PHOTOSYNTHETIC PERFORMANCE OF *Atriplex nummularia* LINDL. GOWN IN LEAD-CONTAMINATED SOIL AND IRRIGATED WITH BRACKISH WATER

Cicero Aparecido Ferreira Araújo[1], Martha Katharinne Silva Souza Paulino[2], Lucas Yago de Carvalho Leal[3], Stanley Lutts[4], Clístenes Williams Araújo do Nascimento[5], Edivan Rodrigues de Souza[5]

ABSTRACT: The halophyte *Atriplex nummularia* Lindl. is employed in programs for the recovery of saline soils and is also reported to be tolerant to heavy metals. The simultaneous contamination of soil by salts and heavy metals poses a growing challenge to agricultural sustainability; however, the physiological responses of this species remain little explored. This study aimed to evaluate the photosynthetic performance of this species grown in soil contaminated with lead (Pb) and irrigated with brackish water containing five concentrations of NaCl. Analyses of gas exchange and chlorophyll a fluorescence were conducted. The results showed that gas exchange parameters decreased linearly with increasing salinity. However, water use efficiency (A/E) and the photochemical efficiency of photosystem II (Fv/Fm) remained stable even under the highest NaCl concentrations, indicating that the photosynthetic apparatus of the species was not compromised. These findings highlight the tolerance of *A. nummularia* to salinity under lead contamination conditions, reinforcing its potential for use in phytoremediation strategies in degraded areas.

KEYWORDS: salinity, chlorophyll fluorescence, phytoremediation.

PERFORMANCE FOTOSSINTÉTICA DE *Atriplex nummularia* Lindl. CULTIVADA EM SOLO CONTAMINADO COM CHUMBO E IRRIGADA COM ÁGUA SALOBRA

RESUMO: A halófita *Atriplex nummularia* Lindl é empregada em programas de recuperação de solos salinizados e também é apontada como tolerante a metais pesados. A contaminação simultânea do solo por sais e metais pesados constitui um desafio crescente à sustentabilidade agrícola, porém as respostas fisiológicas dessa espécie permanecem pouco exploradas. Este

[1] Pesquisador Mestre, Departamento de Agronomia, UFRPE, Rua Dom Manuel de Medeiros, s/n, Dois Irmãos – CEP: 52171-900 Recife, PE
[2] Pesquisadora Doutora, Departamento de Agronomia, UFRPE, Recife, PE
[3] Pesquisador Doutor, Departamento de Agronomia, UFRPE, Recife, PE
[4] Prof. Doutor, Departamento de Ciência do Solo e Gestão Ambiental, Universidade Católica de Louvain, Louvain-la-Neuve, Bélgica
[5] Prof. Doutor, Departamento de Agronomia, UFRPE, Recife, PE

estudo teve como objetivo avaliar o desempenho fotossintético dessa espécie cultivada em solo contaminado chumbo (Pb) e irrigada com água salobra contendo cinco concentrações de NaCl. Foram realizadas análises de trocas gasosas e fluorescência da clorofila a. Os resultados demonstraram que as trocas gasosas apresentaram reduções lineares com o incremento da salinidade. No entanto, a eficiência do uso da água (A/E) e a eficiência fotoquímica do fotossistema II (Fv/Fm) mantiveram-se estáveis mesmo sob as maiores concentrações de NaCl, indicando que o aparato fotossintético da espécie não foi comprometido. Esses resultados evidenciam a tolerância de *A. nummularia* à salinidade em condições de contaminação por chumbo, reforçando seu potencial para uso em estratégias de fitorremediação em áreas degradadas.

PALAVRAS-CHAVE: salinidade, fluorescência da clorofila, fitorremediação.

INTRODUCTION

Abiotic stress in plants refers to any environmental condition that hinders the plant's full genetic development, such as water deficit, salinity, and heavy metals (Taiz et al., 2017). These conditions, especially the presence of heavy metals like lead and excessive salts, directly affect the photosynthetic efficiency of plants.

Lead (Pb) interferes with plant growth through various mechanisms: it induces excessive production of reactive oxygen species (ROS), leading to oxidative stress and lipid peroxidation; it compromises the integrity of cell membranes and disrupts cell division and elongation; it affects the absorption and transport of essential nutrients, altering ionic homeostasis and it reduces seed germination, root growth, and chlorophyll production, negatively impacting physiological processes such as transpiration and photosynthesis (Anamika et al., 2018).

The use of chlorophyll fluorescence parameters and leaf gas exchange measurements enables qualitative and quantitative analysis of light energy absorption and utilization, as well as the detection of potential damage to the plant's photosynthetic apparatus (Martins et al., 2020). Atriplex nummularia, a halophyte widely used in soils degraded by salinity, has been the subject of studies in the semi-arid region of northeastern Brazil (Paulino et al., 2020; Araújo et al., 2025).

However, research on the responses of the photosynthetic apparatus under lead toxicity combined with variations in soil salinity is still scarce. Therefore, the objective of this study was to evaluate the photosynthetic efficiency of *A. nummularia* grown in saline soil contaminated with lead.

MATERIALS AND METHODS

The experiment was conducted in a protected environment at the Plant Research Center (CEPEVE) of the Federal Rural University of Pernambuco (UFRPE). The soil was collected from the Manga de Baixo Irrigation Perimeter, located in the municipality of Belém do São Francisco, PE, Brazil. Samples were taken from the Bt horizon and classified as Luvisols – WRB (IUSS Working Group WRB, 2015), with a silty clay texture and saline characteristics (ECes = 14.23 dS/m).

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 incubated with lead nitrate ($Pb(NO_3)_2$) solution at a concentration of 300 mg kg^{-1} of Pb. Irrigation was carried out to maintain the soil at 80% of its maximum water retention capacity.

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.

The experiment followed a randomized block design, in which *Atriplex nummularia* Lindl. seedlings were cultivated and irrigated with five different NaCl concentrations (0, 50, 100, 150, and 200 mmol L^{-1}) to assess the influence of increasing salinity levels on the absorption and tolerance of *A. nummularia* Lindl. to Pb.Measurements of gas exchange were performed using an Infrared Gas Analyzer (IRGA), model LICOR Li-6400XT.

The following variables were evaluated: net photosynthesis (A), stomatal conductance (gs), and transpiration rate (E), with water use efficiency (WUE = A/E) calculated thereafter.Chlorophyll a fluorescence was also assessed using a portable fluorometer (Model Fluorpen FP 100), determining the following parameters: initial fluorescence (F_0), maximum fluorescence (Fm), and variable fluorescence (Fv), calculated as the difference between Fm and F_0. From these, the Fv/Fm ratio—known as the maximum quantum yield of PSII—was obtained.

The data were subjected to analysis of variance (ANOVA), and variables showing significant differences ($p > 0.05$) were further analyzed using regression analysis, assessing significance and best fit through the coefficient of determination (R^2).

RESULTS AND DISCUSSION

A significant effect ($P < 0.05$) was observed for NaCl concentration on the variables net photosynthesis (A), stomatal conductance (gs), and transpiration rate (E). No significant differences were found for water use efficiency (WUE) or for chlorophyll fluorescence variables.

Net photosynthesis showed a decreasing linear trend, with a 37% reduction between the control plants and those irrigated with 200 mmol L^{-1} of NaCl (Figure 1).

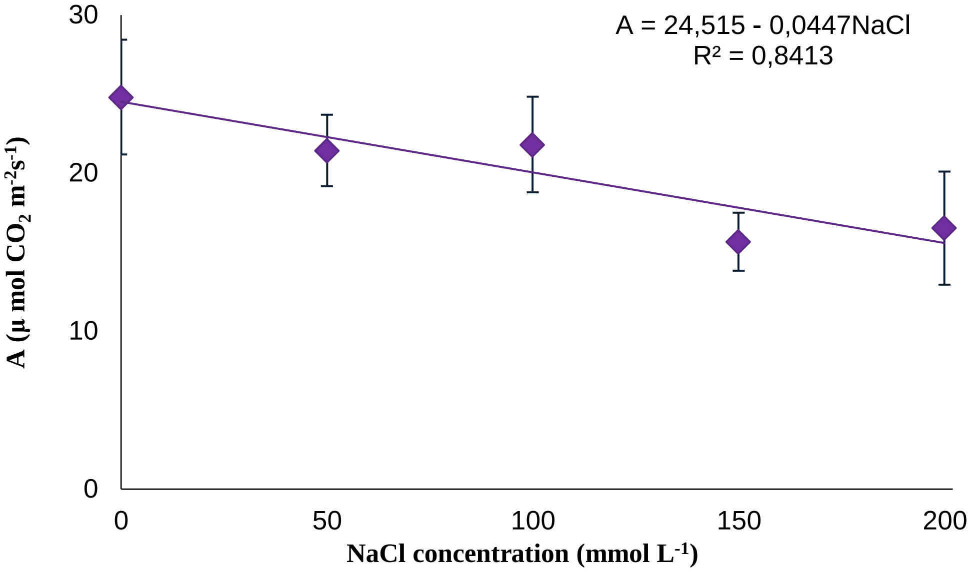

Figure 1. Net photosynthesis (A) of *Atriplex nummularia* Lindl. grown in soil contaminated with 300 mg kg^{-1} of Pb and irrigated with increasing concentrations of NaCl. Significance of regression coefficients: ** ($p \leq 0.01$) and * ($p \leq 0.05$).

Stomatal conductance also exhibited a decreasing linear behavior, with a 44% reduction in plants irrigated with 200 mmol L^{-1} NaCl compared to the control (Figure 2).

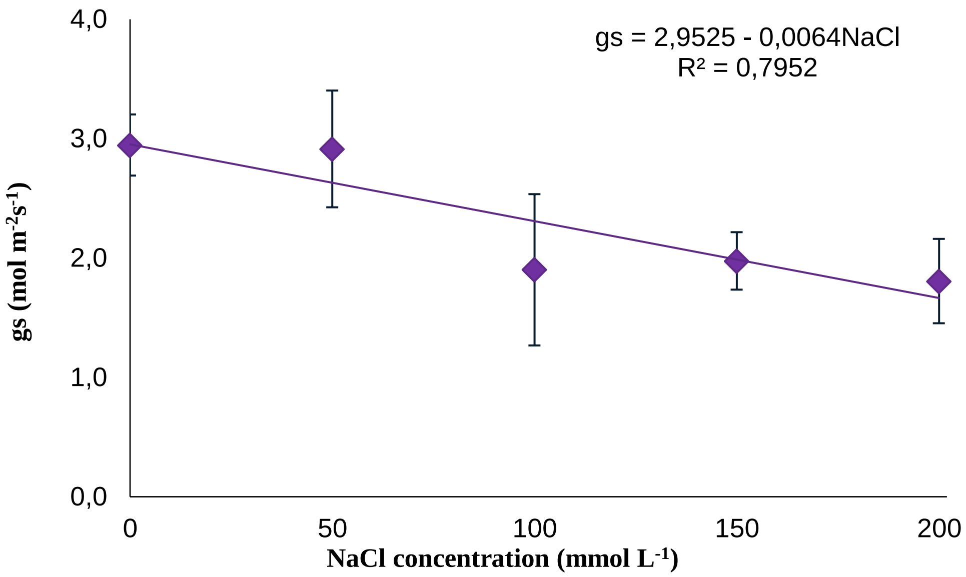

Figure 2. Stomatal conductance (gs) of *Atriplex nummularia* Lindl. grown in soil contaminated with 300 mg kg^{-1} of Pb and irrigated with increasing concentrations of NaCl. Significance of regression coefficients: ** ($p \leq 0.01$) and * ($p \leq 0.05$).

Similarly, transpiration (E) decreased by 54% in plants irrigated with 200 mmol L^{-1} NaCl compared to the control plants (Figure 3).

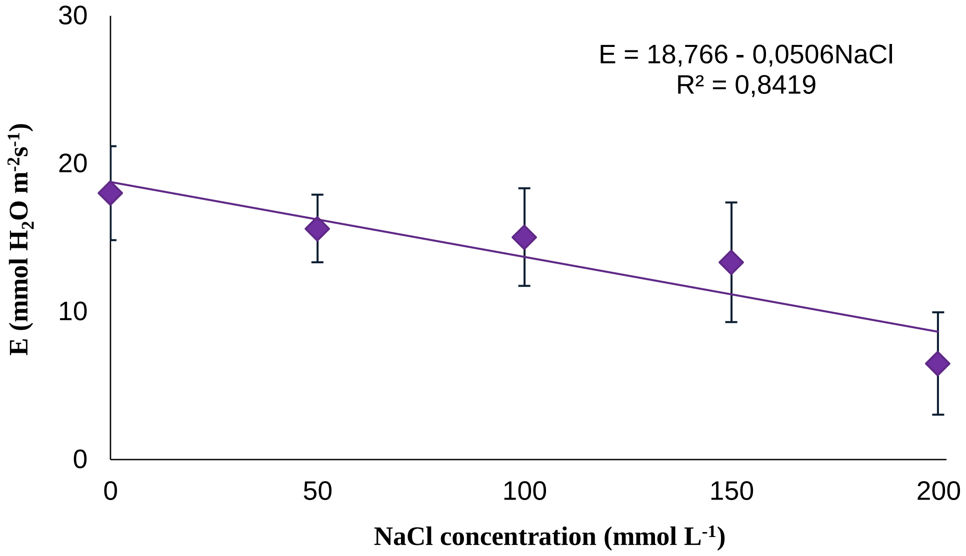

Figure 3. Transpiration (E) of *Atriplex nummularia* Lindl. grown in soil contaminated with 300 mg kg⁻¹ of Pb and irrigated with increasing concentrations of NaCl. Significance of regression coefficients: ** ($p \leq 0.01$) and * ($p \leq 0.05$).

Water use efficiency (WUE) did not differ significantly ($p > 0.05$) across NaCl concentrations, showing an average value of 0.53 (Figure 4).

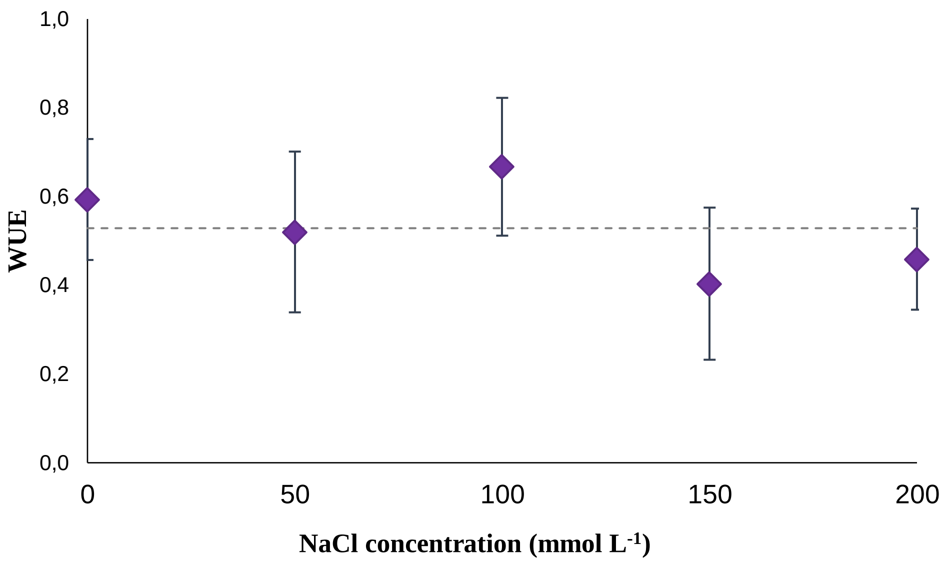

Figure 4. Water use efficiency (WUE) of *Atriplex nummularia* Lindl. grown in soil contaminated with 300 mg kg⁻¹ of Pb and irrigated with increasing concentrations of NaCl. Significance of regression coefficients: ** ($p \leq 0.01$) and * ($p \leq 0.05$).

The *Atriplex nummularia* Lindl. generally performs well when grown under NaCl concentrations between 100 and 300 mmol L⁻¹ (Parvez et al., 2020). However, when cultivated in soil contaminated with 300 mg kg⁻¹ of Pb, as in this study, even in the absence of visible toxicity symptoms, the gas exchange parameters showed a significant reduction with increasing NaCl concentrations.

Moreover, the maintenance of WUE values suggests that the species employed adaptive mechanisms to cope with the imposed stress, reducing stomatal conductance and consequently transpiration, thus avoiding excessive water loss.

Excess NaCl can affect the photosynthetic performance of plants, and this outcome is associated with alterations in the efficiency of the photochemical machinery of photosystem II (PSII) (Pérez-Romero et al., 2020). However, in this study, no significant differences ($p > 0.05$) were observed for the fluorescence variables, indicating the integrity and functionality of the photochemical apparatus of *Atriplex nummularia* Lindl. under salinity and 300 mg kg^{-1} of Pb. In other words, despite the reductions in gas exchange, the species was able to adapt and survive under the imposed conditions.

CONCLUSIONS

Atriplex nummularia Lindl. is tolerant to cultivation in soil contaminated with 300 mg kg^{-1} of Pb, even under increasing salinity levels. Despite the reduction in gas exchange with higher NaCl concentrations, water use efficiency and the integrity of the photochemical apparatus were maintained. These results indicate that the species employs adaptive mechanisms to minimize the effects of combined stress, confirming its potential for the phytoremediation of areas degraded by heavy metals and salinity.

ACKNOWLEDGMENTS

To the National Institute of Science and Technology in Sustainable Agriculture in the Tropical Semi-Arid Region – INCT-AGriS (CNPq/Funcap/Capes), processes 406570/2022-1 (CNPq) and process INCT-35960-62747.65.95/51 (Funcap). To National Institute of Biotechnology for the Mineral Sector – INABIM – processes: 408621/2024-9.

REFERENCES

Anamika, D. A. S.; Osborne, J. W. Enhanced lead uptake by an association of plant and earthworm bioaugmented with bacteria. **Pedosphere**, v. 28, n. 2, p. 311-322, 2018.

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.

Hassine, A. B; Lutts, S. Differential responses of saltbush *Atriplex halimus* L. exposed to salinity and water stress in relation to senescing hormones abscisic acid and ethylene. **Journal of Plant Physiology**, v. 167, n. 17, p. 1448-1456, 2010.

Melo, H. F., De Souza, E. R., De Almeida, B. G., Mulas, M. Water potential in soil and *Atriplex nummularia* (phytoremediator halophyte) under drought and salt stresses. **International journal of phytoremediation**, v. 20, n. 3, p. 249-255, 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 attributes 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.

Pérez-Romero, J. A., Mateos-Naranjo, E., López-Jurado, J., Redondo-Gómez; Torres-Ruiz, J. M. Importance of physiological traits vulnerability in determine halophytes tolerance to salinity excess: a comparative assessment in *Atriplex halimus*. **Plants**, v. 9, n. 6, p. 690, 2020.

Rangani, J., Parida, A. K., Panda, A., Kumari, A. Coordinated changes in antioxidative enzymes protect the photosynthetic machinery from salinity induced oxidative damage and confer salt tolerance in an extreme halophyte *Salvadora persica* L. **Frontiers in plant science**, v. 7, p. 50, 2016

Taiz, L., Zeiger, E., Møller, I.M., Murphy, A.,. **Plant physiology and development**. Artmed Editora,2017