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RESEARCH

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Comparative seed-level lithium tolerance in two ecotypes of Iranian *Scrophularia striata* Boiss.

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Abstract

Lithium (Li), as an emerging environmental contaminant, can disrupt plant physiological processes, underscoring the importance of investigating tolerant species to identify suitable candidates for restoring contaminated soils. This study assessed the impact of Li_2CO_3 and Li_2SO_4 (0, 50, 150, 250 mM) on seed germination and early growth of two drought-tolerant *Scrophularia striata* ecotypes, Lizan and Pahleh. Measured parameters included germination rate, final germination percentage (FGP), mean germination rate (MGR), germination index (GI), coefficient of velocity of germination (CVG), germination rate index (GRI), first and last germination time (FDG, LDG), time spread of germination (TSG), Timson index (TGI), seedling vitality index (SVI), seedling, root, and stem length, as well as fresh and dry weight. The Pahleh ecotype showed strong resistance to both Li forms at 50 and 150 mM, with a significantly higher MGR than the control at these concentrations. The Lizan ecotype maintained higher growth under Li stress, while Pahleh seedlings were about two times shorter under Li_2SO_4 and 1.5 times shorter under Li_2CO_3, indicating the superior Li tolerance of Lizan. The Pahleh ecotype showed no significant biomass change between the control and some Li concentrations. At 150 mM Li_2CO_3, the Pahleh ecotype showed no significant change in germination, indicating high Li tolerance. Li form and concentration influenced tolerance and growth in both ecotypes. S. striata, especially Lizan, appears suitable for Li-contaminated arid lands.

Keywords Arid polluted lands, Lithium toxicity, Germination, Soil erosion, Ecotypic variation

1 Introduction

Lithium (Li) plays a significant role in the global economy; however, the industrial extraction of this metal has led to the contamination of agricultural lands. Most of the lithium-contaminated lands are uncultivable. Li is being released into water and soil from various sources, including mining, smelting, and disposal of Li-ion batteries [1, 2]. The production of electronic waste (e-waste) has risen alongside the increased use of electronic devices. A key component in most portable electronic gadgets is the Li-ion battery, which is a highly efficient energy storage technology. Over recent decades, both consumer and industrial sectors have seen a growing adoption of Li-based batteries [3].

Depending on the geochemical elements, soil structure, and the kind of water bodies, the concentration of Li varies in various situations. Potential sources of Li contamination could be agricultural fields close to Li-based industry [4]. More consideration should be given to the rise in Li contents in soil because the harmful effects on living organisms are dose-correlated [5].

Due to the consideration of Li's effects on human health and the environment, numerous remediation techniques have been suggested to lessen Li's toxicity, such as phytoremediation, Phytoextraction, phytostabilization, soil amendments, immobilization, and using Li-tolerant plant genotypes [6–10]. Li is extremely harmful to plants, alters their physiology and biochemistry significantly, and slows down growth. Briefly, Li stunts plant growth by oxidizing DNA and damaging the photosynthetic system. Li also prevents plants from signaling with calcium and the inositol cycle [11, 12]. These lands are, therefore, vulnerable to erosion because they are not very arable. Introducing species that can be grown on these lands stops soil erosion because of the established vegetation cover. Therefore, it is of crucial importance to find tolerant species for Li-contaminated areas.

Scrophularia striata Boiss. (*S. striata*) has about 300 species and is one of the main genera belonging to the Scrophulariaceae family. A prominent angiosperm family is Scrophulariaceae, which is widely distributed in central Asia, Europe, and North America, and is represented by about 3000 species and 220 genera [13, 14]. *S. striata* is a perennial plant known as "Tashneh Dari", and widely distributed in several regions throughout the world, especially in Iran [15, 16]. The distribution of *S. striata* is in the semi-arid and arid regions of southwest Iran [17]. In traditional medicine, this plant is used for healing allergies, rheumatism, severe inflammatory disorders, and wounds [18]. Alkaloids, phenolics, flavonoids, iridoids, and resin glycosides are active ingredients of *S. striata* that are generally found in various parts of the plant [19–21].

Soil erosion significantly threatens food security, water supplies, biodiversity, and ecosystems, exacerbated by agricultural expansion [22]. To mitigate the concurrent problems of soil degradation and Li contamination in arid areas, cultivating drought-resistant plant species can serve as an effective strategy. For instance, species such as *Atriplex* sp., *Salsola* sp., and the studied species S. *striata* demonstrate remarkable drought tolerance. These plants, by their resilience to water scarcity, can thrive in harsh conditions where other vegetation might fail, thereby stabilizing the soil and preventing erosion [23–25]. The strategic use of such plants on Li-contaminated lands not only controls erosion but also takes care of phytoremediation, since plants have the potential to uptake and immobilize Li, thereby decreasing its mobility and bioavailability. This dual functionality enhances the ecological restoration of degraded lands, promoting soil health and improving environmental quality [26, 27]. Choosing a drought-tolerant species that is specifically suited for Li-polluted soils can enhance these advantages, promoting sustainable land management practices that support environmental conservation efforts. This highlights the critical role of plant-based interventions in addressing complex ecological issues, offering a sustainable pathway to rehabilitate and utilize polluted lands effectively. This study aimed to evaluate the potential of *S. striata* as a tolerant plant for arid areas [28] for Li-polluted lands and also to investigate its Li-related tolerance capacity. The two selected ecotypes were considered more drought-tolerant. Therefore, the purpose of this research is to evaluate the ability of two drought-tolerant *S. striata* ecotypes to be cultivated in arid, Li-contaminated lands, to reduce/stop erosion, and to prevent the erosion of these previously uncultivable lands.

2 Materials and methods

2.1 Plant material

For this investigation, two *S. striata* ecotypes were used. Plants were gathered during the seed setting stage from two areas of Ilam province, Iran; namely Lizan (Longitude: 46° 8′ 19.42″ E; Latitude: 33° 34′ 2.16″ N) and Pahleh (Longitude: 46° 50′ 43.16″ E; Latitude: 33° 2′ 27.28″ N) in the spring, 2022 (Fig. 1). The collection of plant aerial shoots intended for later seed collection was done following national and scientific guidelines as described by Esmaeili et al. (2019) and based on the International Standard for Sustainable Wild Collection of Medicinal and Aromatic Plants (ISSC-MAP) (Version 1.0) prepared by the Medicinal Plant Specialist Group of the IUCN Species Survival Commission (The World Conservation Union) [29]. Also, permission to collect seeds was obtained from the Iranian Natural Resources and Watershed Management Organization. The plant was authenticated and preserved with a specific code. For about a week, the plant was air-dried. After that, the dried seeds were removed and kept for further experiments at 4 °C [30].

2.2 Chemicals

Li carbonate (Li_2CO_3) and Li sulfate (Li_2SO_4) were used to prepare the solutions in this experiment. The mentioned chemicals were purchased from Merck (Germany), diluted in desired concentrations, i.e., 50, 150, and 250 mmol/L, and then used in the germination and initial growth tests. Solutions were prepared on a magnet stirrer. The solvent for both mentioned chemicals was distilled water.

2.3 Pretreatment assay

Before the experiment, the uniform and healthy *S. striata* seeds from the two aforementioned ecotypes were sterilized in a 10% Na-hypochlorite solution for 20 min to stop

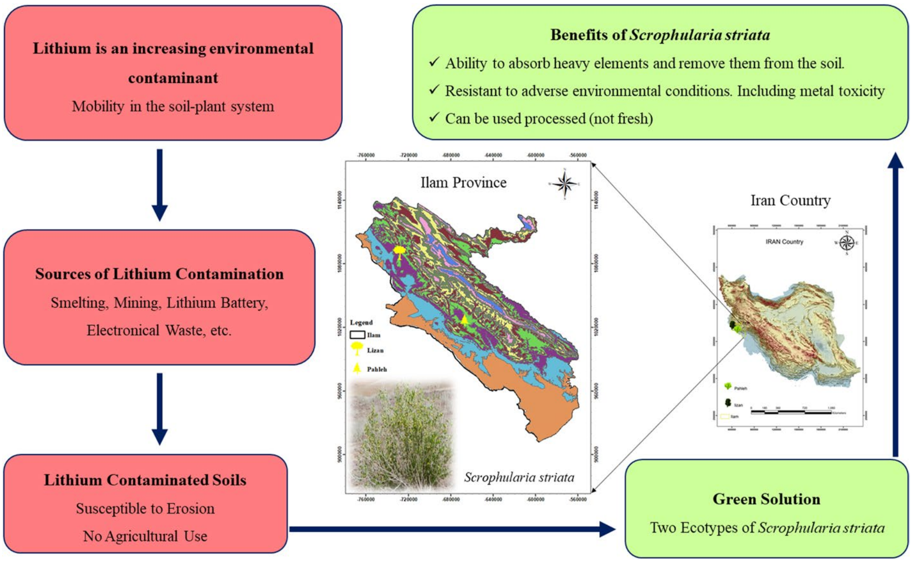

Fig. 1 Methodology flowchart: from material collection to experimental assays

fungal development before being repeatedly rinsed with distilled water. Then, they were exposed to 2 forms of Li solutions, at concentrations of 0 (control, distilled water), 50, 150, and 250 mmol/L. Preliminary tests were used to determine the concentrations. In glass beakers containing 100 mL of each solution individually, seeds of each population were put in and submerged, containing Li_2SO_4 and Li_2CO_3. During imbibition, Li solutions were applied to the seeds (24 h). Seeds submerged in 100 mL of distilled water were used as controls. All the incubation and control solutions were made with distilled water. Continuous aeration was applied to the liquids in which the seeds were submerged. For each pre-treatment, 25 seeds were used, and all experiments were conducted in three replicates.

2.4 Bioassay

To conduct the germination test, 25 treated *S. striata* seeds from each solution concentration (treatment), on Whatman No. 1 filter paper moistened with 4 mL of the prepared solutions were used. To prevent evaporation, plastic containers were sealed with parafilm and placed in a phytotron chamber (1300 STC Mod, Noor Sanat Ferdows Company, Karaj, Iran). The experiment was conducted at 27 ± 2 °C (day) and 23 °C (night), 4000 lx, and 16/8 h (Light/Dark) photoperiod. Whenever the filter paper began to dry, water containing trace metals at the aforementioned concentrations was used to water the seeds instead of just distilled water (the control). The tests lasted 12 days. The germination of the seeds in each dish was monitored every day for the duration of the experiment (12 days). Germination was recorded when the radicle length reached at least 1 mm; germinated seeds were noted but remained in the Petri dishes throughout the observation period. After this time, no seed germinations were seen. The seeds from two separate ecotypes, Lizan and Pahleh, were used in all trials. Following test completion, evaluations included measurements of seedling length, primary roots, shoots, and fresh and dry biomass (after placing seedlings at 50 °C in a hot air oven for 24 h until a constant weight was observed). Daily recorded data are employed to assess other germination and growth indices including final germination percentage (FGP), mean germination rate (MGR), germination index (GI), coefficient of the velocity of germination (CVG), germination rate index (GRI), the first day of germination (FDG), last day of germination (LDG), time spread of germination (TSG), Timson Index (TGI), seedling vitality index (SVI), seedling length, root length, stem length, fresh weight and dry weight for each treatment (Table S1) [18, 31–36]. Initial growth parameters, including stem, root, and seedling length, and fresh and dry biomass, were also measured by ruler and scale (4-digit). All growth indices were calculated using Excel and RStudio [37] with the germination metrics package for calculating various germination and growth indices [38].

2.5 Statistical analysis

Three replications of each treatment were used in the experiment, which was set up using a fully randomized factorial design. Minitab statistical software (version 17) was used to conduct the normality test and evaluate the data's normality. Statistical analysis was performed using Minitab software through a general linear model, specifically a two-way analysis of variance (ANOVA). Statistical significance was set at $p < 0.05$ (Tukey's test). Principal component analysis (PCA) was performed using R software (version 4.1.1) within RStudio (version 2022.05.0-496; Posit, Boston, MA, USA) to reduce the dimensionality of the dataset and identify the main patterns of variation among the measured germination and growth indices. This approach allowed the authors to determine which variables contributed most to the observed differences, thereby supporting the study's objectives.

3 Results

3.1 Seed germination indices of *S. striata* ecotypes following lithium toxicity

Results revealed that Li toxicity affected germination indices of *S. striata* ecotypes variously depending on concentrations and Li forms (Table S2). The FGP and GI of *S. striata* seeds were significantly affected by Li_2SO_4 and Li_2CO_3 (Fig. 2a and d). Pahleh ecotype under the two mentioned forms of Li at concentrations of 50 and 150 mmol/L showed significant resistance. Minimum MGR was related to 250 mmol/L Li_2CO_3 in both ecotypes. MGR in Pahleh ecotype at 50 and 150 mmol/L (both Li_2CO_3 and Li_2SO_4) increased significantly towards the control. Lizan in both forms of Li did not show a significant difference in MGR among studied concentrations (Fig. 2b). Concerning GRI, Lizan ecotype up to 150 mmol/L (Li_2SO_4) did not show a significant difference towards the control treatment, while a significant reduction in GRI at 50 and 150 mmol/L (Li_2CO_3) was observed. Pahleh ecotype at 50 mmol/L in both Li forms showed a significant GRI increase towards control, which can be a promising sign of this ecotype's resistance to Li toxicity (Fig. 2c).

Surprisingly, Pahleh ecotype under Li_2SO_4 showed a significant increase of GI and CVG at 50 mmol/L towards control, while the Lizan ecotype did not show a significant difference at 50 mmol/L towards control at both forms of Li toxicity (Figs. 2d and 3a). Maximum FDG and LDG were significantly observed at 250 mmol/L of Li_2CO_3 in both ecotypes, while there was no significant difference with Li_2SO_4 at various concentrations (Fig. 3b and c). Under Li_2CO_3 toxicity, TSG was enhanced in both ecotypes by increasing the concentration, while TSG under Li_2SO_4 toxicity in both ecotypes did not show significant variation from the control (Fig. 3d). Under Li_2CO_3 toxicity, minimum TGI was

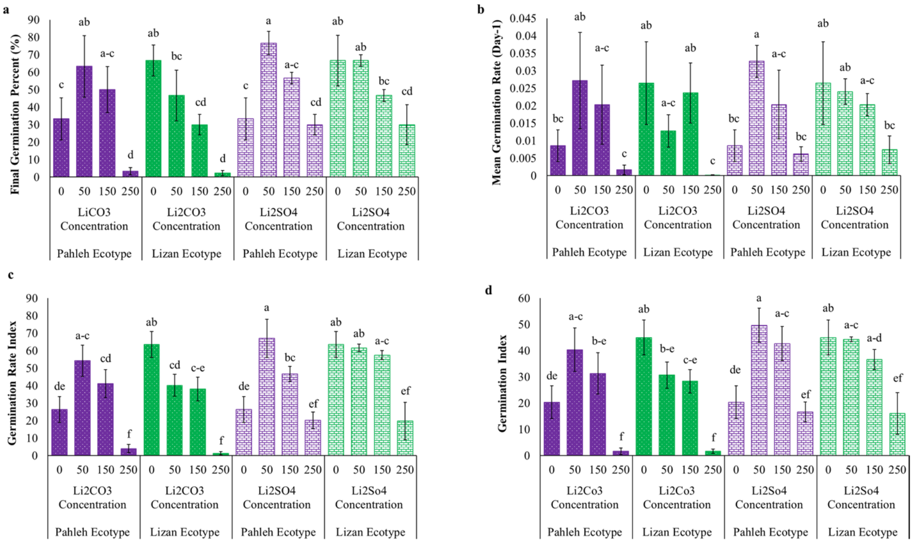

Fig. 2 Effect of different lithium sources and concentrations on germination indices of *Scrophularia striata* ecotypes. **a** Final germination percentage, **b** Mean germination rate, **c** Germination rate index, and **d** Germination index. Mean values (± standard error (SE)). According to Tukey test, the same letters are not significantly different at $p < 0.05$

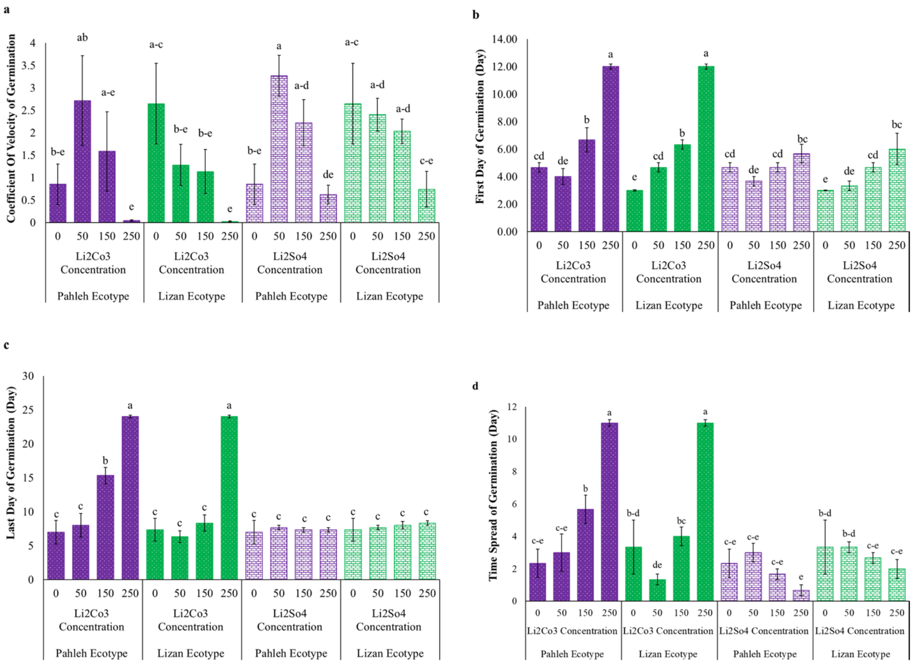

Fig. 3 Effect of different lithium sources and concentrations on germination indices of *Scrophularia striata* ecotypes. **a** Coefficient of variance of germination, **b** First day of germination, **c** Last day of germination, **d** and Time spread of germination. Mean values (± standard error (SE)). According to Tukey test, the same letters are not significantly different at $p < 0.05$

achieved at 250 mmol/L in both ecotypes. Under Li_2SO_4 toxicity, the highest TGI was achieved in Pahleh ecotype at 50 mmol/L, while Lizan did not represent any significant variation among different concentrations (Fig. 4a).

3.2 Initial growth indices of *S. striata* ecotypes following lithium toxicity

Li_2CO_3 and Li_2SO_4 significantly affected the seedling length of the tested plant. In this way, the maximum length was observed under 50 mmol/L Li_2SO_4 toxicity in the Lizan ecotype (approximately 4.66 cm), while the minimum length was achieved under Li_2CO_3 toxicity (250 mmol/L in both ecotypes). Under Li_2CO_3 toxicity, the seedling length of both Lizan and Pahleh ecotypes was significantly reduced at 250 mmol/L. However, under Li_2SO_4 toxicity, no significant variation was observed among the different concentrations (Fig. 4b). Evaluation of biomass showed that the highest fresh and dry biomass was achieved in the Lizan ecotype under Li_2SO_4 toxicity, 50 mmol/L (0.0333 and 0.00227 g, respectively) (Fig. 4c and d). Pahleh ecotype generally had lower fresh and dry biomass towards Lizan, but it was noticeable that there was no significant variation between the control treatment and some other concentrations under both forms of Li, except for Pahleh ecotype in Li_2SO_4 (50 mmol/L) in fresh weight.

Root and stem length also varied depending on various concentrations, Li forms, and ecotypes. In total, Lizan showed higher root and stem length than the Pahleh ecotype, but under Li_2CO_3 toxicity (250 mmol/L), the Lizan ecotype showed a significant reduction towards the control (Fig. 5a and b). In the Pahleh ecotype, the highest SVI was achieved under Li_2SO_4 toxicity (50 mmol/L), but there was no significant variation among concentrations of Li_2CO_3, while for Lizan ecotype, control had the highest SVI in both Li forms (Fig. 5c), which can be a sign of tolerance threshold.

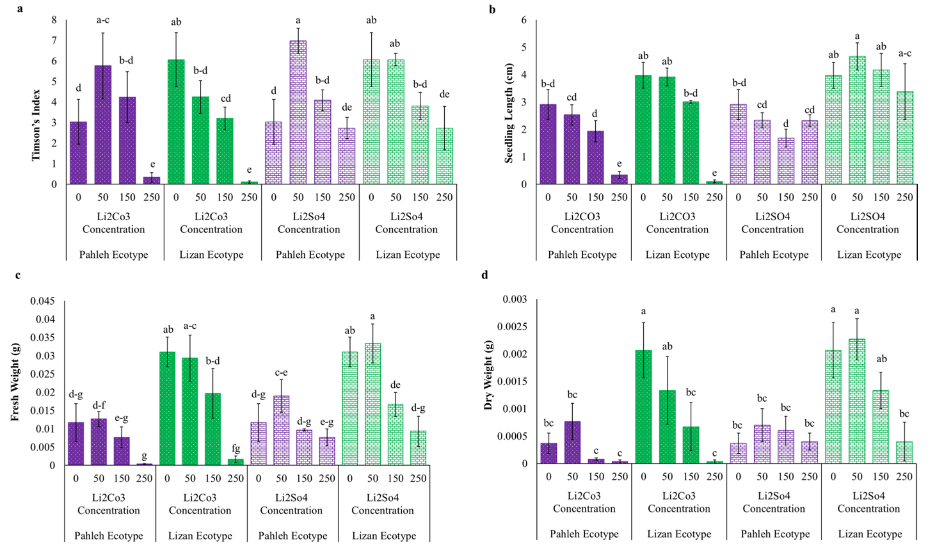

Fig. 4 Effect of different lithium sources and concentrations on germination indices of *Scrophularia striata* ecotypes. **a** Timson index, **b** Seedling length, **c** Fresh weight, and **d** Dry weight. Mean values (± standard error (SE)). According to Tukey test, the same letters are not significantly different at $p < 0.05$

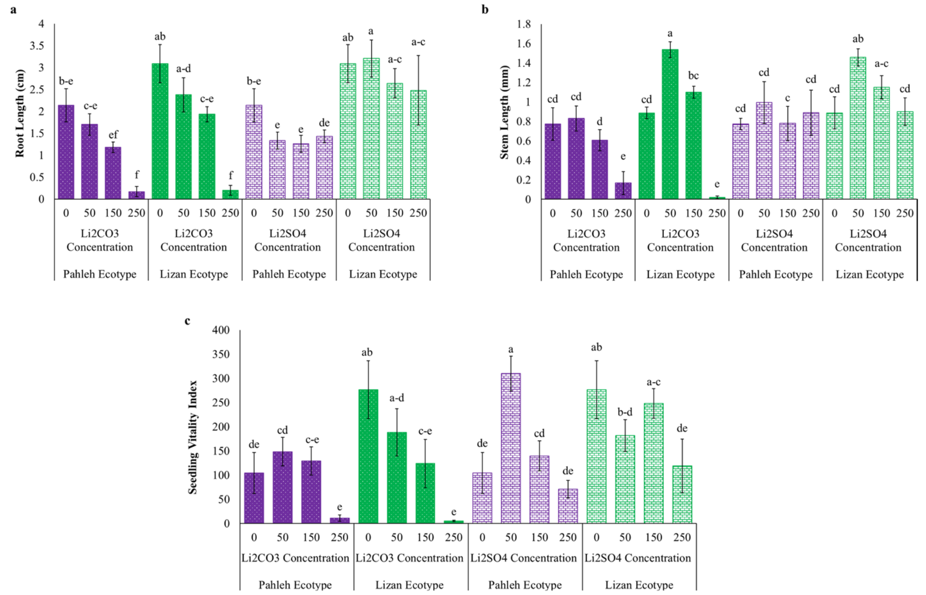

Fig. 5 Effect of different lithium sources and concentrations on germination indices of *Scrophularia striata* ecotypes. **a** Root length, **b** Stem length, and **c** Seedling viability index. Mean values (± standard error (SE)). According to Tukey test, the same letters are not significantly different at $p < 0.05$

3.3 Principal component analysis of germination and initial seedling growth indices of *S. striata* ecotypes under lithium toxicity

A Principal Component Analysis (PCA) was performed on the measured traits of Li treatments to explore the variation among samples and to visualize the grouping patterns. The first two principal components (PC1 and PC2) explained 76.0% and 12.1% of the total variance, respectively, accounting for 88.1% of the cumulative variance (Fig. 6). The first principal component (PC1), which captured the largest portion of variance (76%), was mainly associated with FDG, GRI, SVI, TGI, and GI. These parameters are

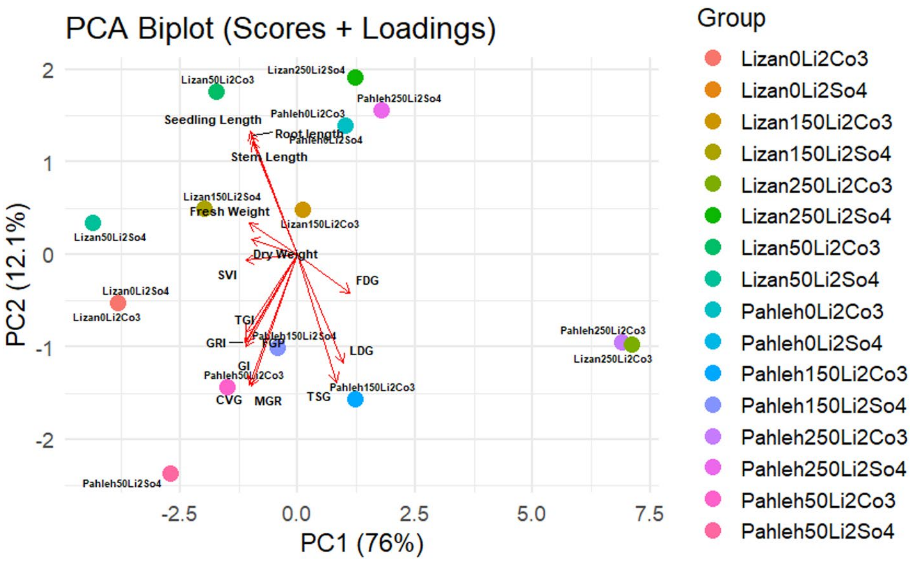

Fig. 6 Principal component analysis of treatments, germination indices, and growth parameters of *Scrophularia striata* under different lithium sources and concentrations

primarily related to seed vigor, germination rate, and early seedling performance. Therefore, PC1 represents a general "germination vigor axis", separating treatments according to their germination efficiency and early growth potential. Treatments positioned on the positive side of PC1 showed higher germination indices and more rapid emergence, while those on the negative side exhibited reduced vigor and slower growth.

The second principal component (PC2) accounted for an additional 12.1% of the total variation and was mainly influenced by MGR, CVG, TSG, seedling length, and root length. These traits are associated with growth uniformity and morphological development of the seedlings. Hence, PC2 can be interpreted as a "seedling growth and uniformity axis", distinguishing treatments based on the physical performance of their seedlings.

The biplot revealed distinct clustering of the treatments, indicating that Li application affected the measured traits differently. Treatments with similar trait profiles were grouped, confirming that PCA efficiently discriminated among Li levels based on their physiological and morphological responses. The loading vectors of FDG, GRI, SVI, and GI were closely aligned, suggesting a strong interrelationship among germination-related parameters. In contrast, traits such as seedling length and root length showed independent vectors, reflecting their distinct contribution to the overall variance.

In summary, the PCA results suggested that germination-related parameters (FDG, GRI, SVI, TGI, GI) were the primary drivers of variability among treatments, while seedling growth traits (MGR, CVG, TSG, seedling length, root length) contributed to secondary differences. This indicates that Li exposure primarily influences seed vigor and germination performance, followed by moderate effects on seedling growth and morphology.

4 Discussion

Li and related compounds are incredibly versatile, and a complete spectrum of their industrial applications has just recently become clear. Li is used in several industrial applications such as lightweight alloys, lubricating greases, air-conditioning systems, polymerization catalysts, detergent compounds, and the treatment of manic-depressive psychoses. This pattern of rising use could result in the release of Li into the environment and the possible contamination of the air, soil, and water [39, 40].

Li is extensively dispersed in the environment, making it simple for plant roots to absorb it. Due to the extreme toxicity of Li-salts, Li significantly reduces plant development [41]. Depending on the Li concentration and the type of plant, Li can either stimulate or inhibit plant growth. Some elements are advantageous when present in micromolar concentrations, but plant development and yield are reduced when their concentrations are raised from ideal to excessive levels. Although Li's biological necessity in plants has not yet been elucidated, Li's beneficial and detrimental impacts on plant growth have been documented. At low concentrations, Li often stimulates plant growth. For instance, in *Lepidium sativum* L., concentrations around 10 mg /L LiCl enhanced seed germination and primary root elongation. Similarly, studies on maize and *Amaranthus viridis* have documented increased shoot biomass and leaf area at specific low Li concentrations. At higher concentrations (typically > 50 mg/L), Li becomes toxic, inhibiting germination and significantly reducing root elongation [9, 42–44].

The impact of Li on seed germination varies depending on the concentration and the plant species involved. In vitro experiments on *Vigna radiata* showed that seed germination was not significantly affected by Li concentrations up to 5 mg/L. However, higher concentrations (3–5 mg/L) led to growth reduction, shoot tip damage, and root growth inhibition [45]. A study on *A. viridis* showed that germination rates decreased with increasing Li concentrations. At 10 ppm, the germination rate was 95%, but it dropped to 41% at 100 ppm. Higher Li concentrations promoted plant biomass but reduced germination rates [46]. Similarly, in the current study, the germination metrics indicated that higher concentrations of Li_2CO_3 (150–250 mg/L) significantly delayed germination (e.g., increased first and last day of germination), particularly in the Pahleh ecotype, compared to Li_2SO_4 treatments. Conversely, lower concentrations of both salts (50 mg/L) exhibited comparatively better germination velocity and reduced time spread in both ecotypes, highlighting the differential sensitivity to Li salts.

As also observed in the current study, Li caused significant growth reduction, considering that Li altered plant physiology and biochemistry. Present observations showed that seedling growth, as measured by root length, stem length, and seedling vigor index, was significantly inhibited at higher Li_2CO_3 concentrations (150–250 mg/L), particularly in the Pahleh ecotype, where the effects were more pronounced. In contrast, Li_2SO_4 treatments showed relatively fewer inhibitory effects, with both ecotypes displaying better root and stem elongation at lower concentrations (50 mg/L). The Lizan ecotype consistently outperformed the Pahleh ecotype across all growth parameters, indicating greater tolerance to Li salts. Li inhibits plant growth by oxidizing DNA and the photosynthetic system. Li toxicity in plant growth was linked to necrotic development and chlorophyll content degradation [47], which can also be the reason for the reduced growth of *S. striata* ecotypes in the current experiment. The observed differences are likely due to variations in ecological conditions between the two ecotypes, such as soil characteristics, moisture availability, and temperature adaptation. These factors may have influenced physiological responses [48].

Similarly, at low concentration (5 mg Li dm^{-3}), Li stimulated maize growth, increasing shoot biomass by approximately 15% compared to control plants. Leaf area in sunflower decreased with increasing Li concentrations at 50 mg Li dm^{-3}. Also, sunflower plants exposed to 50 mg Li dm^{-3} developed necrotic spots of various sizes on older leaves, eventually leading to complete necrosis [49]. Nonetheless, studies showed that *Apocynum venetum* L. would accumulate Li in leaf tissues and survive under a 400 mg kg^{-1} Li supply [50].

Li, often referred to as "white gold," can demonstrate beneficial effects on plants when applied at low concentrations. Research on *Solanum lycopersicum* has shown that at lower concentrations, lithium can stimulate plant growth and increase biomass, as indicated by stress tolerance index estimations. The concentration threshold is critical, as the positive effects on plant growth parameters are only observed at the lower end of the concentration spectrum (likely below 50ppm), whereas higher concentrations (75-100ppm) led to decreased root and shoot length in tomato plants [51]. Similarly, the current experiment found that under low concentrations of Li_2So_4, root length increased towards the control treatment. Likewise, according to some experiments, germination percentage was unaffected by a modest concentration of LiCl (50 mmol/L) [46, 52]These results imply that the type of damage caused by Li toxicity varies with the type of plant and the Li concentration used.

Li exposure leads to increased production of reactive oxygen species (ROS), which causes oxidative stress in plants [53, 54]. ROS can damage cellular components such as lipids, proteins, and nucleic acids, leading to impaired cellular functions and growth inhibition. The oxidative stress induced by Li can result in lipid peroxidation, protein oxidation, and DNA damage, which collectively impair plant metabolism and physiology [55, 56]. Li is transported to leaves by transpiration, where it accumulates and induces injury. Li stress causes lipid peroxidation, a phenomenon primarily caused by ROS. The accumulation of ROS can damage cell membranes and other cellular components, leading to reduced growth [57]. The significant reduction in fresh biomass of *S. striata* under Li exposure can also happen for this reason.

Lithium toxicity was discovered during experiments with trace metals for use in agriculture. Lithium chloride caused necrotic spots on tobacco leaves, especially in older leaves where Li accumulates. It activates several defense-related pathogenesis-related (PR) genes—including PR1, PR5, and PR-P—whose expression parallels necrosis and Li buildup. Lithium also increases ethylene production, which is crucial for this hypersensitive-like response; blocking ethylene synthesis with aminoethoxyvinylglycine prevents both necrosis and PR gene activation. Additionally, Li treatment raises levels of salicylic acid and gentisic acid, two phenolic compounds linked to plant defense mechanisms [58]. Li also caused a reduction in germination rate in *A. viridis* [46], *Oryza sativa* [59], and caused injury in tomato (*Lycopersicon esculentum*) [60], *Ricinus communis* [61], and *Vitis vinifera* [62]. In line with the current experiment, germination percentages of *A. venetum* seeds dropped from 91 to 39% as the concentration of Li_2CO_3 increased from 0 to 50 mmol/L [52]. The extent of damage is determined by the plant type and the Li concentration [63]. By promoting the generation of ROS, Li can result in oxidative damage

[64]. This may explain the reduced growth and biomass of *S. striata* ecotypes in the present investigation.

Citrus plants cannot withstand high Li concentrations, according to research, whereas members of the Solanaceae and Asteraceae families can tolerate Li toxicity. Avocado and sour orange show reduced growth at Li concentrations as low as 6 ppm, with complete growth inhibition occurring at 100–300 ppm, respectively [65]. Plants exhibit diverse physiological mechanisms to manage Li toxicity, including absorption, translocation, sequestration, and detoxification. Li is primarily absorbed through roots via ion transporters (e.g., SOS1/NHX family) and enhanced by root acid exudation and proton gradients. Once absorbed, Li is translocated to shoots, with about 60–70% accumulation and partial excretion through salt glands. For instance, *Chloris gayana* demonstrates effective vacuolar sequestration and Li + excretion through bicellular salt glands, mitigating cytoplasmic toxicity [8]. Significant interference sources and concentrations of Li in seed germination agree with the results reported by the present study. Additionally, Li has been documented to cause some metabolomics and transcriptome modifications in plants [48]. Researchers found that a lower Li content can enhance plant yield by promoting maturation and disease resistance [66]. However, higher Li concentrations significantly reduce plant growth, leading to chlorosis and necrosis in leaves, although the precise balance between Li's essential and toxic roles remains unclear [67, 68]. Lithium toxicity may disrupt ATP production in leaf tissues due to microdephosphorylation in spinach cells, impairing critical energy-dependent cellular functions [48, 69]. Consequently, elevated Li concentrations can inhibit cell elongation and differentiation, decreasing leaf area and plant biomass [70]. Similar physiological disruptions have been reported in Li-exposed plants, including injured root tips, disordered root hair growth, and damaged root caps, leading to reduced root development and biomass [56]. In agreement with these findings, both *S. striata* ecotypes exhibited decreased root length under Li_2CO_3 exposure.

Furthermore, excessive Li stress affects metabolic signaling and redox homeostasis. Li exposure increases H_2O_2 production and alters the expression of glutathione S-transferase genes in Arabidopsis [71], triggering oxidative stress and activation of antioxidant enzymes [72, 73]. In *S. striata*, such physiological disturbances may cascade into generative stages, where disrupted metabolic and hormonal signaling could impair floral development and seed maturation. As a result, plants under severe Li stress may produce premature or abnormal seeds, reducing seed viability and progeny establishment in natural populations. This possible causal relationship between Li-induced physiological stress and reproductive impairment requires further investigation, as it may help clarify the inherited or transgenerational effects that occur under long-term Li exposure [7, 74, 75]. Growing non-edible or industrial-use plants on contaminated soils can help reduce soil erosion and contribute to soil remediation while posing minimal risk to human health. Furthermore, measuring the metal accumulation in these plants is important to accurately evaluate their suitability and efficiency for phytoremediation [76]. Future research should expand on the Li tolerance observed in drought-tolerant plants by examining their long-term viability in heavily contaminated arid lands prone to erosion. The cultivation of plants in which used in processed form or not edible in Li-affected soils is preventing land from erosion, and remediating them with the context of a low human health risk perspective. Also, the amount of Li accumulation in the plant should be analyzed so that its potential in phytoremediation can be accurately obtained.

5 Conclusion

Most of the Li-contaminated lands are not arable. Therefore, if plant species capable of growing in these contaminated lands are introduced, they could contribute to erosion control and soil pollution reduction. At high levels of Li, plants undergo phytotoxicity, but the current results showed that *S. striata* ecotypes can tolerate higher concentrations of Li (250 mmol/L) with lower toxicity signs in germination and growth. In the current experiment, the focus was on Li's effects on seed germination and seedling growth of *S. striata* ecotypes. Li forms and concentrations influenced growth and tolerance in both ecotypes, highlighting S. striata, particularly Lizan, as a promising species for Li-contaminated arid soils.

Supplementary Information

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Supplementary Material 1.

Author contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Seyyed Sasan Mousavi, Akbar Karami, and Tahereh Movahhed Haghighi. The first draft of the manuscript was written by Tahereh Movahhed Haghighi, Filippo Maggi, Azin Taban. Supervision and final revision done by Mehrdad Zarafshar. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability

The dataset generated during and/or analyzed during the current study is available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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