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Soil salinity regulates metal bioavailability and soil–plant transfer in halophytic crops

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Introduction: Soil salinity fundamentally reshapes geochemical controls governing metal mobility and plant uptake, yet its effects across soils with different salinity histories remain poorly resolved.

Methods: We conducted four controlled experiments using NaCl treatments ranging from 1.0 to 20.0 dS m^{-1}, combining freshly salinized soils with soils previously exposed to salinity, and evaluated metal behavior in soil -plant systems of *Tetragonia tetragonioides* and *Portulaca oleracea*.

Results: Increasing salinity reduced the solubility and $CaCl_2$ -extractable (bioavailable) fractions of Fe, Zn, Ba, Sr, and Cu, while total soil metal pools remained largely unaffected, indicating ionic competition, chloride complexation, and ionic-strength -driven shifts in metal partitioning. These patterns show that the observed reductions primarily involve bioavailable metal fractions rather than changes in total soil metal concentrations.

Discussion: Our findings indicate that especially long-standing soil salinity acts as an important regulator of metal bioavailability and soil -plant transfer, providing mechanistic insight into metal dynamics in saline agroecosystems and supporting the strategic use of halophytes for managing metal-affected saline soils.

KEYWORDS
bioavailability, halophytes, metal mobility, phytomanagement, soil geochemistry, soil salinity, soil–plant transfer

1 Introduction

Soil salinization is one of the most widespread forms of land degradation and directly influences the geochemical behavior of nutrient and trace elements in the soil environment (1, 2). Elevated concentrations of soluble salts modify soil ionic strength, alter ion activities, and reshape the electrostatic interactions that govern metal adsorption–desorption processes on mineral surfaces and soil organic matter. As the concentration of Na^+ and Cl^- increases, competition with native cations intensifies, frequently displacing Ca^{2+}, Mg^{2+}, K^+,

and trace metals from exchange sites (3–5). This shift can either increase or decrease metal mobility depending on the dominant chemical species present in the soil solution and the strength of their association with mineral colloids.

In parallel with cation competition, elevated chloride concentrations promote the formation of soluble metal–chloride complexes, thereby modifying free metal ion activities and shifting equilibria between solid-bound and solution-phase forms. (6–9), free metal ion activity and affect the equilibrium between solid-bound and solution-phase forms. Consequently, salinity may either enhance desorption of certain metals or increase immobilization through the precipitation of secondary minerals or decreased diffusion within soil micropores (10, 11). These geochemical changes significantly influence the bioavailable metal fractions that are accessible for plant uptake. As bioavailability rather than total concentration determines metal transfer into vegetation, soil salinity becomes a critical regulator of plant metal acquisition pathways and subsequent accumulation in aboveground tissues (12–14).

Halophytic species are particularly important for understanding salinity–metal interactions because they naturally grow in saline environments and develop physiological strategies to cope with ion toxicity. These strategies include selective ion exclusion, compartmentation, and modified transpiration-driven mass flow, all of which depend strongly on the chemical composition and mobility of ions in the surrounding soil matrix (15, 16). Thus, evaluating metal behavior under different salinity regimes requires simultaneous examination of soil processes and plant uptake responses. Here, the term “trace and major elements” is used to describe a heterogeneous group of elements with differing geochemical roles, including major elements (e.g., Fe, Al), trace nutrients (e.g., Zn, Cu), and potentially toxic trace elements (e.g., Cd, Pb).

Despite extensive studies on halophyte physiology, the mechanisms through which soil salinity alters metal solubility, speciation, and soil–plant transfer remain insufficiently characterized, especially when considering soils with differing salinity histories. Soil “legacy salinity” can result in modified soil structure, altered cation-exchange equilibria (Qadir, et al., 2003; 17), and changes in metal retention capacity that persist even after salts are leached or diluted. These long-term effects may create distinct metal mobility patterns compared to freshly salinized soils, yet this differentiation is rarely studied experimentally (10). Such legacy effects may persist independently of short-term salinity intensity, underscoring the need to distinguish between freshly imposed and long-term salinity when interpreting soil–metal interactions.

To address these gaps, the present study investigates how both newly induced salinity and legacy salinity conditions influence metal dynamics in the soil–plant system of two halophytic vegetables, Tetragonia tetragonioides and Portulaca oleracea. By integrating controlled salinity treatments, soil chemical analyses, and leaf-tissue metal assessments, this research aims to clarify how salinity-driven geochemical processes regulate metal solubility, bioavailability, and subsequent plant uptake. Understanding these interactions is essential for predicting element behavior in saline agricultural soils and for evaluating the potential of halophytes in phytomanagement and remediation of saline–metal-affected lands.

Based on these considerations, we hypothesized that: (i) freshly imposed salinity would primarily alter metal mobility through short-term ionic competition and chloride complexation, whereas (ii) legacy salinity would promote stronger stabilization and reduced bioavailability of metals due to long-term geochemical re-equilibration; and (iii) these contrasting soil processes would be reflected in differential metal accumulation patterns in the leaves of halophytic plants.

2 Materials and methods

2.1 Soil sampling, preparation, and characterization

Soils used in the experiments were collected from the upper 0–20 cm layer of an agricultural field with no known contamination history. The absence of known contamination refers specifically to anthropogenic metal inputs, while elevated concentrations of elements such as Fe and Al reflect natural lithogenic background levels characteristic of the parent material. Samples were air-dried, gently crushed, and sieved through a 2-mm mesh following standard soil preparation procedures. Prior to treatment application, soils were analyzed for physicochemical properties including pH (1:2.5 soil-to-water), electrical conductivity (EC; saturated paste extract), texture (hydrometer method), and cation-exchange capacity (CEC). Salinity-induced changes in the soil matrix were interpreted in the context of established models of ion competition, cation displacement, and salt-driven modification of soil surface charge characteristics (3–5).

Background pseudo-total concentrations of Fe, Zn, Ba, Sr, Cr, Cu, Al, Cd, Pb, and Co were determined using aqua regia digestion followed by inductively coupled plasma–atomic emission spectroscopy (ICP–AES; ISO 11885). The term “metal elements” is used throughout this study to encompass major, trace, and potentially toxic metals with differing geochemical roles. Procedures were consistent with widely accepted protocols for assessing total soil metal content (7, 12).

Baseline soil physicochemical properties, including pH, EC, and macro-/micronutrient composition, were determined prior to salinity treatments. These characteristics are summarized in Table 1.

2.2 Experimental design and salinity treatments (experiment 1)

To evaluate the effects of freshly imposed salinity, soils were mixed with NaCl solutions to achieve electrical conductivity levels of 1.0 (T0), 5.0 (T1), 9.8 (T2), and 20.0 dS m^{-1} (T3). Treated soils were equilibrated for 72 hours to allow stabilization of ion-exchange reactions and salt distribution across soil micropores, a process known to significantly influence subsequent metal mobility (6, 11). Selected EC levels were chosen to represent a gradient from non-saline to highly saline conditions commonly reported in irrigated arid and semi-arid agricultural soils, thereby ensuring field relevance of the imposed salinity treatments.

TABLE 1 Initial soil physicochemical properties and baseline nutrient composition before salinity treatments.

Parameter	Value (mean ± SD)	Unit
pH (1:2.5)	6.0 ± 0.1	–
EC (ECe)	0.30 ± 0.02	dS m^{-1}
Total N	0.01 ± 0.001	%
Available P	0.03 ± 0.002	%
Exchangeable K	0.17 ± 0.01	%
Ca	0.88 ± 0.02	%
Mg	0.21 ± 0.01	%
S	0.14 ± 0.01	%
Fe	340 ± 12	mg kg^{-1}
Al	180 ± 8	mg kg^{-1}
Zn	2.0 ± 0.1	mg kg^{-1}
Na	0.3 ± 0.02	mg kg^{-1}
Cl	10 ± 1	mg kg^{-1}

Values represent means ± standard deviations (n = 3); elevated Fe and Al concentrations reflect natural lithogenic background levels rather than anthropogenic contamination.

Pots (3 L) were filled with 2.5 kg of treated soil and planted with healthy seedlings of *Tetragonia tetragonioides* and *Portulaca oleracea*. Plants were irrigated with tap water at a rate of 0.25–0.50 L per pot, ensuring no leaching occurred that could otherwise alter solution-phase ion concentrations. The experiment was conducted under controlled greenhouse conditions (27–30 °C, 60–70% RH, natural daylight). Each treatment was established with three independent pots per species, representing biological replicates.

2.3 Legacy salinity soil experiment (experiment 2)

A second experiment was established to investigate metal mobility under legacy salinity conditions, where salinity had been applied months prior and soils had undergone structural, mineralogical, and exchange-equilibrium modifications. Unlike freshly salinized soils, legacy-salt soils exhibit altered cation retention patterns, microaggregate stability, and long-term electrolyte effects (17). Soils used in Experiment 2 had been exposed to NaCl salinity for several months prior to planting and were allowed to equilibrate without subsequent leaching, enabling stabilization of exchange reactions and salt distribution within the soil matrix.

These soils possessed EC ranges of 0.8–7.5 dS m^{-1} for T. tetragonioides setups and 0.9–12.1 dS m^{-1} for P. oleracea. Soil preparation, potting, and irrigation followed the same procedures as in Experiment 1. Differences in EC ranges between species reflect inherent variability in soil salinity development and were interpreted in terms of salinity history effects rather than direct quantitative comparison between plant species.

2.4 Soil metal extractability and bioavailable fraction

To determine salinity-driven changes in metal mobility, bioavailable metal fractions were extracted using 0.01 M $CaCl_2$, a well-established extractant that reflects soluble and weakly sorbed forms sensitive to ionic strength changes (10). $CaCl_2$ was selected in preference to chelating agents such as DTPA because it reflects immediately soluble and weakly sorbed metal pools that are particularly sensitive to salinity-induced changes in ionic strength. Extracts were filtered (0.45 µm) and analyzed via ICP–AES.

Changes in extractability were interpreted in relation to salinity-induced shifts in ion activity coefficients, competition of Na^+/Cl^- with trace metals, and potential formation of metal–chloride complexes (6, 8).

2.5 Plant sampling and analysis of leaf tissue metals

After 45 days of growth, fully expanded leaves were harvested, washed with deionized water, oven-dried at 65 °C, and finely ground. Subsamples (0.5 g) were digested using HNO_3:$HClO_4$ mixtures and analyzed via ICP–AES to quantify Fe, Zn, Ba, Sr, Cr, Cu, Al, Cd, Pb, and Co.

Leaf metal concentrations were used to evaluate soil-to-plant transfer efficiency, acknowledging that bioavailability—not total soil concentration—determines assimilation (13, 14).

2.6 Statistical analysis

Data were tested for normality (Shapiro–Wilk test) and homogeneity of variance (Levene's test). One-way ANOVA followed by Duncan's Multiple Range Test (DMRT; $p \leq 0.05$) was selected to facilitate detailed pairwise comparison among treatments, consistent with its frequent application in soil and plant experimental studies with limited replication. Correlations between soil extractable metals and leaf-tissue metals were assessed using Pearson coefficients. All statistical analyses were performed using SPSS 26.0. Correlation analyses were used to assess associations rather than causal relationships between soil and plant metal concentrations.

3 Results

3.1 Effects of salinity on soil physicochemical properties

Soil salinity increased proportionally with treatment intensity in both experiments, confirming successful establishment of the salinity gradient. Increasing NaCl levels caused a measurable rise in electrical conductivity (EC), accompanied by moderate shifts in soil pH. Such changes are consistent with known salinity–induced modifications of soil ionic strength and surface charge behavior (4, 5).

In Experiment 2, soils previously exposed to salinity ("legacy salinity") exhibited inherently higher EC values than newly salinized soils, reflecting long-term accumulation and redistribution of soluble salts (17).

Changes in pseudo-total trace and major element concentrations in soil under salinity exhibited distinct dynamic in Experiments 1 and 2. Elevated salinity levels (T1–T3) were

associated with apparent variations in Ba, Sr, Zn, and to some extent Fe and Al concentrations, reflecting changes in pseudo-total (aqua regia–extractable) fractions rather than true gains or losses of soil metals.

It is important to note that these values represent pseudo-total metal concentrations obtained by aqua regia digestion and are subject to analytical variability, soil heterogeneity, and redistribution effects induced by salinity. Therefore, the observed differences should not be interpreted as absolute changes in total soil metal pools, but rather as shifts in extractable fractions under saline conditions. In the second experiment, where soils had been previously exposed to salinity ('legacy salinity'), metal immobilization patterns appeared more pronounced, consistent with long-term salinity-induced geochemical stabilization. The effects of salinity on total soil heavy-metal concentrations in freshly salinized and legacy-salinity soils in both experiments are summarized in Table 2.

3.2 Salinity-induced changes in soil metal solubility and extractability

Across both experiments, increasing salinity was generally associated with declines in $CaCl_2$-extractable Fe, Ba, Sr, Zn, and Cu, with the strongest reductions observed under the highest salinity level (T3). Observed reductions in extractable metal fractions ranged from approximately 20–55% relative to the control, depending on the element and experimental condition.

This reduction in metal solubility aligns with several salt-driven geochemical mechanisms:

These mechanisms may operate simultaneously, and their net effect on metal mobility depends on soil properties, ionic strength, and salinity history.

1. Ionic competition on soil exchange sites.

High Na^+ concentrations enhanced competition on soil exchange sites, displacing Ca^{2+}, Mg^{2+}, and trace metals and modifying their sorption–desorption equilibria (3, 4).

2. Formation of stable metal–chloride complexes.

Elevated Cl^- activity reduced free metal ion concentrations in solution, altering the balance between complexed, dissolved, and solid-phase metal forms (6, 8).

3. Decreased diffusion and mobility.

High ionic strength reduced activity coefficients, decreasing mobility of Fe, Zn and Cu in the soil pore solution (11).

Legacy-salt soils (Experiment 2) exhibited more pronounced reductions in extractable metal fractions, consistent with long-term salinity-induced modification of sorption equilibria and metal retention capacity (1).

Salinity exerted a pronounced influence on the balance of macro- and micronutrients in the soil. Concentrations of N, P, and K declined under increasing salinity, whereas Cl and Na increased markedly, with Ca and Mg remaining relatively stable. These shifts indicate a reorganization of ionic proportions in the soil solution and reflect the restructuring of ion-exchange reactions under saline conditions. Detailed changes in soil macro- and micronutrient concentrations (N, P, K, Ca, Mg, S, Cl and Na) under salinity in both experiments are summarized in Table 3.

Figures 1A, B illustrates the distribution of major soil metal elements under increasing salinity levels in freshly salinized soils (experiment 1) and legacy-salinity soils (experiment 2), respectively. Warmer colors indicate higher concentrations. Legacy-salinity soils showed stronger metal immobilization than freshly salinized soils, highlighting the long-term effects of salinity history on soil metal retention.

3.3 Associations between soil metal extractability and leaf trace and major element accumulation

Figure 2 presents a correlation heatmap illustrating pairwise relationships among soil metal elements (Fe, Al, Ba, Sr, Zn, Cr, Cu, Pb) under salinity treatments in Experiment 1. The heavy-metal composition of leaf tissues under the different salinity treatments in Experiments 1 and 2 is presented in Table 4. Strong positive correlations indicate co-variation among metals, reflecting shared

TABLE 2 Macro- and microelement composition of leaf tissues (mg/kg) under salinity (T0–T3) in experiment 1 and experiment 2.

Treatment	Macro- and microelement composition of leaves, mg/kg (ppm)							
	N	P	K	Ca	Mg	S	Cl	Na
The first experiment								
T0	53.0	348.9	731.0	20001.4	4155.0	4175.3	2685.8	6096.8
T1	53.8	289.5	603.4	19854.4	4283.0	4138.5	3461.1	15683.9
T2	55.3	327.9	569.5	20162.9	3901.9	4722.7	4055.5	17080.3
T3	35.6	300.6	588.9	20080.1	4143.0	4642.1	3806.4	18829.9
The second experiment								
T0	43.5	212.5	793.2	9259.6	1994.7	1844.2	1502.0	13303.4
T1	42.5	142.3	690.1	7877.7	1739.4	1494.8	723.3	24041.9
T2	42.7	152.8	715.6	7848.1	1670.4	1579.0	447.4	23018.2
T3	33.1	145.8	771.2	7483.0	1804.6	1366.6	617.1	25953.1

Values represent mean ± SD (n = 3).

TABLE 3 **Effect of salinity on pseudo-total metal element concentrations in soil (Experiment 1) and legacy-salinity soils (Experiment 2).**

Treatment	Pseudo-total metal element concentrations in soil (aqua regia–extractable), mg kg^{-1}									
	Fe	Al	Ba	Sr	Zn	Cr	Cu	Pb	Cd	Co
The first experiment										
T0	6352.4	4331.9	17.3	103.9	53.9	5.7	27.3	13.2	–	–
T1	7188.5	4332.3	12.8	93.7	45.1	5.3	27.3	12.2	–	–
T2	6317.1	3407.5	13.0	106.2	41.3	4.4	26.4	12.3	–	–
T3	6675.6	3475.0	12.3	90.4	43.1	4.5	25.1	11.7	–	–
The second experiment										
T0	4405.4	3936.2	11.8	56.7	24.1	4.1	12.5	5.6	0.1	–
T1	4136.8	3856.3	10.8	41.8	18.3	3.8	11.6	5.7	0.1	–
T2	3587.6	3521.9	10.0	46.3	18.1	3.5	12.0	5.4	0.1	–
T3	5403.3	4563.8	10.6	38.9	21.6	4.5	11.9	5.3	0.1	–

Values represent pseudo-total concentrations and reflect extractable fractions rather than absolute total metal contents.
Values represent mean ± SD (n = 3).

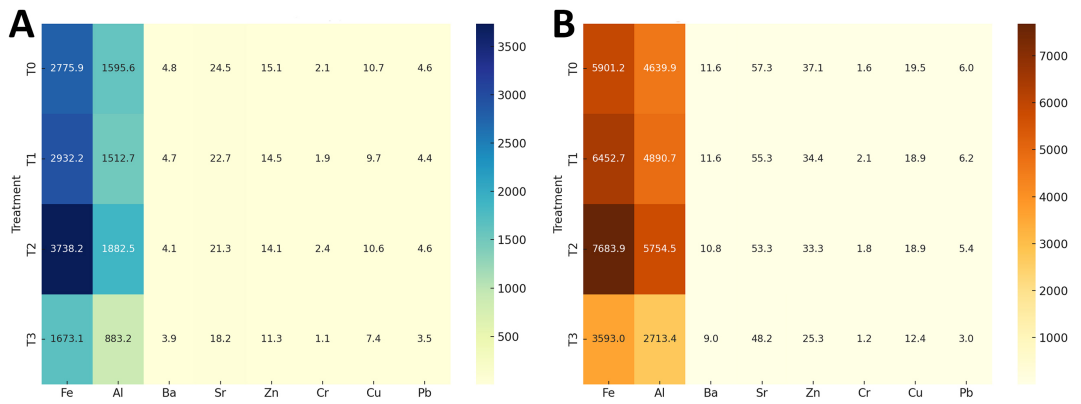


FIGURE 1
Heatmap of soil metal concentrations (Fe, Al, Ba, Sr, Zn, Cr, Cu, Pb) under salinity treatments (T0–T3) in experiment 1 **(A)** and experiment 2 **(B)**.

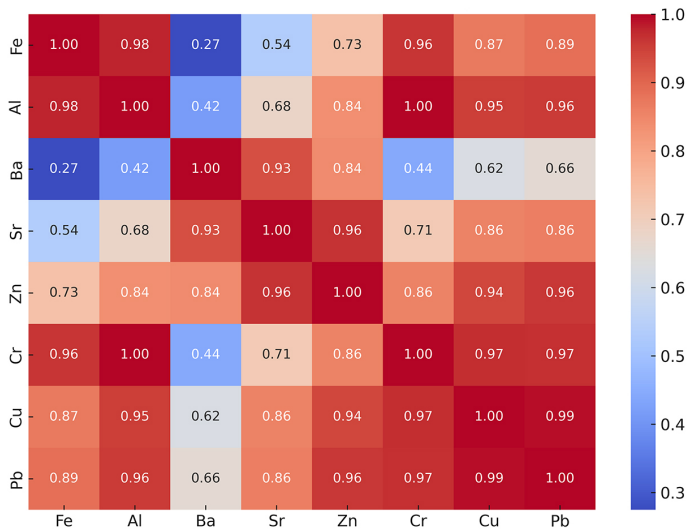


FIGURE 2
Correlation matrix of soil trace and major elements under salinity treatments (experiment 1).

TABLE 4 Effect of salinity on macro- and micronutrient concentrations in soil (mg/kg) in experiment 1 and experiment 2.

Treatment	Macro and microelements in soil content, mg/kg (ppm)							
	N	P	K	Ca	Mg	S	Cl	Na
The first experiment								
T0	44.8	348.9	731.0	20001.4	4155.0	4175.3	148.5	168.6
T1	45.1	289.5	603.4	19854.4	4283.0	4138.5	2468.1	2026.1
T2	46.8	327.9	569.5	20162.9	3901.9	4722.7	3353.1	4016.2
T3	42.0	300.6	588.9	20080.1	4143.0	4642.1	7485.1	8430.3
The second experiment								
T0	35.5	212.5	793.2	9259.6	1994.7	1844.2	91.5	113.2
T1	34.5	142.3	690.1	7877.7	1739.4	1494.8	1599.1	1027.2
T2	32.7	152.8	715.6	7848.1	1670.4	1579.0	2233.4	1699.2
T3	33.1	145.8	771.2	7483.0	1804.6	1366.6	3843.5	3492.2

Values represent mean ± SD (n = 3).

geochemical controls such as ionic strength, competitive sorption, and salinity-driven redistribution within the soil matrix.

Reductions in soil $CaCl_2$-extractable metal fractions were accompanied by corresponding declines in leaf metal concentrations in both halophyte species. Significant positive correlations ($r = 0.62–0.88$, $p \leq 0.05$) suggest a close association between soil metal bioavailability and plant accumulation, indicating that soil chemical constraints play a key role in regulating metal uptake (12, 13).

However, as root metal concentrations and transporter-level responses were not quantified in this study, these relationships should be interpreted as correlative rather than strictly causal.

Species-specific differences:

- Tetragonia tetragonioides showed more pronounced reductions in Fe, Zn, Sr and Ba uptake under high salinity
- Differences in leaf metal accumulation patterns were observed between the two species.

Tetragonia tetragonioides exhibited more pronounced reductions in Fe, Zn, Sr, and Ba concentrations under high salinity, whereas Portulaca oleracea showed comparatively moderated declines. These differences are consistent with known halophytic strategies such as selective ion exclusion and compartmentation, although direct physiological measurements were not conducted in the present study (15, 16).

Increasing salinity levels were generally associated with reduced leaf concentrations of Fe, Al, Ba, Sr, Zn, and Cu. This trend was more pronounced in Experiment 2, suggesting that pre-existing (legacy) salinity further constrains metal bioavailability and limits subsequent plant uptake.

3.4 Comparison of freshly salinized vs. legacy salinity soils

Experiment 2 (legacy salinity) was generally associated with lower soil metal extractability and reduced leaf metal accumulation compared to Experiment 1, even under comparable EC levels. These patterns suggest that:

- Fresh salinity primarily influences short-term geochemical processes such as chloride complexation and ionic competition.
- Legacy salinity is associated with longer-term structural, mineralogical, and exchange-equilibrium modifications that persist beyond initial salt application.

Accordingly, soil salinity history appears to be an important factor influencing metal bioavailability, a process that may be underestimated in short-term salinity studies but is relevant for real field conditions.

The uptake of nitrogen, phosphorus, potassium, calcium, and magnesium declined with increasing salinity, whereas sodium and chloride concentrations increased sharply in leaf tissues. These trends were observed in both experiments and were more pronounced under legacy salinity conditions. Detailed changes in macro- and microelement concentrations in leaf tissues under fresh and legacy salinity conditions are summarized in Table 5.

4 Discussion

4.1 Soil processes governing metal availability under salinity

Increasing soil salinity markedly altered the geochemical environment regulating metal mobility. Across both experiments, increasing salinity was generally associated with lower $CaCl_2$-extractable fractions of Fe, Zn, Sr, Ba, and Cu, with more pronounced reductions observed in legacy-salinity soils. The net effect of salinity on metal mobility reflects the combined influence of multiple geochemical processes, which may operate simultaneously and vary in dominance depending on soil properties and salinity history. This response is consistent with established mechanisms in saline soils:

1. cation competition and exchange-site displacement, where Na^+ displaces divalent cations, reducing metal desorption (3, 4);

TABLE 5 Trace and major element composition of leaf tissues (mg kg^{-1}) under salinity treatments (T0–T3) in experiment 1 and experiment 2.

Treatment	Trace and major element composition of leaves, mg kg^{-1}									
	Fe	Al	Ba	Sr	Zn	Cr	Cu	Pb	Cd	Co
The first experiment										
T0	23.7	12.1	0.7	17.2	17.5	–	1.2	–	–	–
T1	16.2	7.3	0.5	11.6	20.1	–	1.4	–	–	–
T2	11.5	5.7	0.3	8.9	19.9	–	1.3	–	–	–
T3	15.0	6.8	0.3	8.5	19.7	–	1.6	–	–	–
The second experiment										
T0	64.6	26.1	1.6	41.7	69.0	0.8	1.0	–	0	–
T1	10.8	12.0	0.6	23.3	65.8	0.5	1.4	–	0.3	–
T2	16.3	10.0	0.7	20.6	61.7	0.7	1.4	–	0.2	–
T3	11.4	6.2	0.4	12.4	76.2	1.0	1.5	–	0.3	–

Values represent mean ± SD (n = 3).

2. metal–chloride complexation, decreasing free metal ion activity (6, 8);
3. ionic strength–mediated reduction in mobility, lowering metal activity coefficients in the soil solution (11).

Legacy-salinity soils displayed more pronounced reductions in extractable metals compared with freshly salinized soils, reflecting long-term ion redistribution, changes in clay surface charge, and equilibrium stabilization (17). These findings indicate that soil salinity history is an important factor influencing bioavailable metal pools, even when pseudo-total metal concentrations remain relatively stable.

4.2 Plant physiological responses and metal uptake constraints

Reductions in $CaCl_2$-extractable metal fractions in soil were accompanied by decreases in metal accumulation in leaf tissues of both *Tetragonia tetragonioides* and *Portulaca oleracea*. Significant correlations suggest a close association between soil metal bioavailability and plant accumulation (12, 13). However, as root metal concentrations and transporter-level responses were not measured, these relationships should be interpreted as correlative rather than strictly causal.

Salinity produced a dual stress effect:

1. osmotic limitation, reducing transpiration-driven ion transport;
2. ionic stress, altering root membrane permeability and reducing uptake of divalent metals (15, 16).

Key changes—decline of Fe, Zn, Sr, Ba and Cu—support the interpretation that halophytes prioritize Na^+ management, osmotic balance and Cl^- sequestration over micronutrient uptake. The sharp increase in leaf Na–Cl and corresponding decrease in N, P, K, Ca and Mg indicates ion competition at uptake sites, consistent with salinity-induced nutrient imbalance (13). Together, these observations suggest that salinity-induced reductions in leaf metal concentrations reflect both geochemical constraints in the soil and physiological adjustments in ion transport and compartmentation within plant tissues.

4.3 Species-specific strategies in metal accumulation under saline conditions

Although both species exhibited reduced metal accumulation under salinity, the magnitude of response differed. *Tetragonia tetragonioides* showed more pronounced declines in Fe, Zn, Sr, and Ba concentrations compared to P. oleracea, indicating stronger limitation of metal translocation to shoots. In contrast, *Portulaca oleracea* maintained relatively higher metal levels under moderate salinity. These patterns are consistent with species-specific halophytic strategies, such as selective ion exclusion and compartmentation, although detailed physiological mechanisms were not directly assessed in this study (14, 16).

These species-specific differences imply divergent strategies:

Tetragonia → stronger restriction of metal translocation to aboveground tissues.

Portulaca → comparatively moderated decline in metal accumulation under salinity.

Together, these findings highlight that metal dynamics in halophytes arise from the combination of soil geochemical constraints and species-dependent physiological regulation, both of which determine their potential roles in saline-land phytoremediation. Our findings complement previous work on phytoremediation of saline and saline–sodic soils, highlighting the potential of halophytes as tools for managing metal-affected salinity landscapes. (18).

5 Conclusion

This study indicates that increasing soil salinity substantially modifies the soil geochemical environment, resulting in reduced bioavailability of several metal elements and corresponding declines

in their accumulation in halophytic plants. Clear differences were observed between freshly salinized and legacy-salinity soils and legacy-salinity soils, with long-term salinity conditions associated with stronger constraints on metal mobility. Both *Tetragonia tetragonioides* and *Portulaca oleracea* exhibited reduced metal uptake under saline conditions, although the magnitude of response differed between species, reflecting contrasting accumulation strategies. Overall, the results emphasize the important role of soil ionic conditions and salinity history in regulating metal availability and soil–plant transfer, providing a basis for improving the management of metal dynamics and halophyte performance in saline agroecosystems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Author contributions

GB: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. RK: Data curation, Formal analysis, Visualization, Writing – review & editing. KI: Investigation, Methodology, Writing – original draft, Writing – review & editing. AB: Data curation, Investigation, Methodology, Writing – review & editing. QR: Methodology, Resources, Writing – review & editing. SI: Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing. ST: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. UP: Data curation, Investigation, Writing – review & editing. AAz: Investigation, Software, Visualization, Writing – review & editing. JK: Formal analysis, Investigation, Validation, Writing – review & editing. SZ: Investigation, Methodology, Writing – review & editing. MD: Investigation, Resources, Writing – review & editing. EM: Formal analysis, Software, Validation, Writing – review & editing. AAk: Project administration, Resources, Visualization, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Correction note

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The author(s) declared that generative AI was used in the creation of this manuscript. Generative artificial intelligence tools were used for language editing and structural refinement of the manuscript. All scientific content, data interpretation, and conclusions were critically reviewed and validated by the authors.

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