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An Initial Study And Prospective Application Of Sesuvium Portulacastrum L. In The Simultaneous Removal Of Salts And Lead From Polluted Agricultural Soils

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Abstract

Salinization has a negative impact on biodiversity, agricultural productivity, and sustainable development, while the increase of heavy metals in agricultural soil may threaten soil quality and pose a risk to human health, which requires suitable, friendly, and low-cost solutions. This study investigated the potential application of a halophyte (Sesuvium portulacastrum L.) in removing salts and Pb from polluted agricultural soils over a 70-day experimental period. The growth of S. portulacastrum L. under soil salinity (1000, 5000, and 10000 mg/kg NaCl) and Pb pollution (100, 500, and 1000 mg/kg $Pb(NO_3)_2$) conditions was studied. In addition, the change in salt concentration and Pb content in the soils as well as the accumulation in the tissues of S. portulacastrum L. was evaluated. The results revealed that there was a significant increase in biomass of S. portulacastrum L. under the saline and Pb pollution soil conditions. After 70 days of the testing, S. portulacastrum L. eliminated between 33% and 100% of the salt content and 7.15% to 80% of the Pb concentration in the soil treatments. There were 4.8 mg/kg to 8.8 mg/kg of NaCl and 120 µg/g DW to 3420 µg/g DW of Pb found in the shoots of S. portulacastrum L. Particularly, the contents of Pb in the roots were reported in the range of 27.000 µg/g DW and 136.500 µg/g DW. This suggests that S. portulacastrum L. can absorb both salts and Pb in the soils and accumulate these chemicals in its tissues, which plays a pivotal role in decreasing lead pollution and salinity in agricultural soils, enhancing soil quality, and improving crop yield and safety for humans and animals.

Keywords: *desalination, halophyte, lead pollution, Sesuvium portulacastrum L.*

1. INTRODUCTION

Salinization is characterized by the excessive accumulation of soluble salts on the surface of the soil, which contributes to a rapid decrease in land available for agricultural production, particularly in developing countries [1, 2]. In addition, it has a negative impact on biodiversity, agricultural productivity, and sustainable development [3]. The result of soil salinization is severe land degradation and desertification, making it one of the major environmental hazards in the world. According to Periasamy & Ravi (2020)[4], Zhu *et al.* (2023)[5], saline soils were found in dry and semiarid locations with excess evapotranspiration and precipitation, as well as in coastal regions due to seawater intrusion and coastal tidal flooding. Previous studies indicate that a figure of 800 million hectares of agricultural land in the world is influenced by salinity, and the saline soils are estimated to rise more than a half of land for agricultural production over the world by 2050 [6, 7]. On the other hand, growing industrialization and agricultural activities have resulted in heavy metal poisoning of soil on a large scale, which has raised serious environmental concerns worldwide [8, 9]. Heavy metals are big, non-biodegradable metals that build up in the environment and can contaminate things like soil and water, endangering environmental and human health [10]. These components transfer from a lower to a higher trophic level with an increasing concentration, which is known as a biomagnification phenomenon in a living, breathing organism. This process, known as bioaccumulation, occurs in the organism's bodily tissue.

The adverse impacts of heavy metals have resulted in a decrease in the number of soil organisms [11]. Additionally, heavy metals can build up in the food chain and cause health issues for people and animals who eat polluted food. The problem of heavy metal contamination is pervasive and impacts millions of hectares of land globally. Land degradation, expanded persistence at different speeds, and geological cycles are the main recurrent causes of soil pollution or depletion [10]. Excessive exposure to toxins found in soil, like heavy metals, can have negative impacts on plant development and physiological cycles. These consequences can include decreased germination of seeds, restricted plant growth, disturbed nutrient uptake, stifled photosynthesis, and altered enzyme activity[12-16]. The increase of heavy metals in agricultural soils threatens soil quality, sustainable agriculture and there may be more risks to human health.

According to Gu *et al.* (2018)[16], the most significant plant abiotic stressors in agricultural soils are salinity and heavy metal pollution, which threaten soil quality, sustainable agriculture, and food security. Phytoextraction is considered as a pivotal method to recover the salt-affected soils by using plants to store salt in their leaf, shoot, and root tissues, which are harvested to remove the salt from the soil [17]. While a high concentration of salt promotes the growth of halophytes, it is harmful to glycophytes because it interferes with their metabolic processes [18]. Halophytes have a variety of adaptation mechanisms to deal with the conditions caused by excess salt, including the ability to exclude, compartmentalize harmful ions, and use osmoprotectants [19, 20]. With a build up of chloride ions in the cytoplasm, halophytes found in environments rich in chloride have a succulent appearance. When halophytes are deficient in chloride ions, they do not have succulent morphology. Through these modifications, halophytes are able to draw water from the soil, which is necessary for their survival [21]. In addition, plants are widely applied to the removal of heavy metals from soils, which contribute to reducing the human health and environment [22].

S. portulacastrum L. is a facultative halophyte that is a member of the *Aizoaceae* family, which can be used as feed for cattle. This plant can grow even in low-nutrient environments and marshes, sandy soils, salt flats, and coastal limestones, so it may be a perfect fit for the phytoremediation of salt-affected soil [23, 18]. *S. portulacastrum*'s vacuoles can accumulate the excess Na^+ by increasing their size and maintaining cytosolic metabolism [18]. In addition, the accumulation of proline in a substantial quantity as an osmoprotectant is a significant mechanism for salt adaptation [24]. On the other hand, *S. portulacastrum* L. is rich in vitamins and minerals, and it is known as sea vegetables used in many countries in the world, such as China, India, Europe, and the Caribbean [25-28]. Furthermore, this plant contains a high phenolic content and various bioactive compounds with high value in pharmaceuticals, which have been utilized as traditional medicines to enhance human health as well as to treat insect pests and plant pathogens [29, 30]. Additionally, *S. portulacastrum* L. was reported as one of the stress-tolerant plants that can both absorb and remove heavy metals through bioaccumulation. It has previously been demonstrated that these plants, which reside in metal-enriched environments, can continually enhance their tolerance to the relevant metals [31]. This indicates the pivotal roles and potential applications of *S. portulacastrum* L. in the phytoremediation of heavy metal pollution and saline soils, however, less information about the semultaneous removal of salts and heavy metals in the soils.

In this study, we investigated the potential application of *S. portulacastrum* L. in simultaneous removal of salts and lead from the contaminated agricultural soils via its growth under salinity and lead pollution conditions, the ability in desalination and lead removal of *S. portulacastrum* L., as well as the accumulation in the tissues.

2. MATERIALS AND METHODS

2.1. Chemical and materials

S. portulacastrum L. samples were collected from Mai Hung village, Quynh Luu District, Nghe An province, Vietnam, in March 2023, then transffered to the Center for High Technology Research and Development, Vietnam Academy of Science and Technology, Hanoi city, Vietnam, for experiments. Plant samples were

analyzed to confirm that there was no Pb in their biomass before being used for experiments. Pure salt (NaCl) and $Pb(NO_3)_2$ were purchased from OlChemim Ltd. (Czech Republic), while compost fertilizer and soil without salinity and heavy metals, and ACROOTS 10SL contains α-Naphthyl Acetic Acid (NAA) to stimulate rooting were bought from the traditional markets in Hanoi city, Vietnam. In addition, tap water was used during the experiments.

2.2. Experimental setup

The salt concentration chosen for the experiment is based on the general guidelines for plants response to soil salinity (Kotuby-Amacher et al., 2000) as shown in Table 1.

Table 1. General guidelines for plants response to soil salinity

Salinity (dS/m)	Salinity (ppt)	Plant response
0 – 2	0 – 1.4	Moslty negligible
2 – 4	1.4 – 2.8	Growth of sensitive plants may be restricted
4 – 8	2.8 – 5.6	Growth of many plants are restricted
8 – 16	5.6 – 11.2	Only tolerance plants
> 16	> 11.2	Only a few, very tolerant plants

Stems of *S. portulacastrum L.* were cut to 15-20 cm length each and submerged in ACROOTS 10SL root stimulant for 18 hours. The studied plants were grown in pots (50 cm × 15 cm × 20 cm, length × width × height) containing compost fertilizers and moist soil (15 kg), with 20 plants per pot. Different concentrations of NaCl (0-control, 1000, 5000, and 10000 mg/kg) and $Pb(NO_3)_2$ (0-control, 100, 500, and 1000 mg/kg) were added into the pots in the experiments as described in Table 2. Each treatment was repeated in four replications, watered once every 3 days with 500 mL of water, and carried out from March to June 2023 in the greenhouse of the Center for High Technology Research and Development, Vietnam Academy of Science and Technology, with a temperature range of 25-33 °C and an air humidity of 60-70 %.

Table 2: The experimental design

$Pb(NO_3)_2$ (mg/kg)	NaCl (mg/kg)			
	0	1000	5000	10000
0	CT1.1	CT1.2	CT1.3	CT1.4
100	CT2.1	CT2.2	CT2.3	CT2.4
500	CT3.1	CT3.2	CT3.3	CT3.4
1000	CT4.1	CT4.2	CT4.3	CT4.4

Where:

CTi.1-CTi.4 means each NaCl treatment was repeated in four replications

CT1.j-CT4.j means each $Pb(NO_3)_2$ treatment was repeated in four replications

2.3. Measurement of plant growth and biomass

The growth of *S. portulacastrum L.* under salinity and $Pb(NO_3)_2$ exposure conditions was measured by the lengths from the growth point to the cotyledon node at the initial day, days 28, 56, and 70, respectively. After 70 days of the experiments, *S. portulacastrum L.* was harvested (removal of roots) and washed three times with both tap water and deionized water (DI H_2O) for 5 minutes, then dried by tissue paper and immediately weighted for fresh weight to determine its biomass.

2.4. Determination of salt and lead contents

Soil samples are collected once every 7 days, and plant samples are collected after every 14 days. Collected soil samples were dried and ground to a fine powder, then approximately 5g samples were dissolved in 50 mL of deionized water for salinity measurement, while collected plant samples (1 g) were ground and dissolved in 30 mL of deionized water for salinity measurement. Salinity tests are carried out using the Marine Salinity Tester (Hanna Instruments) in parts per thousand (ppt).

In addition, Pb in the soil and plant samples was analyzed by inductively coupled plasma triple quadrupole mass spectrometer (iCAP-TQ ICP-MS) equipment. Dried soil samples (1.5 g) were prepared in a well-labeled 100 mL polytetraflouroethylene (PTFE) Teflon bomb and diluted with 6 mL (98%) HNO_3, 3 mL (35%) HCl, and 0.25 mL (30%) H_2O_2 solutions. Amount of 0.2 g plant samples were digested with 4 mL HNO_3 (65%) and 2 mL H_2O_2 (30%). Prepared samples were allowed to sit for 8 hours to release any excess gas before being digested with a MARS6 microwave with setting conditions, including: power 1100 W, Ramp up time 25 mins, Retention time 15 mins, Temperature 190 °C, Cooling 20 mins.

2.5. Stereomicroscope observation

Fresh roots were thoroughly washed with deionized water. These tissue sections were cut with a sharpened razor-blade, then immediately observed and photographed using a Nikon SMZ800 stereomicroscope and a Nikon DS-Fi1 camera to determine how Pb enters plant cells. NIS-Elements Viewer software was used to analyze images.

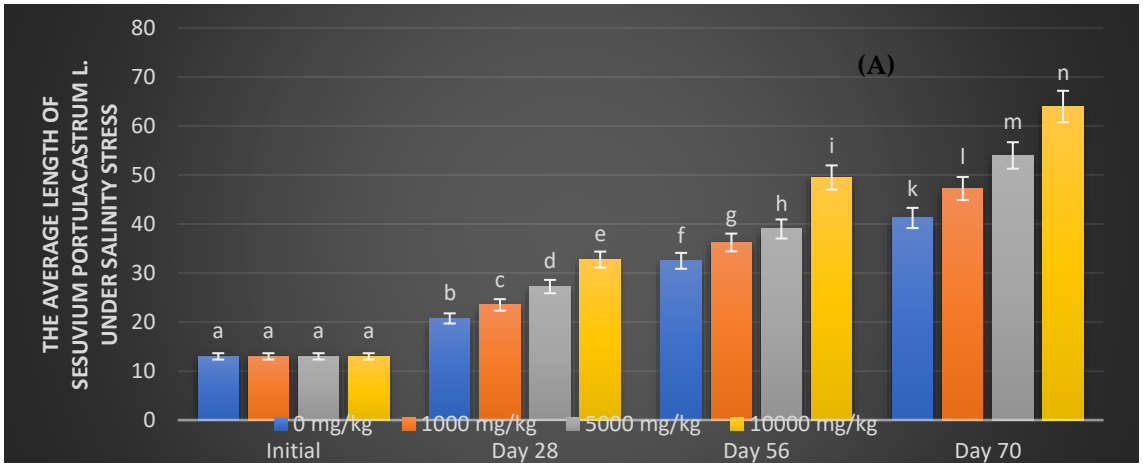
2.6. Data analysis:

The results are shown as the mean ± standard deviation (SD). Statistical analysis was carried out with SPSS 22.0 software, which included one-way ANOVA and independent samples t-tests. A 95% confidence interval ($p < 0.05$) was considered significant in all circumstances

3. RESULTS

3.1. The effects of salinity stress on S. portulacastrum L. growth

Figure 1 illustrates the effects of different salinities on the growth in length and biomass of *S. portulacastrum* L. after 70 days of experiments. Obviously, the length of studied plant growth under salinity stress was significantly higher than that of the control without salinity during the experiments. In addition, a significant difference was reported in the length of plants treated with different salt concentrations in the experiments. There was an increase in the length of *S. portulacastrum* L. among the increase of the salt concentrations from the initial day to the end of the experiments. As can be seen from Figure 1, after 70 days of experiments, the longest average length of *S. portulacastrum* L. was 64.00 cm at the 10.000 (mg/kg) NaCl treatment, which was 35.55% higher than those of the controls (41.25 cm). The following were 54.00 cm and 47.25 cm in plants treated with 5000 and 1000 mg/kg NaCl concentration, respectively, which were 23.61% and 12.79% higher than the plants without exposure to NaCl, respectively (Figure 1A). In addition, the biomass of *S. portulacastrum* L. was increased by increasing the salt concentration from an initial mass of 7 g to 19.5 g, 23.25 g, 28.75 g, and 33.5 g at concentrations of 0, 1000, 5000 and 10000 mg/kg, respectively, at the end of the experiment. The mass of *S. portulacastrum* L. exposed with 1000, 5000, and 10000 mg/kg salt concentrations was 1.19 times, 1.47 times, and 1.72 times higher than those plants without exposure to salt conditions, respectively (Figure 1B). The results illustrated that the length and biomass of *S. portulacastrum* L. increased with the increase of the salt concentration from the initial day to the end of the experiments.



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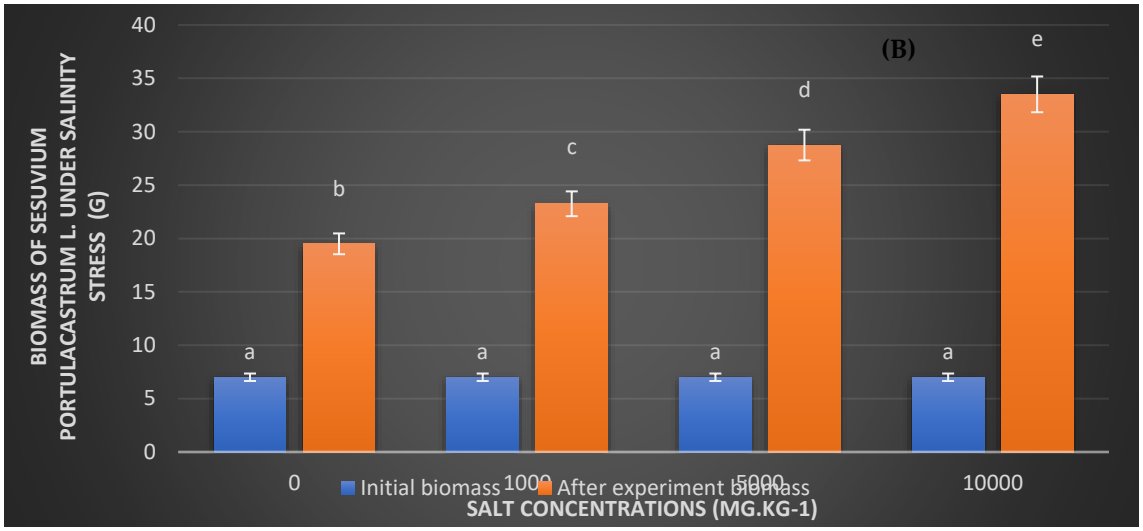

Figure 1. The growth of *S. portulacastrum* L. under salinity stress

(A and B were the average length and biomass of S. portulacastrum L. after 70 days of the experiments, respectively. Different letters on the same DAT in Figure 1A show significant differences at $p < 0.05$ level between different salinity conditions at the same DAT; and different letters on the same salinity concentration in Figure 1B describe the significant differences at $p < 0.05$ level between initial and after experimental biomass)

3.2. The effects of Pb on S. portulacastrum L. growth

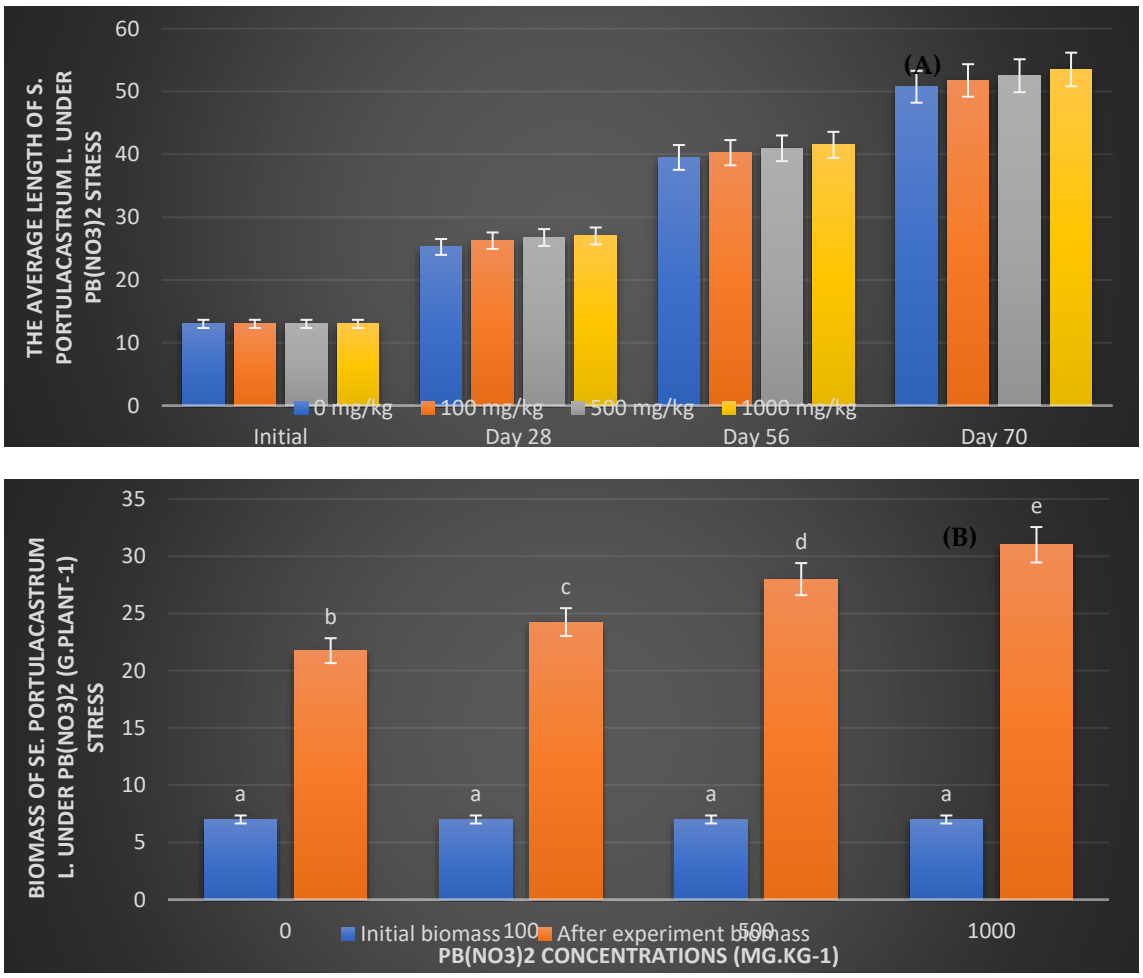

Figure 2. The growth of S. portulacastrum L. under $Pb(NO_3)_2$ stress

(*A and B were the average length and biomass of S. portulacastrum L. after 70 days of the experiments, respectively. Different letters on the same $Pb(NO_3)_2$ concentration in Figure 2B describe the significant differences at $p < 0.05$ level between initial and after experimental biomass*).

As can be seen from Figure 2A, no significant difference was found in the average length of *S. portulacastrum* L. between the control and the exposed with different concentrations of $Pb(NO_3)_2$ stress (100, 500, and 1000 mg/kg) after 70 DAT. After 28 days of experiments, the average lengths of plants were 26.25 cm, 26.75 cm, and 27.00 cm in the *S. portulacastrum* L. exposed with $Pb(NO_3)_2$ at 100, 500, and 1000 mg/kg, respectively, which were longer than those of the controls (25.25 cm). The length of *S. portulacastrum* L. plants was increased to 40.25 cm, 40.95 cm, and 41.50 cm, corresponding to the treatment of $Pb(NO_3)_2$ concentrations at 100, 500, and 1000 mg/kg in comparison with those of the control (39.50 cm) after 56 DAT. The longest length of *S. portulacastrum* L. was 53.50 cm in the plant exposed with 1000 mg/kg $Pb(NO_3)_2$, followed by 52.50 cm and 51.75 cm in the treatment of 500 and 100 mg/kg $Pb(NO_3)_2$, respectively, which were a little bit longer than the length of the control (50.75 cm) after 70 days of experiments. However, no considerable differences were reported in the length of plants exposed to different concentrations of $Pb(NO_3)_2$. However, it is interesting to note that there was a significant difference in the biomass of *S. portulacastrum* L. exposed to $Pb(NO_3)_2$ in comparison with those of the control, and between the different concentrations of $Pb(NO_3)_2$ treatment after 70 days of experiments (Figure 2B). The highest biomass of plants was 31.00 (g/plant) at the 1000 mg/kg $Pb(NO_3)_2$ treatment, which was 42.53% higher than the length of the control (21.75 g/plant). The following were 28.00 (g/plant) and 24.25 (g/plant) in the plant exposed with 500 and 100 mg/kg $Pb(NO_3)_2$, respectively, which were 28.74% and 11.49% higher than plants without $Pb(NO_3)_2$ exposure, respectively.

3.3. The desalination efficiency and salt accumulation of S. portulacastrum L.

There was a significant decrease in the salt concentrations of soil treated with different salinities, including 1000, 5000, and 10000 mg/kg, after 70 days of the experiments (Figure 3). It is clearly shown in Figure 3, the saline soil with 1000 mg/kg was reduced to 500 mg/kg by *S. portulacastrum* L. after 21 days of transplanting, then fell off to 0 mg/kg after 35 DAT. Similarly, the soil salinity in the treatment of 5000 mg/kg was declined to 4600 mg/kg after 21 DAT, then fell off to 3250 mg/kg at the 42 DAT, then continuously diminished to 2250 mg/kg at the 56 DAT, and 1500 mg/kg after 70 days of the experiments, respectively. In the treatment of 10000 mg/kg, the salt content was dropped to 9400 mg/kg after 4 weeks of the experiments, which was then decreased to 8700 mg/kg, 7800 mg/kg, and 6700 mg/kg after 42, 56, and 70 DAT, respectively. Thus, a percentage of 100%, 70% and 33% of salt contents in the soil treatments with 1000, 5000, and 10000 mg/kg NaCl was removed by *S. portulacastrum* L. after 70 days of the experiments, respectively. This demonstrates that the salt contents in the soil treatments were absorbed by *S. portulacastrum* L. during the experiments, which illustrates the potential application of *S. portulacastrum* L. in desalination of soils.

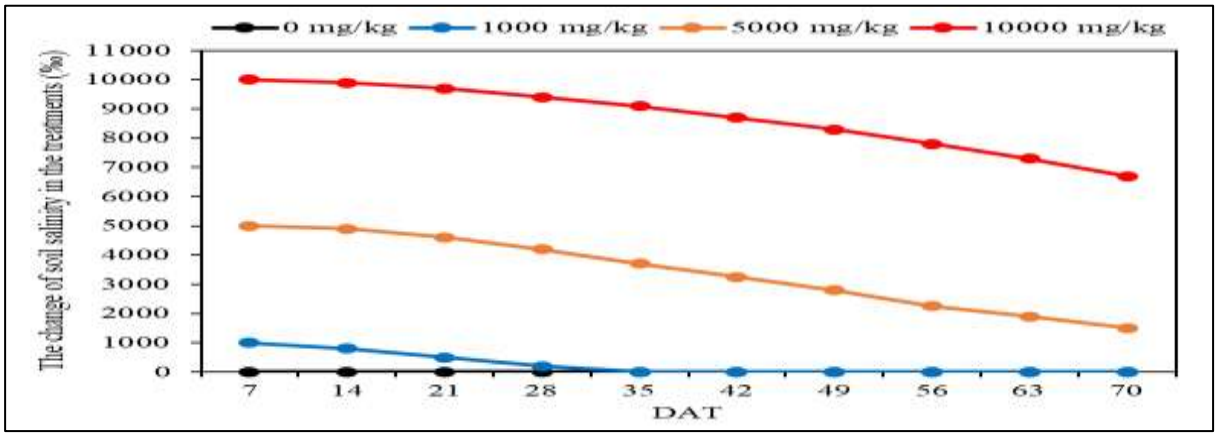

Figure 3. The desalination efficiency in saline soils of *S. portulacastrum* L.

As can be seen from Figure 4, the salt concentrations in plant tissues under various salinity treatments increased with the increase of the experimental time, while that of the control decreased during the experiments. In addition, the higher the concentration of salinity in the soil treatments, the greater the content of salts in the plant tissues. In the first 14 days of transplanting, the salt concentration in the plant tissues was slightly increased from 3.8 mg/kg in the initial samples collected from the fields to 4.0 mg/kg and 4.5 mg/kg in the salinity soil treatments of 5000 mg/kg and 10000 mg/kg, respectively; whereas those of the 1000 mg/kg saline soils were not changed, and those of the control were decreased to 3.7 mg/kg. There was a significant difference in the salt contents in the tissues of plants exposed to different salinities in comparison with those of the control from the 28 DAT to the 70 DAT. In the exposure of 1000 mg/kg, the salt concentration in the plant tissues was increased to 4.2 and 4.5 mg/kg after 42 days and 56 days of the experiments, respectively. Similarly, the salt contents were 5.1 and 5.7 mg/kg in the tissues of plants exposed to 5000 mg/kg, respectively, while those of the 10000 exposure were 6.6 and 7.8 mg/kg, respectively. After 70 days of the experiments, the salt concentrations in the plant tissues were found at 4.8 mg/kg, 6.5 mg/kg, and 8.8 mg/kg, corresponding to the exposures of 1000, 5000, and 10000 mg/kg salinities, respectively, which were 1.71 times, 2.32 times, and 3.14 times higher than those of the control (2.8 mg/kg). This illustrated that different concentrations of salinities showed the difference in the salt contents accumulated in the plant tissues, and the highest concentration of salt was measured at 8.8 mg/kg at the 10000 mg/kg of the salinity after 70 DATs. In addition, the salt content in the control plants was decreased during the experiments due to the growth of *S. portulacastrum* L., changed the distribution of salt concentration in the plant tissues to all parts of the plants.

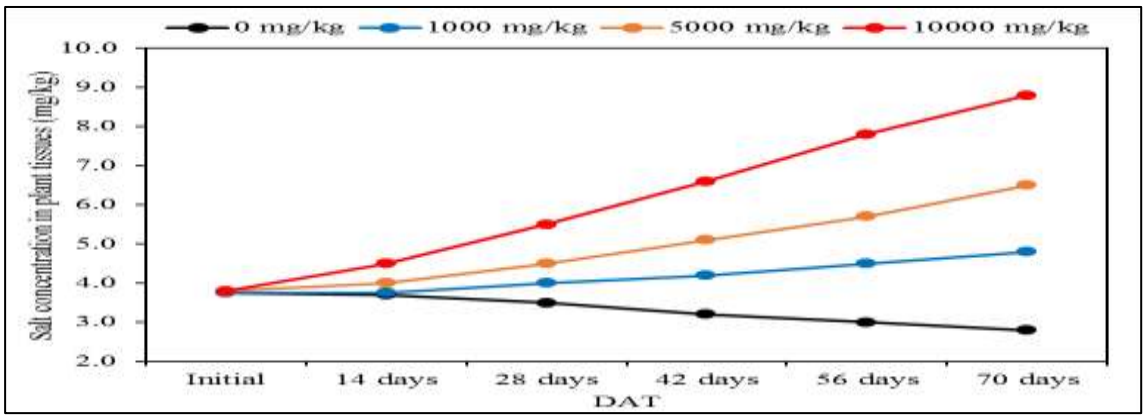

Figure 4. The increase in salt concentration in plant tissues

3.4. Pb removal efficiency and accumulation in the soils by S. portulacastrum L.

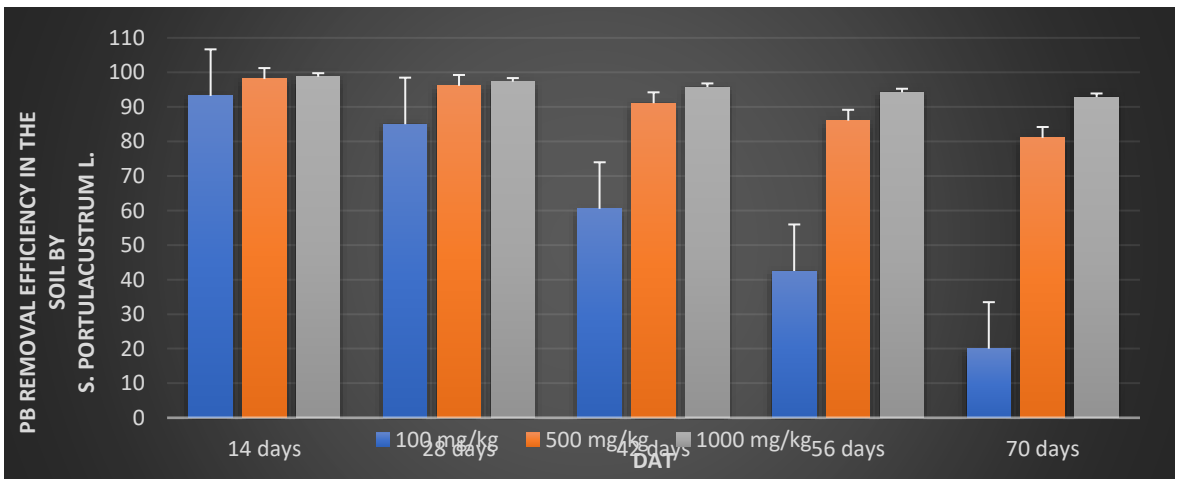

Figure 5. Pb removal efficiency in the soil of *S. portulacastrum* L.

A significant decrease was reported in Pb contents in the soil over the experiments. After the first 14 days of transplanting, Pb levels in the soil were reduced to 93.20%, 98.10%, and 98.73% in the exposures of 100, 500, and 1000 mg/kg $Pb(NO_3)_2$, respectively. These figures were continuously decreased to 60.50%, 91.08%, and 95.76% in the treatments of 100, 500, and 1000 mg/kg $Pb(NO_3)_2$ after 42 days of the experiments, respectively. Particularly, the contents of Pb in the soil treatments remained at 20.00%, 81.04%, and 92.85%, corresponding to 100, 500, and 1000 mg/kg $Pb(NO_3)_2$ treatments after 70 days of the experiments, respectively. It means that figures of 80%, 18.96%, and 7.15% of Pb in the soil treatments of 100, 500, and 1000 mg/kg $Pb(NO_3)_2$ were removed, respectively. This demonstrates that there was a significant difference in Pb removal efficiency in the soil treated with different concentrations of $Pb(NO_3)_2$ by *S. portulacastrum* L. during the experiments. Moreover, with the higher concentrations of $Pb(NO_3)_2$ treatment, the lower Pb concentration was removed after 70 DAT of the experiments.

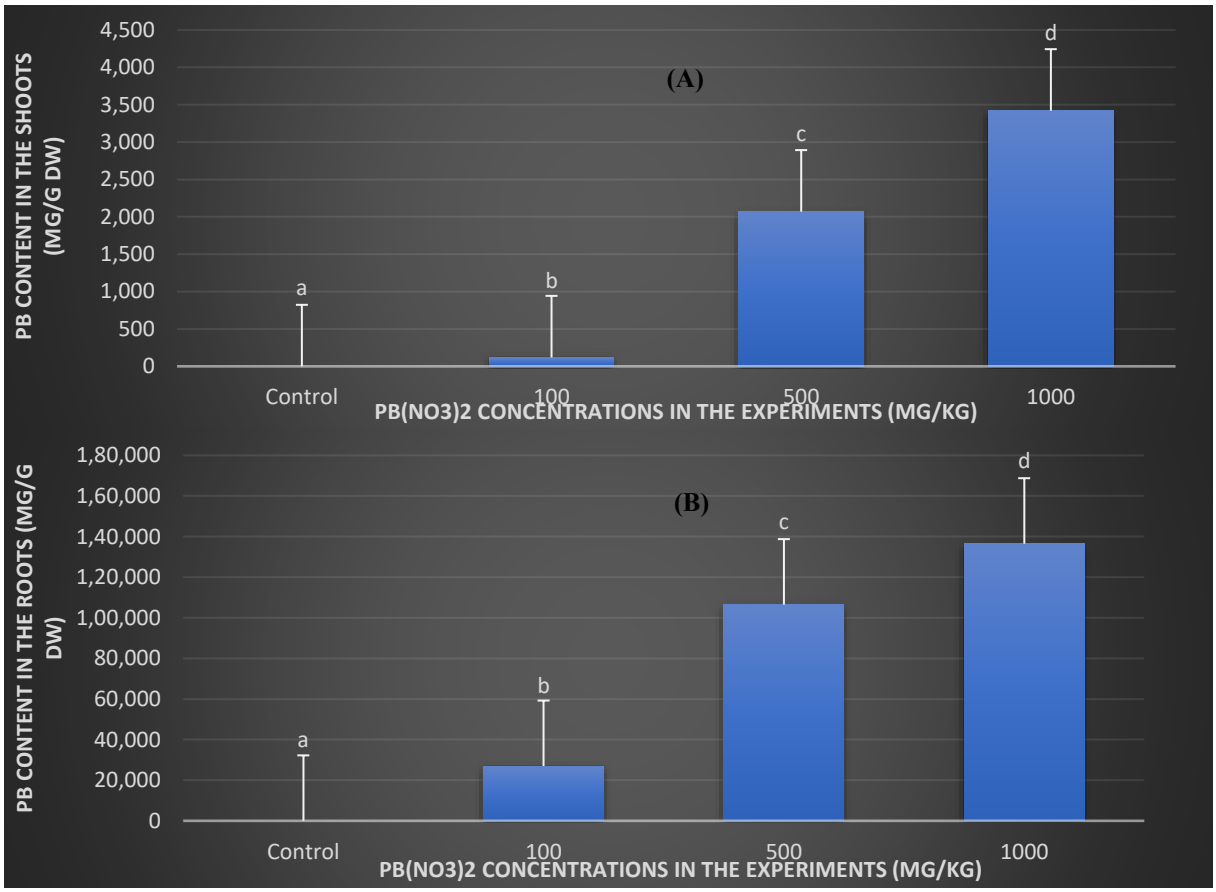

Figure 6. Pb accumulation contents in the roots and shoots of *S. portulacastrum* L.

(*Different letters describe the significant differences at the $p<0.05$ level between Pb contents in roots and shoots compared to the control*)

The accumulation of Pb in *S. portulacastrum* L. shoots and roots after 70 days of the experiments is shown in Figure 6. A significant difference was observed in the contents of Pb accumulated in the shoots and roots between the different treatments of $Pb(NO_3)_2$. The content of Pb in the shoots and roots of *S. portulacastrum* L. increased with the increasing concentration of $Pb(NO_3)_2$ in the experiments. As can be seen from Figure 6, the Pb contents in the shoots were reported at 120 µg/g DW in the 100 mg/kg $Pb(NO_3)_2$ exposure after 70 days of the experiments, while those of the 500 and 1000 mg/kg $Pb(NO_3)_2$ treatments were found at 2070 µg/g DW and 3420 µg/g DW, respectively. In addition, the concentrations of Pb in *S. portulacastrum* L. roots were determined at 27.000, 106.500, and 136.500 µg/g DW in the 100, 500, and 1000 mg/kg $Pb(NO_3)_2$ treatments, respectively. It is interesting to note that, plant roots were shown to have greater Pb concentrations than plant shoots. After 70 days of testing, the concentration of Pb in the plant roots was 225 times greater than that in the plant shoots in the 100 mg/kg $Pb(NO_3)_2$ exposure. Similarly, the Pb contents in roots

of *S. portulacastrum* L. at the 500 and 1000 mg/kg $Pb(NO_3)_2$ treatments were 51.45 and 39.91 times higher than those of the plant shoots after 70 days of the studies, respectively. This suggests that, although *S. portulacastrum* L. preferentially accumulates Pb in the roots, it may also be able to transfer substantial amounts of lead to the shoots, which is essential for its phytoextraction potential. This ability makes *S. portulacastrum* L. a promising candidate for clean up Pb-contaminated soils.

3.5. Pb distribution in the root tissues

The roots of halophyte plants play a crucial role in absorbing water and nutrients essential for their growth and development. Additionally, they demonstrate a notable tolerance to toxic metals and can thrive even in environments with high concentrations of these metals. As illustrated in Figure 7, a significant accumulation of Pb was observed in the root cortex and endodermis, while the thickness of the epidermis decreased substantially with increasing Pb concentrations. Furthermore, root diameter showed a remarkable increase ($p<0.05$) in response to higher $Pb(NO_3)_2$ treatments, reaching 6.04 mm in the 100 mg/kg $Pb(NO_3)_2$ treatment and measuring 6.25 mm and 6.42 mm at the 500 and 1000 mg/kg concentrations, respectively, in comparison to a control group with a lower measurement of 5.38 mm. Intriguingly, the size of the Pb clumps in the vascular cylinder significantly expanded alongside the increasing concentrations of $Pb(NO_3)_2$. This observation suggests that a higher amount of $Pb(NO_3)_2$ in the soil can lead to a greater accumulation of Pb clumps within the root tissues, while the plants continue to grow normally. Although this result indicates that this species may possess adaptable mechanisms for managing high Pb stress, it is necessary to carry out further investigation on a larger scale for a better understanding of this phenomenon and, finally, the application of this finding to treat toxic soil.

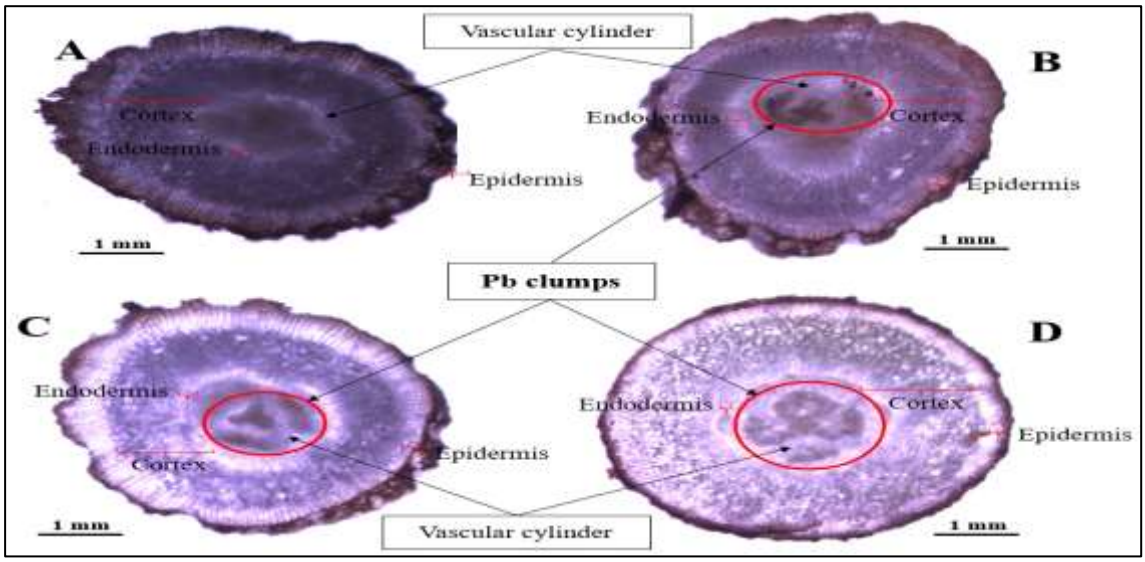

Figure 7. Cross-section of roots of *S. portulacastrum* L. (A 0-control, B, C, D were the cross sections treated with 100, 500, and 1000 mg/kg $Pb(NO_3)_2$, respectively, scale bar: 1 mm)

4. DISCUSSION

The present study indicated that the length and biomass of *S. portulacastrum* L. were increased with the increase of the salt concentrations from 1000 to 10000 mg/kg NaCl in soils after 70 days of the experiments. It illustrates that saline soils did not affect the growth of *S. portulacastrum* L. It is in agreement with the previous studies of Kannan *et al.* (2013)[32], the growth and leaf number of *S. portulacastrum* were increased with the increase of NaCl concentration from 100 to 500 mM in the nutritional solutions. Similarly, Wang *et al.* (2022)[33] reported that *S. portulacastrum* grown in a hydroponic system with 100-500 mM Na showed either equivalent fresh weights or much higher fresh weights than those grown in the same system without Na. It is interesting to note that the salt concentrations of saline soils in the experiments were decreased, while the salt contents in plant tissues were increased with the increase of the experimental time. In addition, the lower the concentration of salts in the saline soils, the higher the percentage of salt content that was removed. Particularly, the higher the concentration of salts in the soil treatments, the greater the content of salts in the plant tissues. It is in harmony with the studies of Yi *et al.* (2014)[34] and Muchate *et al.* (2016)[35], Na content in *S. portulacastrum* was increased with the increase in salt concentration in the soils. According to Wang *et al.* (2022)[33], Na plays an important role in cell expansion, leaf succulence, and shoot development of *S. portulacastrum* in comparison with that of K. On the other hand, *S. portulacastrum* L. is a halophyte,

which possesses a mechanism for salt adaptation by increasing the size of vacuoles and maintaining cytosolic metabolism to accumulate the excess Na^+. That explains the distribution of this species in marshes, salt flats, and coastal limestone areas, etc [18]. These data demonstrate that *S. portulacastrum* L. is a potential plant species in the remediation of saline soil.

On the other hand, this study also reported that the growth in length of *S. portulacastrum* L. was not affected by $Pb(NO_3)_2$ exposure in comparison with that of the control, but plant biomass was increased with the increasing of $Pb(NO_3)_2$ concentration after 70 DAT. It is in contrast with the studies of Zaier et al. (2010), who indicated that plant biomass of *S. portulacastrum* L. was decreased with the increase in concentration of $Pb(NO_3)_2$ exposures (200, 400, 800, and 1000 µM) in the environment without salinity in comparison with that of the control. Similarly, Pb treatments reduced *S. portulacastrum* L. biomass versus the control after four weeks of the experiments [36]. In other studies of Sędzik-Wójcikowska *et al.* (2023)[37], the fresh weight of Barley seedlings was declined by $Pb(NO_3)_2$ exposure during a 10-experiment-day at 25 °C and the photoperiod was set to 16:8 hours. In addition, Pb contamination of Pb inhibited the biomass growth of *Cyamopsis tetragonoloba* L. and *Sesamum indicum* L. after 12 weeks of the experiments [38]. The biomass of a plant is considered as a pivotal indicator for determining the growth performance of plants exposed to heavy metals. Plant biomass may be restricted by high concentrations of Pb, which disturb the uptake of essential nutrients in plants [39]. Interestingly, the plant biomass of *S. portulacastrum* L. was raised up upon the soil conditions exposed to $Pb(NO_3)_2$ and salinity together. Particularly, *S. portulacastrum* L. is a halophyte, known as one of the stress-tolerant plants that widely distributed in coastal located in the tropical and sub-tropical regions America, Asia, Australia, Africa, etc. [40]. This illustrates that the presence of salinity in the soil contributed to improving the biomass of *S. portulacastrum* L. under $Pb(NO_3)_2$ exposure.

Among the development of *S. portulacastrum* L., the content of Pb in the soil treatment was decreased. The data reported that Pb in the experimental soil was absorbed and mostly accumulated in the roots before transported by xylem to the shoots of *S. portulacastrum* L. during the experiment. This explains why the Pb concentrations in the soil gradually decreased during the course of the investigation. This finding was in agreement with studies by Al-Asadi *et al.* (2022)[36] and Ghnaya *et al.* (2013)[41], which found that *S. portulacastrum* L. could take up heavy metals and store them in its roots before the xylem transferred them to the shoots and leaves. In contrast, the root cells of other plants inhibit transportation of heavy metals from the roots to the shoots [42]. According to Feng *et al.* (2018)[43] reported the accumulation of Cd and Cu in *S. portulacastrum* seedlings. There was an increase in the concentration of heavy metals in the roots and shoots of *S. portulacastrum* grown in the contaminated soil [44]. Moreover, the bioaccumulation of heavy metals was also reported in other halophytes. Bareen & Tahira (2011)[45] discovered the accumulation of Cr in shoots of *Suaeda fruticosa*. In addition, *S. argentinensis* was proposed as a salt marsh halophyte that could accumulate Cr in the soil and was suggested to restore Cr-contaminated soils [46]. According to these findings, the majority of halophytes in general and *S. portulacastrum* in particular have the ability to absorb and accumulate heavy metals from contaminated soils in their roots and shoots, which helps to eliminate these harmful substances from the soil medium. Therefore, *S. portulacastrum* L. is not just a halophyte that can desalinate saline soil; it can also remove heavy metals from the soil, contribute to reducing environmental pollutants, improve agricultural soil quality, increase crop productivity and efficiency, and improve human safety.

5. CONCLUSION

In summary, the growth of *S. portulacastrum* L. was not affected by salinity and Pb pollution in the soils. The length and biomass of *S. portulacastrum* L. increased with the increase of the salt concentration during the experiments, while the biomass of *S. portulacastrum* L. exposed to $Pb(NO_3)_2$ was significant higher than that of the control. *S. portulacastrum* L. eliminated between 33% and 100% of the salt content and 7.15 to 80% of the Pb from the soil treatments after 70 days of testing. Furthermore, *S. portulacastrum* L. accumulated 4.8 to 8.8 mg/kg of salt content in its plant tissues, whereas the lead (Pb) concentration was from 120 to 3420 µg/g DW in the shoots and from 27.000 to 136.500 µg/g DW in the roots, respectively. This suggested that *S. portulacastrum* L. could absorb both salts and Pb in the soils, which contributed to reducing lead pollution

and salinity in agricultural soils, improving soil quality, increasing crop yield, and safety for humans and animals.

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Abbreviations

The following abbreviations are used in this manuscript:

DI	Deionized water
DAT	Days after transplanting
Ppt	Part per thousand
PTFE	Polytetraflouroethylene
SD	Standard deviation

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