



Research article

Sesuvium portulacastrum L. as a salt-tolerant phytostabilizer for lead (Pb) immobilization in saline agricultural soil

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Abstract

Importance of the Work: The increasing prevalence of heavy metals in agricultural soil threatens soil quality and poses serious risks to human health and requires eco-friendly and low-cost remediation solutions.

Objectives: To evaluate the potential of *Sesuvium portulacastrum* L. to remediate lead-contaminated agricultural soil by assessing its growth response under different concentrations of $\text{Pb}(\text{NO}_3)_2$ exposure.

Materials and Methods: The phytoremediation potential was evaluated during 70 d of the halophyte *S. portulacastrum* L. in $\text{Pb}(\text{NO}_3)_2$ -contaminated agricultural soil, based on quantification of the lead distribution in plant tissues, the biological concentration factor (BCF) and the translocation factor (TF).

Results: Pb accumulated predominantly in roots rather than shoots, with consistently low TF values (0.004–0.025), indicating limited root-to-shoot transport. Furthermore, the BCF values supported strong belowground enrichment, with BCF (root/soil) in the range 235.11–2,117.81 and BCF(shoot/soil) in the range 5.89–9.41 across treatments. Based on soil measurements, *S. portulacastrum* decreased soil Pb by 79.62%, 18.96% and 7.15% in soils initially amended with $\text{Pb}(\text{NO}_3)_2$ at 100 mg/kg dry weight (DW), 500 mg/kg DW and 1,000 mg/kg DW, respectively.

Main finding: Overall, the findings supported the use of *S. portulacastrum* primarily for Pb phytostabilization and risk mitigation in saline soils.

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Introduction

Growing industrialization and agricultural activities have resulted in heavy metal accumulation in agricultural soils, which has raised serious environmental concerns worldwide (Chaoua et al., 2019). Non-biodegradable heavy metals can contaminate soil and water and have a detrimental effect on human health (Priya and Nagan, 2015). The adverse impacts of heavy metals, such as lead (Pb), include a decrease in the number of soil organisms (Devi and Kumar, 2020). The problem of heavy metal contamination is pervasive and has impacted millions of hectares of land globally (Hou et al., 2025). Land degradation with expanded persistence at different speeds and geological cycles is the main recurrent cause of soil pollution or depletion. Excessive exposure to heavy metals, can negatively impact plant development and physiological cycles (Mohamed et al., 2025). The consequences include decreased germination of seeds, restricted plant growth, disturbed nutrient uptake, stifled photosynthesis and altered enzyme activity (Li et al., 2021b). Heavy metal increases in agricultural soil threaten soil quality, sustainable agriculture, food security and compound risks to human health (Nasircilar et al., 2024).

In recent years, phytoremediation has been recognized increasingly as an eco-friendly and cost-effective approach for mitigating metal-contaminated soils. Among phytoremediation candidates, halophytes have attracted considerable attention because they can tolerate saline environments where metal bioavailability, ionic interactions and rhizosphere processes differ markedly from those in non-saline soils (Van Oosten and Maggio, 2015). Recent studies have emphasized that salinity can have a substantial influence on metal uptake, translocation and compartmentalization in plants by modifying ion competition, membrane transport and metal complexation in the rhizosphere (Alsherif et al., 2023, Zhang et al., 2024). Van Oosten and Maggio (2015) noted that halophyte-based remediation may proceed through different mechanisms, including phytoextraction (involving metal uptake and translocation to harvestable shoots) and phytostabilization (where metals are immobilized or sequestered primarily in roots and the surrounding soil). Distinguishing between these mechanisms is critical for selecting appropriate remediation strategies and for accurately interpreting soil metal removal in halophyte-soil systems (Alsherif et al., 2023, Kumawat et al., 2025).

Sesuvium portulacastrum L. is a halophyte belonging to the Aizoaceae family and is salt-tolerant with high contents of vitamins and minerals that can be fed to cattle (Naman et al., 2025). It is also known as sea vegetable and is used in many

countries, including China and India, as well as in Europe and the Caribbean (Main and Waldrop, 2020). Additionally, this species contains various bioactive compounds, has a high phenolic content and is utilized commonly in traditional medicines to treat plant- and insect-based problems, as well as to improve human health (Youssif et al., 2019). Furthermore, this species is stress-tolerant and can both absorb and remove heavy metals through bioaccumulation (Sharma and Dietz, 2006). According to Feng et al. (2018), Cd and Cu were found in its roots, while Mnasri et al. (2015) indicated that the combination of Ni and Cd promoted plant growth. In addition, *S. portulacastrum* cultivated in nutritional solutions containing more than 50 mM of Ni exhibited chlorosis in the leaves due to the accumulation of Ni in the chlorenchymal tissues (Fourati et al., 2020). However, Zaier et al. (2010) noted that the dry biomass of *S. portulacastrum* L. was not affected by $\text{Pb}(\text{NO}_3)_2$ at 200 mM, while Pb was found in its shoots and roots (Ghnaya et al., 2013).

Although recent reviews and experimental evidence have suggested that many halophytes tend to retain metals in roots under saline conditions implying a phytostabilization-dominant behavior (Alsherif et al., 2023, Zhang et al., 2024), there is still no acceptable clarification of the Pb remediation mechanism of *S. portulacastrum* in agricultural soil. In particular, the available results are fragmented regarding Pb partitioning between the roots and shoots and how salinity may shift Pb uptake and translocation, which limits robust selection between shoot-harvest (phytoextraction-oriented) versus stabilization (phytostabilization-oriented) implementation in agroecosystems.

Therefore the present study investigated the ability of *S. portulacastrum* to remove lead pollution in an agricultural soil via the growth of *S. portulacastrum* under different concentrations of $\text{Pb}(\text{NO}_3)_2$ exposure, with specific attention being paid to changes in the lead content in the soil and in the uptake, distribution and accumulation of lead in plant roots and shoots. The findings may have potential applications for the phytoremediation of Pb in agricultural soils.

Materials and Methods

Chemicals and materials

S. portulacastrum L. samples were collected in March 2023 from Mai Hung village in Quynh Luu District, Nghe An Province, Vietnam, which were then used in this research at the Center for High Technology Research and Development, Vietnam Academy of Science and Technology, Hanoi, Vietnam.

The plant samples were analyzed to confirm that there was no Pb in their biomass before being used for experiments. Lead nitrate powder [$\text{Pb}(\text{NO}_3)_2$] was purchased from OlChemim Ltd. (Czech Republic), while compost fertilizer and the clean soil (without heavy metals) and ACROOTS 10SL (containing α -naphthyl acetic acid (NAA) to stimulate rooting), were purchased locally in Hanoi, Vietnam. Prior to use, the soil and compost were screened for background Pb to confirm suitability for spiking experiments. The soil was treated with 5,000 mg/kg NaCl, which restricted the growth of many plants (Kotuby-Amacher et al., 2000). Soil physicochemical properties were characterized prior to pot preparation because they strongly influence Pb bioavailability (Lu et al., 2023). Soil pH was determined using a soil-to-water ratio of 1:2.5, following standard soil analysis procedures. In addition, background Pb in the ‘clean soil’ and in the compost was measured prior to spiking to confirm suitability for the experiment

Experimental setup

The stems were cut into 12–15 cm lengths and submerged in ACROOTS 10SL root stimulant for 18 hr, prior to being grown in pots for experiments. In total, 20 young plants were grown in each pot (50 cm long $\times$ 15 cm wide $\times$ 20 cm high) containing 15 kg (fresh weight) of growth substrate prepared using a NaCl-amended soil-to-compost ratio of 14:1 (weight per weight). $\text{Pb}(\text{NO}_3)_2$ was added to obtain final soil $\text{Pb}(\text{NO}_3)_2$ concentrations of 0 mg/kg dry weight (DW) as the control, 100 mg/kg DW, 500 mg/kg DW and 1,000 mg/kg DW. For each treatment, the corresponding mass of $\text{Pb}(\text{NO}_3)_2$ was dissolved first in a small volume of deionized water and then mixed thoroughly with the soil to ensure homogeneous distribution prior to planting. Each treatment was replicated four times and watered once every 3 d with 500 mL of filtered water. Pots were arranged randomly in the greenhouse and re-randomized weekly to minimize positional effects due to light and temperature gradients. Soil moisture was maintained consistently across treatments by applying the same watering regime to all pots. These experiments were carried out from March to June 2023 in the greenhouse at 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%. The experimental unit was the pot ($n = 4$ pots per treatment), with 20 plants per pot.

Measurement of plant growth and biomass

The growth of *S. portulacastrum* under $\text{Pb}(\text{NO}_3)_2$ exposure was measured by the lengths from the growth point to the cotyledon

node at the initial day, day 14, day 28, day 56 and day 70. After 70 d, plants were harvested and their roots were processed to minimize externally adsorbed Pb. First, the roots were rinsed with tap water to remove any adhered soil particles, followed by rinsing with deionized water. Next, to desorb the surface-bound Pb and better distinguish it from the internally accumulated Pb, the roots were immersed in 20 mM CaCl_2 solution for 10 min with gentle agitation, followed by three rinses with deionized water. Plant tissues were blotted dry with absorbent paper and weighed immediately to determine fresh biomass.

Determination of heavy metal contents

Soil samples were collected once every 7 d and plant samples were collected every 14 d. The Pb in the soil and plant samples was analyzed using an inductively coupled plasma triple quadrupole mass spectrometer (Thermo Fisher Scientific) equipment. Analyzed samples were prepared in well-labeled polytetrafluoroethylene (PTFE) Teflon tubes. Each dried soil sample (1.5 g) was prepared in a well-labeled 100 mL PTFE Teflon tube and diluted with 6 mL (98%) HNO_3 , 3 mL (35%) HCl and 0.25 mL (30%) H_2O_2 solutions. An amount of 0.2 g of plant sample was digested with 4 mL of HNO_3 (65%) and 2 mL of H_2O_2 (30%). Prepared samples were allowed to sit for 8 hr to release any excess gas before being digested using a MARS6 (CEM Corporation) microwave with settings of power at 1,100 W, ramp-up time of 25 mins, retention time of 15 mins, temperature at 190 °C and cooling for 20 mins. In each analytical batch, quality assurance/quality control procedures were applied to ensure the reliability of the Pb measurements. Ultrapure water (18.2 M Ω ·cm, 25°C) and acid-washed labware were used for all dilutions and sample preparation. Reagent blanks were included in each digestion batch to monitor background contamination and blank correction was applied where appropriate. Instrument calibration was performed using multi-point external calibration standards and calibration was accepted when linearity met the laboratory criterion (coefficient of determination ≥ 0.995). Continuing calibration verification (CCV) standards and calibration blanks were analyzed periodically throughout the run to confirm instrument stability; CCV results were accepted if they were within $\pm 5\%$ of the expected value. Method detection limits (LOD) for Pb were determined using a 3σ approach and results below LOD were reported as non-detects. Method trueness was evaluated based on spike recovery experiments, yielding recoveries of 94.15–100.00% (mean approximately 98%). Analytical precision was assessed using replicate measurements, with acceptable repeatability percentage relative standard deviation (generally %RSD < 5%).

Determination of biological concentration factor and translocation factor

Plant capacity for the removal of Pb from the soil was determined based on the biological concentration factor (BCF) index, which was measured by dividing the concentration of Pb in the plant by the Pb concentration in the soil (Abbas et al., 2019), using Equation 1:

$$\text{BCF} = \text{Lead concentration in plant} / \text{Lead concentration in soil} \quad (1)$$

The translocation factor (TF) is an index that describes the plant's capacity to translocate Pb from roots to shoots, which was determined from the shoot-to-root heavy metal concentration ratio (Alharbi et al., 2019), using Equation 2:

$$\text{TF} = \text{Lead concentration in shoots} / \text{Lead concentration in roots} \quad (2)$$

Stereomicroscopic observation

Fresh roots were thoroughly washed with deionized water, cut into tissue sections using a sharp razor blade and then observed immediately and photographed using a stereomicroscope (Nikon SMZ800) with a base magnification of 1–8 $\times$ and a 5 megapixel digital camera (Nikon DS-Fi1) to determine how Pb²⁺ entered plant cells. The NIS-Elements Viewer software (Nikon Instruments Inc.) was used to analyze images.

The tolerance index (TI = Final treatment biomass / Final control biomass) values were 1.115, 1.287 and 1.425 for the Pb(NO₃)₂ treatments at 100 mg/kg DW, 500 mg/kg DW and 1,000 mg/kg DW, respectively, indicating no growth inhibition under the tested conditions.

Data analysis

The experimental unit was the pot ($n = 4$ per treatment). For time-series outcomes, namely plant length over days after transplanting (DAT) and soil Pb remaining over time, data were analyzed using linear mixed-effects models with treatment, time and their interaction as fixed effects and pot as a random intercept (repeated measures). *Post-hoc* comparisons were adjusted for multiple testing. For end-point variables measured once (final biomass, tissue Pb, BCF, TF, and TI), one-way analysis of variance (ANOVA) was used when assumptions were met; otherwise, appropriate transformations or non-parametric tests were applied. Alongside p -values ($\alpha = 0.05$), effect sizes (partial η^2 for ANOVA, where η^2 is the proportion of variance explained by a given variable

of the total variance remaining after accounting for variance explained by other variables in the model) and 95% confidence intervals were reported. All results were presented as mean $\pm$ SD values. For repeated-measures variables, statistical comparisons distinguished between: 1) differences among treatments within the same sampling time; and 2) temporal changes within each treatment across sampling times. These comparisons were derived from the linear mixed-effects model consisting of treatment, time and treatment $\times$ time interaction.

Results

Effects of Pb on *S. portulacastrum* growth

Plant length increased progressively over time in all treatments, indicating that *S. portulacastrum* maintained normal growth under Pb exposure. Overall, time had a highly significant effect on plant length ($p < 0.001$), reflecting continuous growth throughout the experimental period. Generally, differences among treatments at individual sampling times were small, although significant ($p < 0.05$) differences were observed during later growth stages. The longest plant length (53.50 cm) was observed in the Pb(NO₃)₂ treatment at 1,000 mg/kg DW treatment, followed by 52.50 cm and 51.75 cm in the Pb(NO₃)₂ treatments at 500 mg/kg DW and 100 mg/kg DW, respectively, which were slightly greater than the control (50.75 cm) at 70 DAT (Fig. 1).

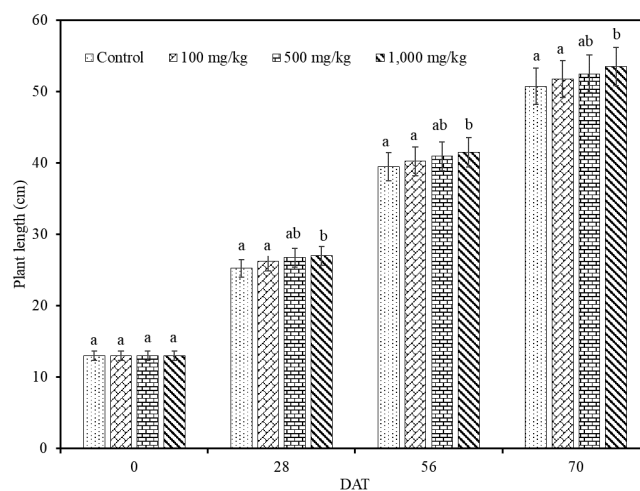


Fig. 1 Growth of *Sesuvium portulacastrum* L. in length under Pb(NO₃)₂ treatments, where different lowercase letters indicate significant ($p < 0.05$) differences among Pb(NO₃)₂ treatments within same sampling time, bars represent mean $\pm$ SD values ($n = 4$), DAT = days after treatment and statistical comparisons were performed using linear mixed-effects models (treatment, time and treatment $\times$ time interaction, followed by *post-hoc* comparisons)

Based on these results, $\text{Pb}(\text{NO}_3)_2$ exposure did not inhibit plant growth under saline conditions and may have been associated with increased biomass production, although treatment differences became more apparent mainly at later time points.

Notably, there was a significant ($p < 0.05$) difference in plant biomass between the initial and final experiments in the control as well as for the different concentrations of $\text{Pb}(\text{NO}_3)_2$ and in the final biomass of plants after 70 d of experiments between the control and the different concentrations of $\text{Pb}(\text{NO}_3)_2$ treatments. There was a large increase in the plant biomass with increasing concentrations of $\text{Pb}(\text{NO}_3)_2$ after 70 d of experiments (Fig. 2). In particular, the highest plant biomass was 31.00 g/plant for the treatment with 1,000 mg/kg $\text{Pb}(\text{NO}_3)_2$ DW, followed by 28.00 g/plant and 24.25 g/plant in the plants exposed to the $\text{Pb}(\text{NO}_3)_2$ treatments at 500 mg/kg DW and 100 mg/kg DW, respectively, and was the lowest (21.75 g/plant) in the control. These findings illustrated that $\text{Pb}(\text{NO}_3)_2$ boosted *S. portulacastrum* growth rates by 42.53%, 28.74% and 11.49% for exposures to $\text{Pb}(\text{NO}_3)_2$ treatments at 1,000 mg/kg DW, 500 mg/kg DW and 100 mg/kg DW, respectively, compared to the control (Fig. 2). Notably, Pb was applied as $\text{Pb}(\text{NO}_3)_2$; therefore, increasing the $\text{Pb}(\text{NO}_3)_2$ levels also introduced additional nitrate-derived nitrogen, which may have partially contributed to the observed increase in biomass. Based on stoichiometric calculations, $\text{Pb}(\text{NO}_3)_2$ contains approximately 8.45% nitrogen by mass; thus, the highest Pb treatment

(1,000 mg/kg $\text{Pb}(\text{NO}_3)_2$ DW) corresponds to about 84.5 mg N/kg soil, while the 500 mg/kg and 100 mg/kg treatments corresponded to approximately 42.3 and 8.45 mg N/kg soil, respectively. This additional nitrogen input should be considered when interpreting the biomass response shown in Fig. 2.

Pb removal efficiency in the soils by S. portulacastrum L.

The soil Pb concentration decreased progressively over time in all treatments, indicating continuous Pb removal during the experimental period. Time had a highly significant ($p < 0.001$) effect on soil Pb concentration. Differences among treatments within the same sampling time were also significant ($p < 0.05$), indicating that Pb removal efficiency varied depending on the initial contamination level. A significant treatment $\times$ time interaction was also observed, indicating that the rate of Pb reduction differed among treatments over the experimental period. The greatest reduction was observed in the 100 mg/kg treatment, where soil Pb decreased to 20.38% of the initial concentration after 70 d, corresponding to 79.62% removal efficiency. In contrast, lower removal efficiencies were observed at higher Pb concentrations, with 18.96% and 7.15% removal for the 500 mg/kg and 1,000 mg/kg treatments, respectively (Table 1). Based on these results, both time and initial Pb concentration influenced remediation efficiency.

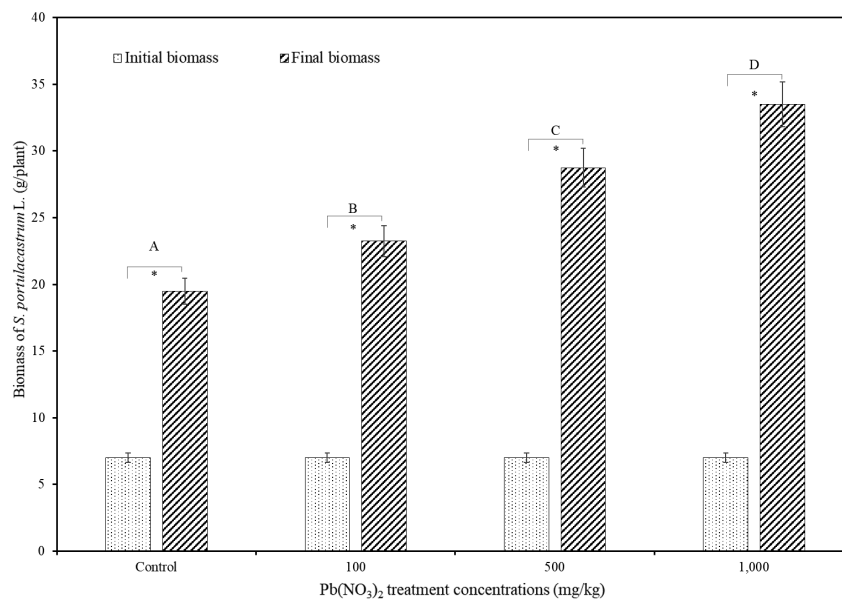


Fig. 2 Growth of *Sesuvium portulacastrum* L. in biomass under $\text{Pb}(\text{NO}_3)_2$ treatments after 70 d. An asterisk (*) above each pair of bars indicates significant difference ($p < 0.05$) between initial and final biomass, while different uppercase letters above the final biomass bars indicate significant differences ($p < 0.05$) among $\text{Pb}(\text{NO}_3)_2$ treatments at 70 d (one-way analysis of variance, followed by Tukey's honestly significant difference test). Error bars represent mean $\pm$ SD ($n = 4$).

Table 1 Soil Pb remaining (%) relative to initial concentration at various days after treatment (DAT)

Treatment (Pb mg/kg)	Initial	14 DAT	28 DAT	42 DAT	56 DAT	70 DAT
100	100.00	93.20	90.00	61.13	42.38	20.38
500	100.00	99.00	98.00	97.00	86.08	81.04
1,000	100.00	100.00	99.50	98.11	94.21	92.85

Accumulation of Pb in shoots and roots of *S. portulacastrum*

Notably, there was a significant ($p < 0.05$) difference in the Pb content in shoots and roots between the different treatments of $\text{Pb}(\text{NO}_3)_2$ after 70 d of the experiments (Fig. 3). Among the increasing of $\text{Pb}(\text{NO}_3)_2$ concentration, the Pb content rose substantially in both roots and shoots, especially the significantly higher Pb content in the roots. In particular, the Pb content measured in the shoot DW harvested from plants grown in the soil treated with $\text{Pb}(\text{NO}_3)_2$ at 100 mg/kg was 120 mg/kg. Shoots from the treated soil with 500 mg/kg and 1,000 mg/kg $\text{Pb}(\text{NO}_3)_2$ had significantly higher concentrations, with levels around 2,070 mg/kg (approximately 17-fold greater) and 3,420 mg/kg (about 28.5 times greater), respectively (Fig. 3A). A similar pattern was observed in the roots, where Pb concentrations were notably higher at 27,000 mg/kg DW, 106,500 mg/kg DW and 136,500 mg/kg DW in the $\text{Pb}(\text{NO}_3)_2$ treatments at 100 mg/kg DW, 500 mg/kg DW and 1,000 mg/kg DW, respectively (Fig. 3B). It was particularly noteworthy that in the case of the 100 mg/kg $\text{Pb}(\text{NO}_3)_2$ treatment, the Pb concentration in the roots was 225 times greater than that in the shoots following at 70 days. Furthermore, for plants exposed to $\text{Pb}(\text{NO}_3)_2$ at 500 mg/kg and 1,000 mg/kg, the Pb contents in the roots were 51.45 times and 39.91 times higher, respectively, compared to those in the shoots after 70 d of the experiment. Based on these results, Pb accumulated in significant amounts in both the shoots and roots of *S. portulacastrum*, with a markedly higher rate of accumulation in the roots than the shoots.

Biological concentration factor and translocation factor

The BCF and TF values (Table 2) were calculated to evaluate the Pb uptake and within-plant partitioning. The TF (the shoot Pb-to-root Pb ratio) values were in the range 0.004–0.025, confirming there was very limited root-to-shoot translocation across all $\text{Pb}(\text{NO}_3)_2$ treatments.

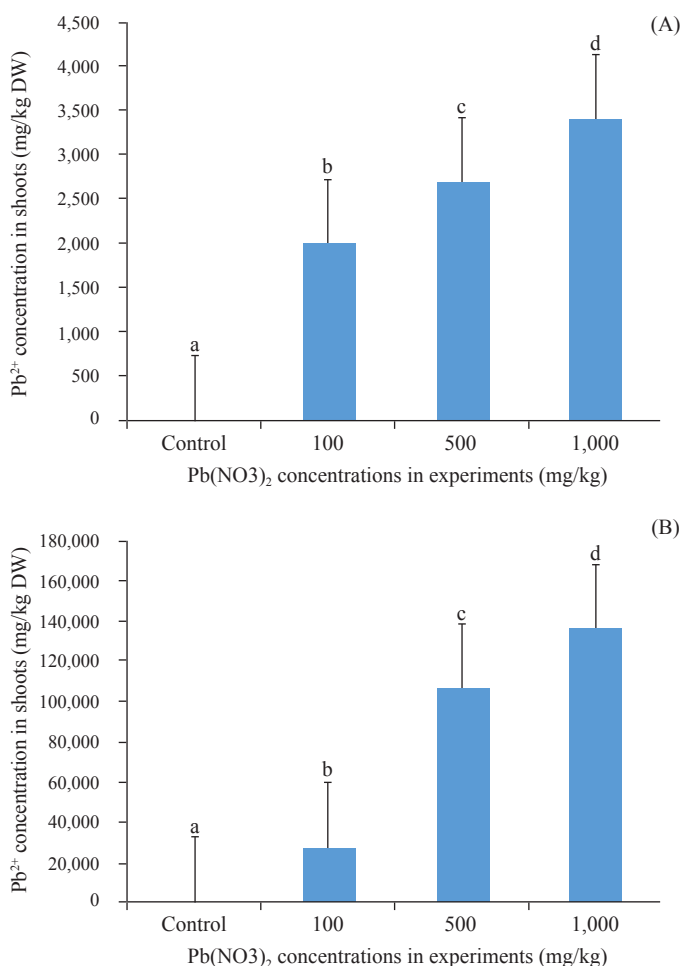


Fig. 3 Accumulation of Pb in *Sesuvium portulacastrum* L. in: (A) shoots; (B) roots. Different lowercase letters above bars indicate significant differences among treatments within same plant organ ($p < 0.05$) based on one-way analysis of variance, followed by Tukey's honestly significant difference test. Bars represent mean $\pm$ SD ($n = 4$).

Table 2 Indexes for biological concentration factor (BCF) and translocation factor (TF)

Index	Pb(NO ₃) ₂ concentration treatment (mg/kg)		
	100	500	1,000
BCF (shoots/soil)	9.41	8.17	5.89
BCF (root/soil)	2,117.81	420.31	235.11
TF	0.004	0.019	0.025
TI	1.115	1.287	1.425

The BCF (the ratio of tissue Pb concentration to the corresponding remaining soil Pb concentration at 70 DAT) is shown in Table 2. The BCF root value was substantially higher than for the shoots in all treatments, consistent with the predominant Pb retention in the roots. Specifically, for the $\text{Pb}(\text{NO}_3)_2$ treatments at 100 mg/kg DW, 500 mg/kg DW and 1,000 mg/kg DW, the BCF(shoot/soil) decreased from 9.41 to 8.17 and 5.89, respectively, while the BCF(root/soil) decreased from 2,117.81 to 420.31 and 235.11, respectively. The decreasing BCF trend with increasing $\text{Pb}(\text{NO}_3)_2$ dose reflected the much higher remaining soil Pb at higher initial contamination levels (lower percentage reduction at 500–1,000 mg/kg), rather than a shift toward greater shoot accumulation.

Pb distribution in root tissue

The plant roots 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 (Li et al., 2021a). As illustrated in Fig. 4, there was a large accumulation of Pb in the root cortex and endodermis, while the thickness of the epidermis decreased substantially with increasing $\text{Pb}(\text{NO}_3)_2$ concentration. Furthermore, the root diameter increase notably ($p < 0.05$) in response to higher $\text{Pb}(\text{NO}_3)_2$ exposures, reaching 6.04 mm in the 100 mg/kg DW treatment and 6.25 mm and 6.42 mm in the

500 mg/kg DW and 1,000 mg/kg DW, respectively, compared to the control group with a lower measurement of 5.38 mm. Also notable was the size of the Pb aggregates in the vascular cylinder that significantly expanded with the increasing concentration of $\text{Pb}(\text{NO}_3)_2$. This observation suggested that a higher amount of $\text{Pb}(\text{NO}_3)_2$ in the soil can lead to a greater accumulation of Pb aggregates within the root tissues, while the plants continue to grow normally. Although this finding indicated that this species may possess adaptable mechanisms for managing high Pb stress, further investigation are required on a larger scale for a better understanding of this phenomenon and, eventually, the application of this finding to treat toxic soil.

Discussion

The growth of *S. portulacastrum* under different concentrations of $\text{Pb}(\text{NO}_3)_2$ was investigated; however, the results contrasted with other published studies. According to Zaier et al. (2010), the biomass of *S. portulacastrum* L. decreased with an increasing concentration of $\text{Pb}(\text{NO}_3)_2$ (200 μM , 400 μM , 800 μM , 1,000 μM) in the environment without salinity compared to the control. Similarly, (Al-Asadi et al., 2022) reported that Pb treatments reduced the biomass of *S. portulacastrum* L. versus the control after 4 wk of the experiment. In addition, the effects of Pb on the biomass of other plants has been studied. For example, the fresh weight of barley seedlings declined following $\text{Pb}(\text{NO}_3)_2$ exposure during a 10 d experiment at 25°C with the light:darkness photoperiod set to 16:8 hours (Sędzik-Wójcikowska et al., 2023). Elsewhere, soil contaminated with Pb inhibited the biomass growth of *Cyamopsis tetragonoloba* L. and *Sesamum indicum* L. after 12 wk of the experiment (Amin et al., 2018). Thus, the biomass of plants serves as a crucial indicator in assessing the growth performance of those exposed to heavy metals. High concentrations of Pb can hinder plant biomass by disrupting the uptake of essential nutrients (Gopal and Rizvi, 2008). However, in the present study, the biomass of *S. portulacastrum* increased when grown in soil contaminated with $\text{Pb}(\text{NO}_3)_2$ and exposed to high salinity. Notably, *S. portulacastrum* L. is a halophyte, recognized for its stress tolerance, and is widely distributed in coastal areas across tropical and subtropical regions of America, Asia, Australia and Africa (Heneidy et al., 2024). According to Song and Wang (2014), salt promotes halophytes to grow larger and more rapidly in an appropriate salt concentration environment than in conditions with little or no salt.

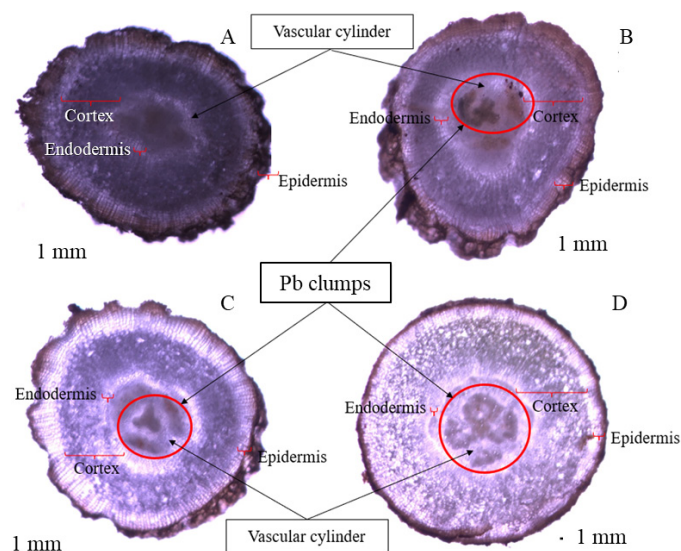


Fig. 4 Cross sections of roots of *Sesuvium portulacastrum* L. under different treatments of $\text{Pb}(\text{NO}_3)_2$: (A) 0 mg/kg $\text{Pb}(\text{NO}_3)_2$ dry weight (DW) (control); (B) 100 mg/kg $\text{Pb}(\text{NO}_3)_2$ DW; (C) 500 mg/kg $\text{Pb}(\text{NO}_3)_2$ DW; and (D) 1,000 mg/kg $\text{Pb}(\text{NO}_3)_2$ DW.

In particular, high salt concentrations are advantageous to most halophytes throughout a range of processes from seed germination to seedling growth. For example, higher germination percentages of halophytes, such as *Cakile maritima* and *Chloris virgata* were reported at slightly elevated salinity levels (0.5% NaCl or 50–90 mM) than with distilled water (Zhang et al., 2012, Qu et al., 2007). In addition, the appropriate NaCl concentrations in the soil increase the seedling growth of halophytes compared to non-salt conditions. Consequently, the seedling biomass is greater, the leaf area is larger and the photosynthetic efficiency and yield are enhanced, thus leading to improve seed production for the next generation (Yuan et al., 2018, Balnokin et al., 2004, Guo et al., 2018). This supports the results of the present study where salinity in the soil enhanced the biomass of *S. portulacastrum* grown in an environment exposed to $\text{Pb}(\text{NO}_3)_2$.

Sustainable agricultural development is being threatened increasingly by heavy metal contamination due to the persistence of these pollutants and their harmful impacts on ecosystems and human health (Rajkumar et al., 2009). Heavy metals can disrupt plant physiological and molecular processes, including nutrient uptake and metabolism and may be absorbed by roots with variable degrees of translocation to shoots, depending on the metal and the soil conditions (Zhang et al., 2024, Wei et al., 2003, Carrier et al., 2003). In the present study, Pb was taken up from the contaminated soil and accumulated predominantly in roots, with only limited transfer to shoots, indicating that root sequestration was the main uptake outcome under the saline conditions tested. This root-dominated Pb partitioning was consistent with other reports for *S. portulacastrum*, where metals were largely retained in belowground tissues, while shoot translocation was comparatively lower (Ghnaya et al., 2013, Al-Asadi et al., 2022). Similar accumulation patterns have been reported in other halophytes, supporting the view that halophyte-based remediation in saline environments often operates mainly through stabilization and immobilization in the roots and the rhizosphere rather than through efficient phytoextraction via the shoot harvesting (Bareen and Tahira, 2011, Redondo-Gómez et al., 2011).

The BCF and TF provide important insights into the Pb remediation mechanism of *S. portulacastrum*. In the present study, Pb accumulated predominantly in the roots, while TF values consistently remained far below unity (0.004–0.025), indicating very limited root-to-shoot translocation. This uptake pattern clearly differed from that required for effective phytoextraction, which relies on high metal

translocation to harvestable aboveground biomass. Instead, the observed Pb distribution is characteristic of phytostabilization, where metals are immobilized or sequestered mainly in root tissues and the rhizosphere, thereby reducing metal mobility and bioavailability in soil.

Therefore, the steady decline in the soil Pb concentration observed during the present experiment could be attributed primarily to Pb uptake and retention in the roots rather than to efficient translocation to the shoots. This interpretation was consistent with other studies reporting that *S. portulacastrum* preferentially accumulated heavy metals in the roots under both saline and non-saline conditions (Ghnaya et al., 2013, Al-Asadi et al., 2022, Feng et al., 2018). Similar root-dominated accumulation patterns have been reported in other halophytes, such as *Suaeda fruticosa* and *S. argentinensis*, where metal sequestration in the belowground tissues contributed to the stabilization of contaminated soils rather than metal removal via shoot harvesting (Bareen and Tahira, 2011, Redondo-Gómez et al., 2011).

Salinity plays a crucial role in modulating metal uptake and partitioning in halophytes. Under the NaCl-amended conditions applied in the present study, Pb translocation to the shoots remained limited, despite enhanced plant growth, suggesting that salinity favored root retention rather than long-distance transport of Pb. Elevated ionic strength and competitive cation interactions under saline conditions may promote Pb immobilization in root tissues and cell walls, thereby reinforcing a phytostabilization-dominant behavior. Similarly, recent studies on halophytes have reported that salinity can shift metal accumulation toward roots and reduce shoot translocation, emphasizing stabilization rather than extraction as the dominant remediation pathway (Zhou et al., 2023, Ishtiyag et al., 2023). Taken together, these findings demonstrated that *S. portulacastrum* functioned primarily as a phytostabilizer in Pb-contaminated saline soils. Although the species had high stress tolerance and substantial biomass production, its low TF values indicated limited suitability for phytoextraction-based remediation strategies. Instead, *S. portulacastrum* could be applied more appropriately for Pb stabilization and risk mitigation in saline agricultural soils, where reductions in metal mobility and bioavailability are priorities.

Alsherif et al. (2023) reported that *S. portulacastrum* deployed multiple physiological and biochemical mechanisms to mitigate heavy metal stress, including enhanced carbohydrate metabolism (amylase activity and sucrose-related pathways), activation of antioxidant molecules (tocopherols) and shifts in amino-acid profiles (associated with stress tolerance and

adjustments in fatty-acid composition that support membrane stability). These coordinated responses could help to explain the strong tolerance and biomass maintenance observed in *S. portulacastrum* under combined salinity and Pb stresses. Notably, in the present study the consistently low TF values and the pronounced Pb retention in the roots indicated that this species would be more suitable for Pb phytostabilization and risk mitigation in saline soils than for Pb removal via shoot harvesting.

Conclusions

Sesuvium portulacastrum maintained strong biomass production under Pb(NO₃)₂ exposure in NaCl-amended soil. Lead was taken up primarily by roots, while only limited Pb was translocated to shoots (TF = 0.004–0.025). After 70 d, soil Pb decreased by 79.62%, 18.96% and 7.15% in soils initially amended with Pb(NO₃)₂ treatments at 100 mg/kg DW, 500 mg/kg DW and 1,000 mg/kg DW, respectively. Given the consistently low TF values and strong root accumulation, the dominant remediation pathway of *S. portulacastrum* was phytostabilization rather than phytoextraction. Bioconcentration factors further supported root sequestration, with BCF (root/soil) in the range 235.11–2,117.81 and BCF(shoot/soil) in the range 5.89–9.41 (70 DAT). Therefore, this species appears particularly suitable for Pb stabilization and risk mitigation in saline soils, whereas Pb removal through shoot harvesting could be expected to be limited under the conditions tested.

Author contributions

Van Nhan Le, Quang Minh Bui conceived and designed the experiments; Thi Quynh Bui, Thi Nguyet Linh Nguyen, Van Duong Giap and Ha Minh Duc Tran performed the experiments; Ha Minh Duc Tran, Thi Nguyet Linh Nguyen, Hai Linh Hoang, Hung Manh Nguyen analyzed the data; Dinh Vinh Nguyen, Van Diep Le, Thi Thanh Mai Nguyen, contributed reagents/materials/analysis tools; Van Nhan Le, Van Diep Le and Thi Thanh Mai Nguyen wrote the paper.

Conflicts of Interest

The authors declare no conflicts of interest. This study was supported by the Vietnam Academy of Science and Technology (project title “Research on phytochemicals and bioactive compounds in *Suaeda maritima* L. Dumort and *Sesuvium portulacastrum* L. species”) with project code QTHU01.02/26-28.

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