CADMIUM ACCUMULATION IN *Atriplex nummularia* Lindl. IRRIGATED WITH BRACKISH WATER

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ABSTRACT: Species such as *Atriplex nummularia* Lindl., adapted to arid and semi-arid environments, stand out in the phytoremediation of salt-affected soils; however, little is known about their potential for phytoremediation in areas simultaneously contaminated by heavy metals and salinity. This study evaluated the cadmium (Cd) phytoextraction capacity of *A. nummularia* cultivated in a saline soil contaminated with 30 mg kg^{-1} of Cd and irrigated with brackish water at increasing NaCl concentrations (0, 50, 100, 150, and 200 mmol L^{-1}). After 30 days, Cd concentrations in the shoot (CdSH), vesicles (CdVES), and roots (CdRT) were analyzed, along with the translocation factor (TF). Results showed that CdSH varied significantly ($p<0.01$), with a maximum accumulation of 86.99 mg kg^{-1}. CdVES showed a linear decreasing trend, with a 46% reduction at 200 mmol L^{-1} of NaCl. CdRT reached a maximum of 66.42 mg kg^{-1} at 84.87 mmol L^{-1}. TF was greater than 1 at all concentrations, demonstrating the potential of *A. nummularia* for Cd phytoextraction under saline conditions. *A. nummularia* shows promise for Cd phytoextraction in salinity-degraded soils, particularly in semi-arid regions, contributing to the development of sustainable soil remediation technologies.
KEYWORDS: old man saltbush; phytoremediation; luvisol

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ACÚMULO DE CÁDMIO EM *Atriplex nummularia* Lindl. IRRIGADA COM ÁGUA SALOBRA

RESUMO: Espécies como *Atriplex nummularia* Lindl., adaptadas a ambientes áridos e semiáridos, destacam-se na fitorremediação de solos afetados por sais, porém pouco é abordado sobre seu potencial para fitorremediação em áreas contaminadas simultaneamente por metais pesados e salinidade. Assim, esta pesquisa avaliou a capacidade de fitoextração de cádmio (Cd) por *A. nummularia* cultivada em solo salino contaminado com 30 mg kg^{-1} de Cd e submetido a irrigação com águas salobras de concentrações crescentes de NaCl (0, 50, 100, 150 e 200 mmol L^{-1}). Após 30 dias, avaliaram-se os teores de Cd na parte aérea (CdPA), nas vesículas (CdVES), nas raízes (CdR), e o fator de translocação (FT). Os resultados revelaram que o CdPA apresentou variação significativa ($p<0,01$), com acúmulo máximo de 86,99 mg kg^{-1}. O CdVES exibiu comportamento linear decrescente, com redução de 46% no teor sob 200 mmol L^{-1} de NaCl. O CdR apresentou acúmulo máximo de 66,42 mg kg^{-1} com 84,87 mmol L^{-1}. O FT foi superior a 1 em todas as concentrações, evidenciando o potencial de *A. nummularia* para fitoextração de Cd em condições salinas. A espécie é indicada para a fitoextração de Cd em áreas contaminadas, contribuindo para o desenvolvimento de tecnologias sustentáveis de remediação de solos.

PALAVRAS-CHAVE: old man saltbush. fitorremediação. luvissolo.

INTRODUCTION

The remediation of areas contaminated by anthropogenic activities using conventional techniques, such as soil excavation and removal, involves high economic costs and significant environmental impacts, which limits their large-scale application.

In this context, alternative technologies have emerged, aiming for remediation with lower cost and less environmental interference. Among these, phytoremediation stands out as a promising and ecologically viable approach that uses plants to remove, stabilize, or degrade contaminants present in the soil. One of the main mechanisms involved is phytoextraction, characterized by the uptake of toxic elements by the roots and their accumulation in the aerial parts of the plant, which has been widely studied, particularly in relation to heavy metals (Nascimento et al., 2021).

Halophytes such as *Atriplex nummularia* Lindl. can tolerate high concentrations of ions such as Na^+ and Cl^- and thriving in environments with high salinity ions such as Na^+ and Cl^- and thriving in environments with high salinity—an attribute commonly found in semi-arid regions (De Souza et al., 2012).

Recent studies have also demonstrated the potential of these species in extracting heavy metals such as cadmium (Cd), lead (Pb), copper (Cu), and arsenic (As), especially in plants that can excrete salts and metals through specialized glands (Vromman et al., 2016; Araújo et al., 2025). In the case of *A. nummularia* Lindl., several studies indicate that its growth and biomass accumulation are stimulated under salinity levels ranging from 150 to 200 mmol L^{-1} of NaCl (Parvez et al., 2020), reinforcing its suitability for use in saline, contaminated environments. Given its proven salinity tolerance and potential for heavy metal uptake, it is essential to evaluate its specific performance in the phytoextraction of toxic elements.

Therefore, the present study aims to assess the influence of soil salinity on the cadmium phytoextraction efficiency of *Atriplex nummularia* Lindl., focusing on the processes of metal uptake, translocation, and accumulation. The findings are expected to contribute to a better understanding of the mechanisms involved and support the development of sustainable remediation strategies for saline-contaminated environments.

MATERIALS AND METHODS

The experiment was conducted in a protected environment at the Federal Rural University of Pernambuco (UFRPE), located on the main campus in Recife, PE, Brazil. The soil was collected in the municipality of Belém do São Francisco, PE, and classified as a Luvisol – WRB (IUSS Working Group WRB, 2015), a silty clay loam with saline characteristics (LS) (ECe = 14.23 dS m^{-1}), according to the classification of Richards (1954).

After collection, the soil was stored, subsequently broken up, sieved (Ø 4 mm), homogenized, and placed in pots with a capacity of 5 L. For physical and chemical characterization (Tables 1 and 2), subsamples were passed through a 2 mm mesh sieve.

Table 1 – Chemical characterization

	EC	pH	Na	K	Ca	Mg	S	H+Al	CEC	V	ESP	P
	dS.m^{-1}	(H_2O)			cmol$_c$.dm^3					%		
Média	14,23	6,21	1,11	0,13	15,90	4,3	21,4	1,07	22,6	95	5%	2,0
Desvio Padrão	±0,61	±0,04	±0,01	±0,01	±0,01	±0,01	±0,01	±0,01	±0,01	±0,01	±0,01	±0,01

EC: electrical conductivity; pH: hydrogen potential; CEC: cation exchange capacity; ESP: exchangeable sodium percentage V: base saturation.

The physical characterization of the soil (Table 2) was carried out through particle size analysis, separating the fractions into fine sand, coarse sand, silt, and clay; clay dispersed in water using the hydrometer method; soil bulk density using the graduated cylinder method; and particle density using the volumetric flask method (Teixeira et al., 2017).

Table 2 – Physical characterization

	Bd	Pd	TP	TS	CS	FS	Clay	Silt	Classe textural	CDA	DF
	$g.cm^{-3}$		%				$g.kg^{-1}$				%
Média	1,68	2,74	38,94	63,0	48,9	14,1	462,9	474,1	Argilo siltosa	175,29	63,03
Desvio Padrão	±0,01	±0,03	±0,01	±0,80	±1,00	±0,50	±0,80	±0,01		±0,01	±0,01

Bd: bulk density, determined by the graduated cylinder method; Pd: particle density, determined by the volumetric flask method; TP: total porosity; TS: total sand; CS: coarse sand; FS: fine sand; CDA: clay dispersed in water; DF: degree of flocculation.

The soil was artificially contaminated by incubation with a cadmium chloride ($CdCl_2$) solution at a concentration of 30 mg kg^{-1} of Cd. After the addition of the solution, the soil moisture in the experimental units was adjusted to 80% of the maximum water-holding capacity, which was maintained by daily replenishment of water lost through evaporation. This procedure was maintained for 30 days to achieve chemical equilibrium.

Atriplex seedlings were initially grown in polyethylene bags containing washed sand as substrate and irrigated daily with half-strength Hoagland and Arnon (1950) nutrient solution. Sixty days after planting, when the seedlings were fully rooted and acclimated, they were removed from the washed sand and transplanted into the previously characterized polyethylene pots, where they remained until the end of the experiment.

Irrigation was initially performed by gradually and proportionally applying NaCl via irrigation water until reaching the concentrations of 0, 50, 100, 150, and 200 mmol L^{-1}. Subsequently, irrigation was carried out daily using a digital balance, with water replenishment based on evapotranspiration losses, maintaining the soil at 80% of its maximum water-holding capacity.

The experiment followed a randomized block design, in which *Atriplex nummularia* Lindl. seedlings were grown and irrigated with five different NaCl concentrations (0, 50, 100, 150, and 200 mmol L^{-1}). After 30 days of salt treatment, trichomes were removed by brushing the adaxial and abaxial leaf surfaces with a nylon brush (Tsutsumi et al., 2015). The collected leaves were then dried, and their dry mass was recorded. The Cd content in these structures was determined by analyzing the solution obtained from the brushing process using inductively coupled plasma optical emission spectrometry (ICP-OES; Optima 7000, Perkin Elmer).

In addition, at 30 days of treatment, samples of the aboveground parts (leaves + stems) and roots were collected and oven-dried at 65 °C in a forced-air circulation oven until constant weight. The samples were then ground, and 0.5 g subsamples of plant material were digested following a modified version of Method 3050B (USEPA, 1996). The translocation factor (TF) was calculated to evaluate the plant's ability to transfer cadmium (Cd) from roots to shoots by dividing the concentration of Cd in the shoots by the concentration in the roots. A TF value greater than 1 indicates efficient translocation of the metal from roots to shoots.

The samples digested were stored at 4 °C for subsequent ICP-OES analysis. The results were subjected to analysis of variance (ANOVA), and variables showing significant differences ($p < 0.05$) were further evaluated by regression analysis, assessing significance and the best model fit based on the coefficient of determination (R^2).

RESULTS AND DISCUSSION

Cadmium content in the aerial parts (CdAP) varied significantly ($p < 0.05$) with increasing NaCl concentrations, showing a fit to a quadratic model, with a maximum accumulation of 86.99 mg kg^{-1} at the estimated concentration of 147.66 mmol L^{-1}. Although a decrease in Cd levels was observed beyond this point, the accumulation at 200 mmol L^{-1} was still 38% higher than that observed in the control plants (Figure 1a).

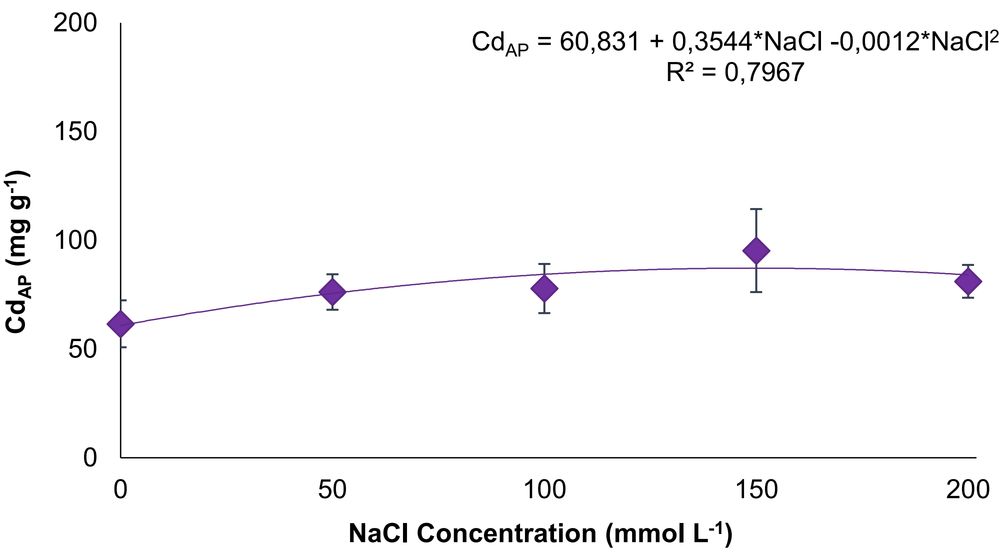

Figure 1. Cadmium content (CdAP) of *Atriplex nummularia* Lindl. grown in soil contaminated with 30 mg kg^{-1} of Cd and irrigated with increasing concentrations of NaCl. Significance of regression coefficients: ** ($p \leq 0.01$) and * ($p < 0.05$).

Cadmium content in the salt bladders (CdSB) showed a significant difference ($p < 0.01$), with a linear decrease as NaCl concentration in the irrigation water increased. At 200 mmol L^{-1}, there was a 46% reduction compared to the control plants, with an accumulation of 3.62 mg g^{-1} (Figure 1b).

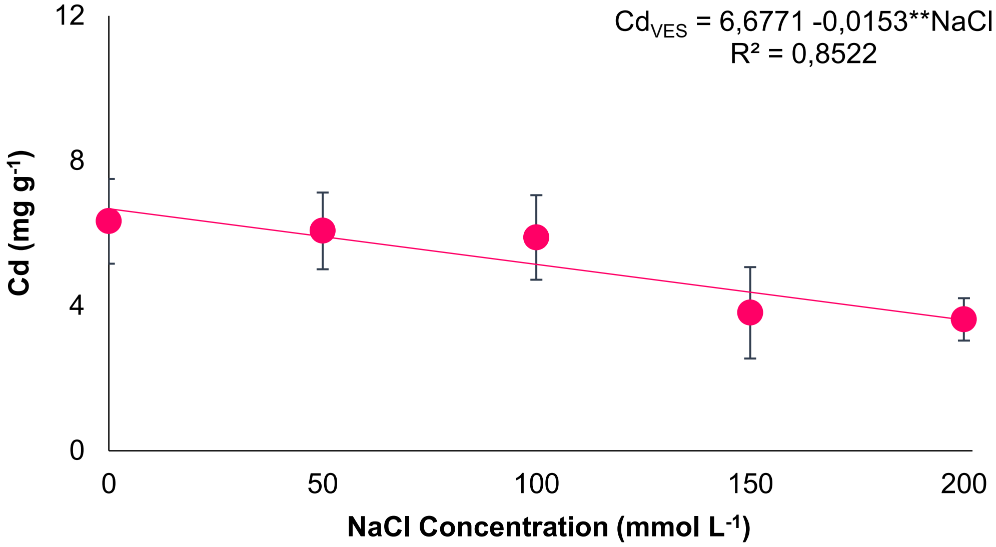

Figure 2. Cadmium in salt bladders (CdVES) of *Atriplex nummularia* Lindl. grown in soil contaminated with 30 mg kg^{-1} of Cd and irrigated with increasing concentrations of NaCl. Significance of regression coefficients: ** ($p \leq 0.01$) and * ($p < 0.05$).

Cadmium concentrations from the NaCl dose of 100 mmol onward did not vary with increasing NaCl levels, suggesting that the species reached a limit in Cd accumulation despite the amount of NaCl. Salt excretion through salt glands is considered an essential mechanism that contributes to the increased salinity tolerance of halophytes (Meng et al., 2018).

In *Atriplex nummularia*, these structures located on the leaf epidermis not only serve an excretory function but also contribute to the development of a favorable water potential gradient for water absorption and maintenance of cell turgor (Paulino et al., 2020).

The excretion of contaminant elements is an ideal strategy for phytoremediation of contaminated soils through the bioprocess of absorption, translocation, and excretion, facilitating phytomanagement by means of washing and leaf collection.

Additionally, another advantage of phytoexcretion is to prevent excessive Cd accumulation and toxicity in plant tissues, allowing the use of the species for remediation of more heavily contaminated soils (Nascimento et al., 2021).

Cadmium content in the roots (CdR) showed a significant difference ($p < 0.01$) with increasing NaCl concentrations, displaying a quadratic behavior with maximum accumulation of 66.42 mg kg^{-1} at 84.87 mmol L^{-1} (Figure 1c).

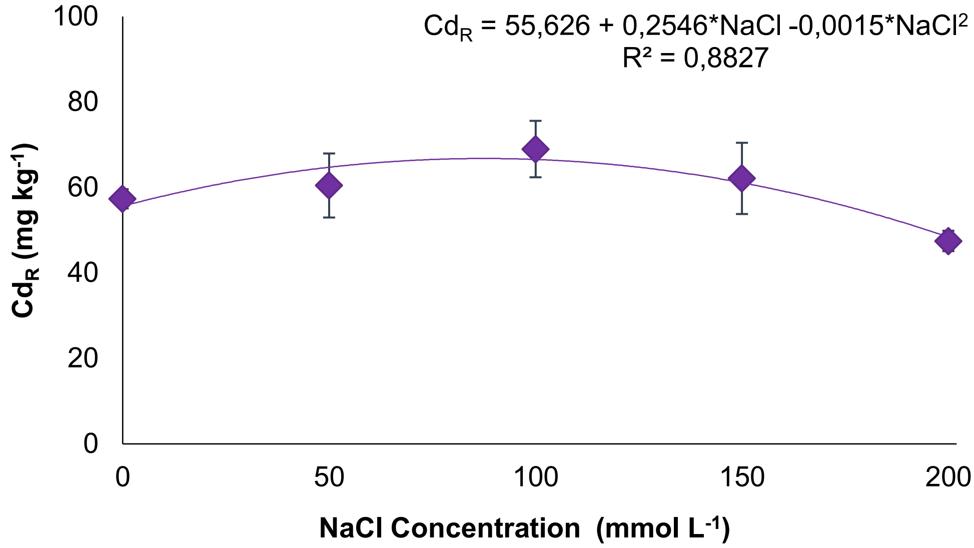

Figure 3. Cadmium in roots (CdR) of *Atriplex nummularia* Lindl. grown in soil contaminated with 30 mg kg^{-1} of Cd and irrigated with increasing concentrations of NaCl. Significance of regression coefficients: ** ($p \leq 0.01$) and * ($p < 0.05$).

The highest Cd accumulation was concentrated in the aerial parts, also reflected in the translocation factor, which showed values greater than 1 for all NaCl doses (Figure 1d), indicating phytoextraction.

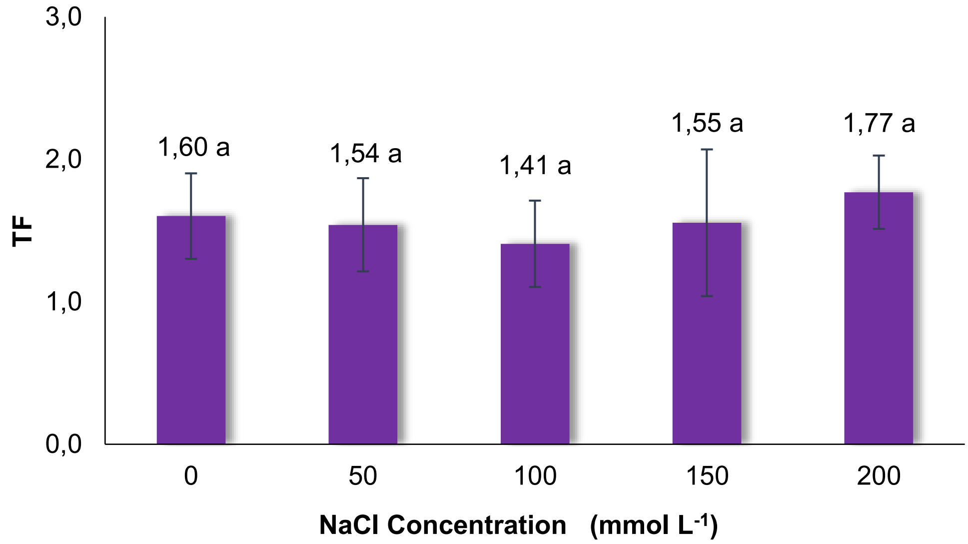

Figure 4. Translocation factor (TF) of *Atriplex nummularia* Lindl. grown in soil contaminated with 30 mg kg^{-1} of Cd and irrigated with increasing concentrations of NaCl. Significance of regression coefficients: ** ($p \leq 0.01$) and * ($p < 0.05$).

The increase in Cd content in the studied species may be related to greater Cd availability due to increased desorption from soil particles, thus favoring Cd uptake by the plant (Nikalje & Suprasanna, 2018). Thus, the translocation of the metal to the aerial parts is facilitated, indicating that the presence of salinity in contaminated soils increases the metal's availability in the environment. However, no significant differences were observed with increasing concentrations, suggesting that *Atriplex* has a limit for metal uptake under these saline conditions. This finding highlights the plant's adaptive capacity to limit metal uptake beyond a certain threshold, which may be beneficial for managing phytoremediation efficiency in highly contaminated environments.

CONCLUSIONS

Atriplex nummularia exhibits high tolerance to both cadmium and salinity, being able to accumulate Cd predominantly in the aerial parts even under elevated NaCl concentrations. The maintenance of the translocation factor above 1 under all saline conditions evaluated reinforces its potential as a phytoremediator species. Thus, *A. nummularia* proves promising for Cd phytoextraction in areas degraded by salinity, especially in semi-arid regions, contributing to the development of sustainable soil remediation technologies.

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REFERENCES

Araújo, C. A. F., Paulino, M. K. S. S., Costa, D. H. G. Da, Silva, A. R. Da, Leal, L. Y. De C., Nunes, J. A., Bezerra, F. S., Berto, S. D. Da C., Gonçalves, W. J. F., Nascimento, C. W. A. Do,

& Souza, E. R. De. Soil salinity improves the capacity of *Atriplex nummularia* Lindl. to phytoextract cadmium. **Journal of Hazardous Materials**, 491, 137955,2025.

De Souza, E.R., Dos Santos Freire, M.B.G., Da Cunha, K.P.V., Do Nascimento, C.W. A., Ruiz, H.A., Lins, C.M.T. Biomass, anatomical changes and osmotic potential in *Atriplex nummularia* Lindl. cultivated in sodic saline soil under water stress. **Environ Exp Bot** v. 82, 20–27.2012

Meng, D., Li, J., Liu, T., Liu, Y., Yan, M., Hu, J; Yin, H.Efeitos do potencial redox na solubilidade do cádmio no solo: uma visão da comunidade microbiana. **Revista de Ciências Ambientais**, v. 75, p. 224-232, 2019.

Nascimento, C. W. A. D., Biondi, C. M., Silva, F. B. V. D., & Lima, L. H. V. Using plants to remediate or manage metal-polluted soils: an overview on the current state of phytotechnologies. **Acta Scientiarum. Agronomy**, v. 43, 2021.

Nikalje, Ganesh C.; Suprasanna, Penna. Coping with metal toxicity–cues from halophytes. **Frontiers in plant science**, v. 9, p. 777, 2018.

Parvez, S., Abbas, G., Shahid, M., Amjad, M., Hussain, M., Asad, S. A; Naeem, M. A., Effect of salinity on physiological, biochemical and photostabilizing atributes of two genotypes of quinoa (Chenopodium quinoa Willd.) exposed to arsenic stress. **Ecotoxicology and environmental safety**, v. 187, p. 109814, 2020.

Paulino, M. K. S. S., De Souza, E. R., Lins, C. M. T., Dourado, P. R. M., Leal, L. Y., Monteiro, D. R., De Carvalho Silva, C. U. Influence of vesicular trichomes of *Atriplex nummularia* on photosynthesis, osmotic adjustment, cell wall elasticity and enzymatic activity. **Plant Physiology and Biochemistry**, v. 155, p. 177-186, 2020.

Richards, Lorenzo Adolph (ed.). **Diagnosis and improvement of saline and alkali soils**. US Government Printing Office, 1954.

Tsutsumi, K., Yamada, N., Cha-Um, S., Tanaka, Y., & Takabe, T. Differential accumulation of glycinebetaine and choline monooxygenase in bladder hairs and lamina leaves of *Atriplex* gmelini under high salinity. **Journal of plant physiology**, v. 176, p. 101-107, 2015.

USEPA - United States Environmental Protection Agency (1996). Method 3050B: Acid Digestion of Sludges, **Sediments, and Soils**, Revision 2. Washington DC

Vromman, D; Lefèvre, I; Šlejkovec, Z; Martínez, J. P; Vanhecke, N; Briceno, M; Lutts, S. Salinity influences arsenic resistance in the xerohalophyte *Atriplex* atacamensis Phil. **Environmental and Experimental Botany**, v. 126, p. 32-43, 2016.