soil, which was consistent with the effect of gypsum on increasing the biomass of saline–alkali soil [17,63].

Table 6. Biomass of roquette and radish under different LS treatments after harvest.

Cultivar	Treatment	Fresh Weight (g/plant)	Dry Weight (g/plant)
Roquette	CK0	0.382 ± 0.074^{a}	0.018 ± 0.004^{a}
	CK1	0.138 ± 0.026^{b}	0.006 ± 0.001^{b}
	LS0.5	0.143 ± 0.023^{b}	0.008 ± 0.001^{b}
	LS1.0	0.139 ± 0.022^{b}	0.007 ± 0.001^{b}
	LS2.0	0.089 ± 0.016^{b}	0.004 ± 0.001^{b}
	LS5.0 and LS10.0	–	–
Radish	CK0	0.650 ± 0.021^{a}	0.031 ± 0.005^{a}
	CK1	0.291 ± 0.058^{b}	0.017 ± 0.004^{c}
	LS0.5	0.553 ± 0.041^{a}	0.030 ± 0.002^{a}
	LS1.0	0.546 ± 0.069^{a}	0.029 ± 0.006^{a}
	LS2.0	0.283 ± 0.061^{b}	0.022 ± 0.002^{a}
	LS5.0	0.232 ± 0.002^{c}	0.018 ± 0.001^{b}

– means no harvest in the treatment. The lower cases indicate the variances between different LS amount treatments ($p < 0.05$).

In addition, soil EC and soluble salt inhibited the increase in biomass. Significant difference was found between soluble salt and the biomass of roquette, but no obvious difference existed between soluble salt and the biomass of radish. Radish exhibited preferable morphological and physiological responses to increase production in saline–alkali soil and had better adaptability to saline–alkali soil [42].

4. Conclusions

Potted plant experiments were carried out to investigate the impact of LS on saline–alkali soil amelioration and vegetable growth. As a soil amendment, LS exhibited an excellent effect on soil pH reduction by acid-base neutralization or carbonate precipitation. EC and total soluble salt content in soils increased with the increase in LS dosage, whereas salt stress was significantly alleviated in roquette and radish shoots at the addition of 0.5% and 1.0% of LS (w/w). Consequently, the germination and growth of roquette and radish were considerably enhanced by LS application, especially at the optimum amount of 0.5% and 1.0% (w/w). Compared to the untreated saline–alkali soil, LS addition at 0.5% and 1.0% (w/w) levels increased the roquette height by 49.7% and 36.1% and increased the radish height by 54.6% and 53.7%, respectively. The biomass of radish was increased by LS addition at 0.5% and 1.0% (w/w) levels, while a high amount of LS ($\geq$5%) would inhibit the growth of vegetables and even lead to death.

These results revealed that LS had a potential application prospect in ameliorating soil physicochemical properties and boosting crop growth in saline–alkali soil. On this basis, there is the need to take on the research in finding better ways of LS utilization to improve the crop yield and fertility of saline–alkali soil in the future.

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